Journal of Environmental Informatics 37(1) 49-61 (2021)

Journal of Environmental Informatics

www.iseis.org/jei

Conservation-Targeted Hydrologic-Economic Models for Water Demand Management

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Received 20 December 2017; revised 7 May 2018; accepted 26 July 2018; published online 11 December 2019

ABSTRACT. Two basin-wide hydrologic-economic optimization models taking into account two interpretations of water consumption are presented to estimate how much water can be conserved while maintaining at least the same level of economic output. The key characteristics of different users, such as the consumption ratio and productivity, and the interactions among users are considered. Water consumption is interpreted as either being water diverted to consumptive users or water consumed by all users. The models are applied to the South Saskatchewan River Basin (SSRB) in southern Alberta, Canada, where water scarcity is a severe issue. The results reveal that a substantial amount of water can be conserved without sacrificing the overall economic output. Specifically, irrigation users contribute the most to water conservation and experience economic losses because of less water consumption but are compensated by benefits transferred from the municipal and industrial (MI) users. Because MI users produce additional economic benefits by utilizing the conserved water, the same level of system-wide aggregated benefits is retained. A further analysis indicates that taking interactions among irrigation and MI users into account is of great importance because the overall water conservation is very limited if MI users act independently. The implications of the results are helpful for facilitating a better understanding of current water usage and can assist policy makers in making informed decision for water demand management.

Keywords: consumptive users, demand management, optimization, productivity, water conservation, water policy

1. Introduction

A shift from traditional supply-oriented management to demand management is in progress in the development of water management techniques (Richter et al., 2013; Speed et al., 2013). Supply management seeks to increase water availability to meet the growing demand, whereas demand management attempts to promote efficiency and productivity of water use such that future demand does not exceed water availability. In the context of an intense competition of limited water resources, demand management is playing an increasingly important role as a complement to supply management, and perhaps should be given higher priority over supply management. In fact, it is very important to integrate demand and supply management, such that they can be simultaneously adopted in the effective management of water resources.

Studies on water demand management (WDM) can be broadly found in the literature, ranging from technologic, hydrologic, economic, legal, even to psychologic perspectives (Stevens et al., 1992; Baumann et al., 1997; Renzetti, 2002; Maas, 2003; Butler and Memon, 2006; Kindler, 2010; Kampragou et al., 2011). A number of applications of WDM are reported globally in the literature (Kreutzwiser and Feagan, 1989; Kenney et al., 2008; Kampragou et al., 2010; Tsai et al., 2011; Araral and Wang, 2013). It is found that most existing studies focused on one particular sector, especially residential sector. However, there are extensive interactions among different sectors, like municipal, industrial, and agricultural sectors, in which changes of water consumption in one sector may affect, positively or negatively, the water availability to other sectors. In addition, WDM beyond the sector level could provide more viable options by enabling the integration of demand-side and supply-side management for enhanced water management. Therefore, it is of significant importance to investigate WDM at the scale of inter-sectors, such as at the basin level.

WDM at the basin scale can be considered from two perspectives: either increase aggregated benefits given the currently available water, or decrease aggregated water consumption without a sacrifice of total benefits. The former perspective was examined in the work of Xiao et al. (2016), and the latter perspective is investigated in this paper. This investigation provides a better understanding of current water usage, and can be used to set achievable conservation targets for WDM policy design.

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ISSN: 1726-2135 print/1684-8799 online
 doi:10.3808/jei.201900418

To design a policy for WDM, one must first determine the potential of having water conservation in a region and how would conservation activities in one sector affect other sectors, which still remains unclear in existing studies. In this investigation, the problem of how much water can potentially be conserved without decreasing the total benefits is estimated by using the proposed optimization-based method considering the interactions among various sectors in a basin. Unlike most existing studies which investigated only one particular sector, the incorporation of interactions among various sectors in this study makes the proposed method more realistic and suitable for being applied to real case studies. Some key characteristics of different users are also taken into account in the proposed method, such as total demand, consumption, productivity and seasonality. Moreover, depending on different interpretations on how to measure the amount of conserved water, two formulations of water consumption: minimum water withdrawal by consumptive users or minimum water consumed by all users, are proposed and used to construct two basin-wide hydrologic-economic optimization models. The results of water withdrawal, water consumed, and the economic implication of water utilization are examined under both formulations. The models developed are applied to the South Saskatchewan River Basin (SSRB) in southern Alberta, Canada, where the majority of the provincial population live with limited water.

2. Perspectives on Water Demand Management

From various more complex definitions of WDM (Tate, 1989; Savenije and van der Zaag, 2002; Brooks, 2006), it can be concluded that WDM aims at improving water use efficiency and productivity through a series of socially beneficial strategies. How to quantitatively measure the improvement needs to be answered before any attempt of WDM implementation is made (Brooks, 2006). Hence, a concept called water productivity (WP) was proposed by Molden (1997), and it is defined as the ratio of benefits gained from water utilization to the amount of water used to produce those benefits (Molden et al., 2010; Cai et al., 2011). When operational costs are taken into account, net benefits can be calculated by extracting the costs from the benefits. A modified version of the definition for water productivity can be expressed as:

$$\text{WP} = \frac{\text{Net benefits gained from water use}}{\text{Water input}} \tag{1}$$

The numerator, net benefits gained from water use, can be expressed by physical outputs, economic values, or other feasible measurements; while the denominator, water input, can also be examined in several forms depending on the study objecttives under consideration, such as gross/net inflow or evapotranspiration (Cai et al., 2011). Based on Equation (1), an improvement of WP can be achieved from two aspects: (1) to increase net benefits produced from water utilization given the currently available water; and (2) to decrease water input subject to achieving net benefits not less than the current ones. These two aspects imply two underlying principles for modeling purpose: either to increase aggregated net benefits given the currently available water or to decrease aggregated water consumption while achieving net benefits not less than current ones.

The calculation of WP involves the estimation of both net benefits and water use. Hydrologic-economic models are commonly used to study water management problems, such as the one in this paper, since these models consider the hydrologic, operational, and economic aspects of a water system in an integrated manner and capture key hydrologic and economic features within a coherent framework (Harou et al., 2009). A comprehensive overview of hydrologic-economic models, includeing how to design a hydro-economic model and its main application areas, can be found in the work of Harou et al. (2009). Optimization, rather than simulation techniques, is selected in this paper since the problem studied is “what is the best” type of question.

According to the two aforementioned principles, different optimization problems can be formulated: the former one implies to maximize net benefits as the main objective subject to the constraints of water availability, for which one can refer to the work of Xiao et al. (2016); while the latter indicates to minimize water consumption as the primary target constrained by physical requirements and net benefit goals, which is examined in this paper. Most existing hydro-economic models focus on estimating the maximum net benefits (Wang et al., 2003, 2008a; Harou et al., 2009), while few studies use the second principle. In fact, a key issue within the WDM context is to investigate how much water can be conserved without sacrificing economic output, which constitutes the application of the second principle discussed earlier. This investigation can be of great benefit to policy makers to determine an achievable conservation target considering various physical and policy constraints.

With respect to water conservation, one main purpose is to reduce unnecessary water consumption, either by end users or during transportation, in a socially beneficial manner to complete a specific task or to achieve a desired objective. A traditional way to measure water consumption is to calculate the total water diverted to consumptive users. However, this measurement does not take into account various return flow ratios of different users. For instance, a thermoelectric power plant may withdraw a large amount of water for cooling purposes, but most of its withdrawal is returned to the water source after treatment and is available for diversion by downstream users. Ignoring the return flows could significantly impact the water balance equations in a water system and thereby result in an overestimate or underestimate of conservation, as demonstrated by a simple example in the research of Huffaker and Whittlesey (2003). Therefore, an alternative measurement of consumption is designed in which return flows from upstream users are considered as a source of water for downstream users, and only the portion of water not available for other users is calculated as consumption. Moreover, water losses during transportation constitute a large portion of unnecessary consumption. These transportation water losses are also taken into consideration in the alternative measurement.

3. Key Characteristics of Consumptive Users

According to the purpose of water requirements, all water uses are grouped into the following broad categories: municipal, large industrial, waste dilution, agricultural, hydropower, and navigation purposes (Gupta, 2016). Among them, agricultural, industrial, and municipal users are the three main types of consumptive users which typically refer to "water that is unavailable for reuse in the short term in the water sources from which it was extracted" (Gleick et al., 2011). In agriculture, water demand includes the need of water for raising crops (irrigation) and for breeding livestock (factory farm). Thermoelectrical power plants and large water-consuming manufacturers, such as steel, paper, textiles, chemicals and petroleum refining, constitute main industrial water users. Municipal water usage generally refers to water utilized for domestic (residential), commercial and public facilities in a city. These three typical consumptive users possess distinguishable characteristics in terms of total demand, consumption ratio, and sensitivity to price, productivity and seasonality.

With respect to total water demand, agricultural demand is the largest worldwide whereas demand in the municipal and industrial (MI) sectors is increasing significantly (Shiklomanov, 2000). Almost 70% of the extracted fresh water is utilized for crop-raising activities globally (FAO, 2013), and more water is required in order to produce more food in the future. The demand of MI users is expected to increase rapidly in the near future due to burgeoning urbanization and industrialization. More specifically, the increase between 2000 and 2050 will mainly come from manufacturing (400%), electricity generation (140%), and domestic uses (130%) (Leflaive et al., 2012). Because of agriculture's large share in total water demand, a small reduction in agriculture use may provide a substantial amount of water for other users. A study in southern Alberta indicates that a 4.6% improvement in irrigation efficiency could conserve enough water to cover the annual demand of all municipalities in the basin (AIPA, 2010). As a result, agriculture is believed to have the most significant potential to free-up water for other users.

Moreover, agriculture is also the largest water consumer in most regions, since it consumes a majority of the water it takes. For instance, agriculture in Canada accounted for only five percent of total water withdrawal in 2013, but was still the largest water consumer (ECCC, 2017a). In contrast, most water withdrawn by MI users are returned to the water body, which means water consumed is much less than the water taken by them. It is reported that less than 10% of global water consumption comes from MI sectors (Richter et al., 2013). Consequently, agriculture should be the first sector to investigate in order to reduce overall water consumption in a region.

Because water is a scarce resource, economic instruments, such as price, can be introduced for managing water demand like an economic good. Many studies have been conducted on estimating the price elasticity of water demand for both the MI (Arbués et al., 2003; Olmstead and Stavins, 2009) and agricultural sectors (Scheierling et al., 2006). Empirical studies suggest that elasticity in the municipal sector is relatively low, with an average value of −0.51, and normally varies from case to case (Espey et al., 1997). Industrial usage is inelastic as well, with an average elasticity of −0.29 and ranging from −0.79 to −0.1 according to an investigation of 51 industrial plants in France (Reynaud, 2003). Agriculture water usage is also not very sensitive to price changes, with a mean value of price elasticity of −0.48 (Scheierling et al., 2006). With increasing competition for valuable water resources, price signal plays an important role in WDM, but needs to be evaluated carefully according to specific conditions of dif- ferent cases.

Value of water utilization also varies from sector to sectors. How much benefit can be generated by one user can be estimated by using statistical methods or optimization models. Benefit functions constitute an appropriate form to indicate the relationship between water consumption level and benefits generation. The benefit functions can be represented by different structures like linear, quadratic, or inverse demand forms (Wang et al., 2008a, b). With respect to the benefits produced per unit of water, MI users generally perform better than agriculture users. Consequently, many studies on efficient use of water resources suggest water transfer from low-value users to high-value ones (Booker and Young, 1994; Mahan et al., 2002, Wang et al., 2008b).

Another important feature of agriculture demand is its seasonality. Specifically, agriculture normally requires a sizable amount of water during the crop growing season, and much less water during the other months of the year; while the MI demand is generally evenly distributed throughout the year. The foregoing characteristics of different water users are reflected in the input data and parameters of the optimization models described in the next section.

4. Hydrologic-Economic Optimization Models

As indicated by Harou et al. (2009), most hydrologic-economic models consider a water system as a set of physical components connected by conveyance links. This node-link format captures key hydrologic and engineering features of a water system such as hydrologic flows, storage nodes, demand sites, and spatial distribution of the components. Moreover, economic aspects like costs or benefits can be easily taken into account when economic activities are occurring at certain nodes.

Consider a river basin represented by a node-link network $G(K, L)$ where $K = \{k_1, k_2, \ldots, k_m\}$ denotes a set of nodes representing physical components, such as reservoirs or demand sites, of the river basin, and $L = \{(k_1, k_2): k_1, k_2 \in K$ and $k_1 \neq k_2\}$ stands for a water conduit connecting two nodes k_1 and k_2 (Wang et al., 2007). Let $N = (1, 2, \ldots, i, \ldots, n)$ be a subset of nodes representing consumptive users, and the overall planning period is defined as $T = \{1, 2, \ldots, t, \ldots, \tau\}$.

In the proposed method, the main objective is to estimate the minimum requirement of total water consumption during all planning periods, subject to various physical and policy constraints, without decreasing the total benefits. Based on the two different interpretations of water consumption specified for

WDM: water withdrawal by consumptive users or water consumed by all users, two different formulations are developed. The former with the minimum water withdrawal objective (refers to "minimum withdrawal formulation" hereafter) is expressed as:

$$\min Q_W = \sum_{t \in T} \sum_{i \in N} Q(i,t)$$
$$\text{subject to} \begin{cases} h(Q) = 0 \\ g(Q) \geq 0 \\ Q \in \Omega \end{cases} \tag{2}$$

where Q_W indicates the total water withdrawal by consumptive users, and $Q(i, t) = \sum_{(k,\, i) \in L} Q(k, i, t)$ means the sum of all flows towards user i during period t; $h(Q) = 0$ and $g(Q) \geq 0$ represent the equality and non-equality constraints respectively, which are given in Equations (5) to (13); and Ω is used to denote the feasible solution space of the problem. The latter with the minimum water consumed objective (refers to "minimum consumed formulation" hereafter) is shown as:

$$\min Q_C = \sum_{t \in T} \left(\sum_{k \in K} Q(k,t) \times e_N(k,t) + \sum_{(k_1,k) \in L} Q(k_1,k,t) \times e_L(k_1,k,t) \right)$$
$$\text{subject to} \begin{cases} h(Q) = 0 \\ g(Q) \geq 0 \\ Q \in \Omega \end{cases} \tag{3}$$

where Q_C implies the total water consumed by all users, including water loss during transportation, and $Q(k, t) = \sum_{(k_1,\, k) \in L} Q(k_1, k, t)$. The term of $e_N(k, t)$ means the consumption coefficient (the ratio of water that is not returned to the water source) of node k during period t, and $e_L(k_1, k, t)$ is the water loss coefficient during transportation due to evaporation or seepage in the link (k_1, k) during period t. These coefficients are considered as given parameters in this paper, and the specific values are described in the case study section.

There are three major types of constraints in these models: physical constraints, policy restrictions, and system control rules. The physical constraints mainly consist of water balance equations and capacity limits. Water balance equations normally are used to describe the flow of water in and out of a system, and are generally expressed as (Gupta, 2016, p. 40):

$$P + Q_{SI} + Q_{GI} - E - Q_{SO} - Q_{GO} - \Delta S - \varepsilon = 0 \tag{4}$$

where P is precipitation; Q_{SI} and Q_{GI} represent inflows from outside of the system through surface water and groundwater, respectively; E means water loss by evaporation, including transpiration; Q_{SO} and Q_{GO} stand for outflows from the system in forms of surface water and groundwater, respectively; ΔS denotes the change of storage volume in reservoirs or aquifer; and ε is a discrepancy term. In practice, depending on the purpose of computation, various water balance formulations can be built. In this study, a general form of water balance equation for each node of the network during each period is written as:

$$Q_{in}(k,t) + Q_a(k,t) - Q_c(k,t) - Q_l(k,t) - \Delta S(k,t) = Q_{out}(k,t) \tag{5}$$

where $Q_{in}(k, t)$ and $Q_a(k, t)$ refer to the inflow from upstream users and adjustment flow from local tributaries to account for precipitation to node k during period t, respectively; $Q_c(k, t)$ and $Q_l(k, t)$ indicate the amount of water consumed due to economic activities and the volume of water lost during transportation, respectively; $\Delta S(k, t)$ is the change of storage volume in reservoirs or aquifers; and $Q_{out}(k, t)$ means the outflow to downstream users. This equation can be modified accordingly based on the specific type of node which it is describing. For example, for non-storage nodes ΔS is equal to zero, and for non-consumptive users, Q_c can be omitted. It should be noted that symbols of water flow (Q) in the equations of this research have the following relationship:

$$Q_x(k,t) = \sum_{(k_1,k) \in L} Q_x(k_1,k,t) \tag{6}$$

where x could imply inflow (Q_{in}), outflow (Q_{out}), water consumed (Q_c) or lost (Q_l), because in many cases, there are more than one link toward one specific site. For instance, when there exist two or more conduits from different sources to divert water to a site, the sum of water volume in all of the links constitutes the total amount of water available at that node.

How much water can be diverted to a demand site is restricted not only by the maximum demand of that site but also by the capacity limit of conduits going toward that site. Therefore, a capacity constraint is expressed as:

$$Q(k,t) \leq \min \left\{ Q_D(k,t), \sum_{(k_1,k) \in L} Q_{\max}(k_1,k,t) \right\} \tag{7}$$

where $Q_D(k, t)$ represents the maximum demand of node k during period t; and $Q_{max}(k_1, k, t)$ indicates the maximum capacity of a conduit that is used to divert water to node k during period t. The smaller value of the demand volume and the sum of capacity of all conduits flowing toward node k is the amount of water that can be diverted to that node.

In addition to the physical constraints, there are also some policy restrictions in these models. For example, one may want to relinquish all water obtained from its initial allocation, but this is not likely to happen in reality because some economic activities are required to be maintained at a certain level or because a high level of reduction is hard to achieve due to technological difficulties. A parameter ρ is introduced to indicate this conservation limit. Therefore, water diverted to node k during period t should be no less than its initial allocation minus the amount of water one can conserve, and this restriction is shown as:

$$Q(k,t) \geq Q_{ini}(k,t) \times (1 - \rho(k,t)) \tag{8}$$

where $Q_{ini}(k, t)$ represents the initial water allocation to node k during period t.

Furthermore, a reduction of water consumption should not jeopardize the performance of the system. As indicated in Equation (1), the net benefits gained from water utilization and its associated water productivity are main indicators of system performance. The net benefits are measured using net benefit functions in monetary terms here because monetizing all water uses makes comparisons among uses and net benefit transfers much easier. To indicate that net benefits would not become worse, a system control rule is specified as:

$$\sum_{k\in K}\sum_{t\in T} NB(k,t) \geq \sum_{k\in K}\sum_{t\in T} NB_{ini}(k,t) \tag{9}$$

where $NB(k, t)$ and $NB_{ini}(k, t)$ represent the net benefits obtained from water utilization, and the initial net benefits produced by using initial water allocation for node k during period t, respecttively.

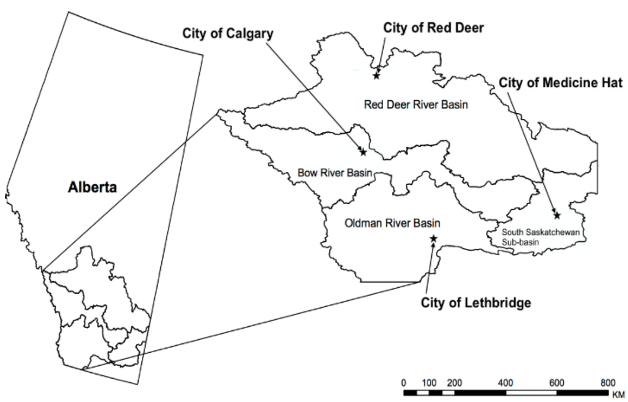

Figure 1. Location of the South Saskatchewan River Basin (SSRB) within Alberta, Canada.

The estimation of net benefits obtained from water utilization can vary depending on the types of uses. A traditional economic approach is to derive net benefits from a pricedemand curve. Additionally, constant price-elasticity forms are widely employed for estimating the net benefits of water use in the urban sector (Harou et al., 2009). In this paper, a constant price-elasticity demand function with choke price and choke quantity is utilized to derive MI uses' net benefits, as expressed by:

$$P(k,t) = \begin{cases} P_0(k,t), & 0 \leq Q(k,t) \leq Q_0(k,t) \\ \left[Q(k,t) / \alpha(k,t) \right]^{1/\beta(k,t)}, & Q(k,t) \geq Q_0(k,t) \end{cases} \tag{10}$$

where $P(k, t)$ is the price of willingness to pay to retrieve water; $P_0(k, t)$ and $Q_0(k, t)$ are the choke price and choke quantity of the price-demand function, respectively; $\alpha(k, t)$ and $\beta(k, t)$ are scale parameter and price elasticity for the water price-demand function, respectively ($\alpha(k, t) > 0$, $\beta(k, t) < 0$). The price elasticity $\beta(k, t)$ is constant within one time period and could vary slightly over different time periods. The net benefits derived from the above demand function are shown as:

$$\begin{aligned} NB(k,t) &= \int_0^{Q(k,t)} P(k,t)\,dQ(k,t) - Q(k,t)wc(k,t) \\ &= \int_{Q_0(k,t)}^{Q(k,t)} \left[Q(k,t) / \alpha(k,t) \right]^{1/\beta(k,t)} dQ(k,t) \\ &\quad + P_0(k,t)Q_0(k,t) - Q(k,t)wc(k,t) \\ &= \frac{\left(1/\alpha(k,t) \right)^{1/\beta(k,t)}}{1 + 1/\beta(k,t)} \left[Q(k,t)^{1+1/\beta(k,t)} - Q_0(k,t)^{1+1/\beta(k,t)} \right] \\ &\quad + P_0(k,t)Q_0(k,t) - Q(k,t)wc(k,t), \forall k \in \text{MI} \end{aligned} \tag{11}$$

where $wc(k, t)$ represents the supply cost per unit of water diverted to node k during period t.

Net benefits in agriculture are normally estimated by using crop-water production functions, for which quadratic equations are commonly used (Harou et al., 2009). The quadratic function for agriculture use in this paper is formulated as:

$$\begin{aligned} NB(k,t) &= b_0(k,t) + b_1(k,t)Q(k,t) + b_2(k,t)Q(k,t)^2 \\ &\quad - Q(k,t)wc(k,t), \forall k \in \text{AGR} \end{aligned} \tag{12}$$

where b_0 to b_2 are coefficients.

In an abstract node-link network, a double-direction link or two opposite-direction links between two nodes represent that there exists water flow from a source node to a demand site and return flow from that demand site to the source node. When two or more demand sites share one water source and return some water to that source node, the return flow may cause an overestimation of water available at that source node in a time period. Because return flow from one demand site is not available to other sites during the same time period, a constraint to reflect the exclusion of return flow from the available supply is written as:

$$\begin{aligned} \sum_{(k,k_1)\in L} Q(k,k_1,t) &\leq \sum_{(k_2,k)\in L} \left[Q(k_2,k,t) - Q_l(k_2,k,t) \right] \\ &\quad - \sum_{(k,k_1)\in L} \left[Q(k_1,k,t) - Q_l(k_1,k,t) \right] \\ &\quad + Q_a(k,t), \forall (k_1,k),(k,k_1),(k_2,k) \in L \end{aligned} \tag{13}$$

where the right side of the equation indicates that for time period t, total return flow from demand site k_1 to k should be subtracted from the total inflow towards source node k. The remaining flow plus local adjustment flow $Q_a(k, t)$ are the total available water at source node k during that period.

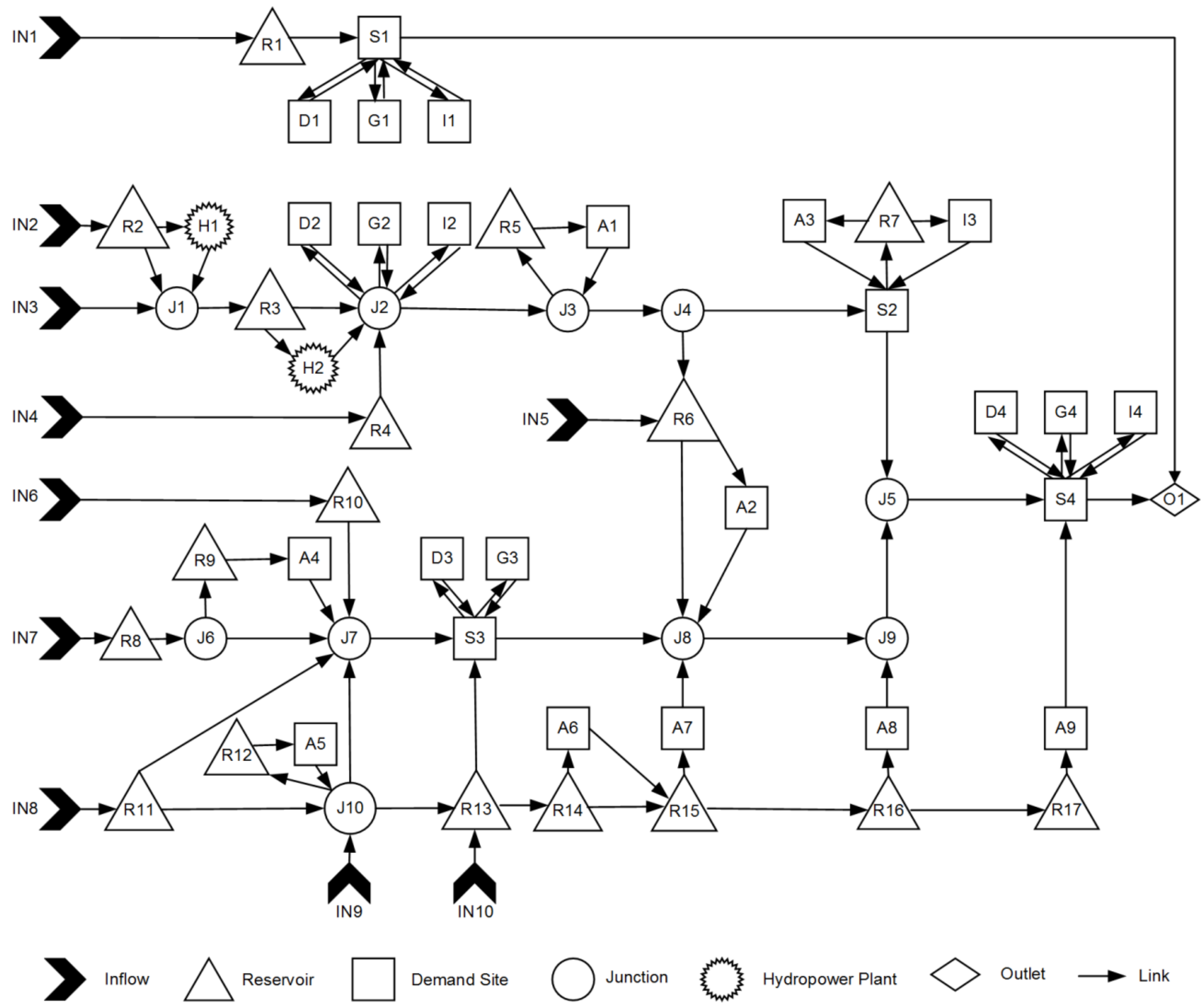

Figure 2. Network of the SSRB (based on Wang et al. (2008b)).

5. Case Study

The foregoing hydrologic-economic optimization models are applied to the South Saskatchewan River Basin (SSRB) in southern Alberta, Canada, as shown in Figure 1. The SSRB includes four major municipalities: Calgary, Lethbridge, Red Deer and Medicine Hat, and thirteen irrigation districts, which account for 13 and 75% of total water allocation, respectively, in the basin (Alberta Environment, 2003, 2007). Therefore, irrigation is the dominant water user in the SSRB. The SSRB adopts a priority-based water rights system in which a water license is required for water diversion except for the predetermined statutory right for traditional agricultural users (6,250 m^3/year) and household users (1,250 m^3/year). The application for a license follows the principle of "first in time, first in right", and hence some recent (junior) users may not be able to receive any water during water shortage periods. This restriction may prevent many heavy water-consuming industrial companies from moving into this region.

5.1. Network and Input Data

As shown in Figure 1, the SSRB is comprised of four sub-basins: Red Deer, Bow, Oldman river basins and the portion of the South Saskatchewan River sub-basin located within Alberta. An abstracted node-link network of the SSRB is depicted in Figure 2, which includes 9 irrigation, 4 domestic, 4 general, 4 industrial, 10 inflow, 1 outflow, 2 hydropower plants, 17 reservoirs, and 4 instream flow requirement nodes. In this study, 13 irrigation districts are aggregated into 9 irrigation regions according to the source of water diversion and agroclimatic conditions. Specifically, the irrigation districts of Mountain View, Aetna, United, and Leavitt are considered as one demand node, as are the Raymond and Magrath districts. General demand refers to municipal excluding domestic need, such as the demand for water for commercial, institutional and public infrastructural purposes. Irrigation, domestic, general and industrial users are categorized as consumptive users, and the remaining are non-consumptive users. Note that even though reservoirs and instream flow requirements are considered as non-consumptive users, there still is a specified demand for each of them in order to maintain a certain water depth for fisheries, recreation and ecosystem protection purposes. The names of those consumptive users and their associated nodes in the network are summarized in Table 1. Their projected annual water demand in millions of cubic meter (Mm^3) is listed in the rightmost column of the table, and the total annual demand of all consumptive users is about 3.88 billion cubic meter (Gm^3).

Table 1. Name and Annual Water Demand of Consumptive Users in SSRB

Node	Name of Consumptive Users	Annual Demand (Mm^3)
A1	Western Irrigation Region	150.65
A2	Bow River Irrigation Region	542.33
A3	Eastern Irrigation Region	861.51
A4	Lethbridge Northern Irrigation Region	381.64
A5	Mountain View, Aetna, United, Leavitt Irrigation Regions	55.58
A6	Raymond and Magrath Irrigation Region	81.26
A7	St. Mary River - West Irrigation Region	362.09
A8	Taber Irrigation Region	224.87
A9	St. Mary River - East Irrigation Region	575.83
D1	City of Red Deer - Domestic	6.03
D2	City of Calgary - Domestic	147.79
D3	City of Lethbridge - Domestic	14.15
D4	City of Medicine Hat - Domestic	7.04
G1	City of Red Deer - General	5.69
G2	City of Calgary - General	79.59
G3	City of Lethbridge - General	16.77
G4	City of Medicine Hat - General	8.35
I1	City of Red Deer - Industrial	139.67
I2	City of Calgary - Industrial	154.14
I3	Eastern Industrial Region - Industrial	15.38
I4	City of Medicine Hat - Industrial	50.99

*Mm^3: million cubic meters

Monthly water supply consists of inflows from sources and adjustment flows from small local tributaries to account for precipitation. Based on the work of Wang et al. (2008a) and data from the Water Survey of Canada's HYDAT database (ECCC, 2017b), the long term averaged annual flow of the ten inflow nodes is about 4.4 Gm^3, and inflows during the crop growing season (May to September) is higher than those during the winter season. In this study, the monthly supply data of a drought year is selected, with an annual total inflow volume of 2.19 Gm^3 and total adjustment flow of 2.31 Gm^3. It should also be noted that at least 50% of the annual natural flow must be passed on to the downstream province of Saskatchewan according to the *1969 Master Agreement on Apportionment* (Alberta Environment, 2003). Consequently, the annual outflow at outflow node O1 shall be no less than 2.25 Gm^3, which makes the water available for users in the SSRB to be more restrained. In other words, a total demand of 3.88 Gm^3 from consumptive user needs to be satisfied with 2.25 Gm^3 of water availability.

According to a detailed background study in the research area (Alberta Environment, 2003), about 75% of the water resources is allocated for irrigation purposes, and 13% for municipal usage. The prediction of future water demand reported by Alberta Environment (2007) indicated that the majority of demand increase comes from petroleum refining operations as a result of the development of the oil sands industry in Alberta. Agricultural demand will increase and stabilize once irrigation areas reach the maximum capacity, while demand in municipalities is expected to increase by a fairly small percentage.

Water is consumed during economic activities at consumptive sites with different percentages. For irrigation, it is reported that about 10 to 30% of water diverted to farms in the SSRB are returned to the water system (Alberta Environment, 2003; Adamowicz et al., 2010). In this study, the consumption coefficient for irrigation is set as 75%, and the remaining 25% is returned to the water system. For municipal users, consumption ratios are 15 and 25% for domestic and general users, respectively. In a region, there are often a number of different types of industries, which have different levels of water consumption. The average consumption level of industries in a region is utilized in this case study and various average water consumption ratios are assumed for different industrial regions. Specifically, there are four industrial regions in this investigation, and the average consumption ratios for the four industrial regions are set to 3.5, 5.1, 4.2, and 3.5%, respectively, according to the research by Mahan (1997) for the SSRB. In addition, water evaporated during transportation is set to be 3%, and could potentially be up to 7% (AIPA, 2010).

5.2. Results of the Two Formulations

The results obtained from the minimum withdrawal and minimum consumed formulations under a series of conservation limit scenarios are discussed and compared in this section. It should be noted that the aggregated economic benefits of consumptive users under all scenarios are equal to the value in the baseline scenario (1,512.7 million dollars), which indicates that the same level of economic performance is achieved under all scenarios considered within the two formulations. It is also worthwhile to mention that even though the scenario of no conservation limit is also examined, it is unlikely for one user to reduce water usage by too much in the short term. Therefore, it is more meaningful to focus on the results under low conservation limit scenarios. In fact, the consumption level change of different users can be clearly observed within a 50% conservation limit. The baseline scenario is obtained from a priority-based initial allocation method proposed by Wang et al. (2007). In the baseline scenario, the irrigation districts of Western (A1), Eastern (A3), Mountain View, Aetna, United, and Leavitt (A5), and Raymond and Magrath (A6) are able to divert water to their maximum demand, and all MI users except general and industrial demand in the city of Calgary (G2 and I2) are fully satisfied. Return flow is considered under both formulations. In the baseline scenario, the total amount of water diverted to all consumptive users is 3,467.6 Mm^3, and irrigation accounts for 2,927.3 Mm^3, which is 84.4% of the total diversion.

Table 2. System Performance under the Scenarios of Different Conservation Limits and Minimum Withdrawal Formulation

Scenarios:	Baseline	10%	20%	30%	40%	50%
Total Water Withdrawal (Mm^3)	3467.6	3151.9	2842.4	2543.9	2251.8	1967.5
Irrigation Water Withdrawal (Mm^3)	2927.3	2634.6	2341.9	2049.1	1756.4	1463.7
MI Water Withdrawal (Mm^3)	540.3	517.3	500.5	494.8	495.4	503.8
Irrigation Withdrawal Percentage (%)	84.4	83.6	82.4	80.6	78.0	74.4
Total Water Conservation (%)	-	9.1	18.0	26.6	35.1	43.3
Irrigation Conservation Contribution (%)	-	92.7	93.6	95.1	96.3	97.6
Overall Productivity ($/$m^3$)	0.44	0.48	0.53	0.59	0.67	0.77
Scenarios:	**60%**	**70%**	**80%**	**90%**	**No limit**	
Total Water Withdrawal (Mm^3)	1688.3	1411.9	1192.7	1192.7	1192.7	
Irrigation Water Withdrawal (Mm^3)	1170.9	879.1	647.1	647.1	647.1	
MI Water Withdrawal (Mm^3)	517.4	532.8	545.6	545.6	545.6	
Irrigation Withdrawal Percentage (%)	69.4	62.3	54.3	54.3	54.3	
Total Water Conservation (%)	51.3	59.3	65.6	65.6	65.6	
Irrigation Conservation Contribution (%)	98.7	99.6	100.2	100.2	100.2	
Overall Productivity ($/$m^3$)	0.90	1.07	1.27	1.27	1.27	

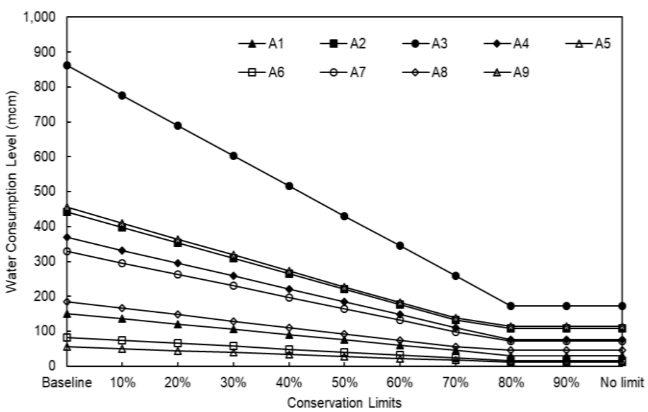

Figure 3. Water consumption level of irrigation users under the scenarios of different conservation limits and minimum withdrawal formulation.

5.2.1. Results under the Minimum Withdrawal Formulation

Under the minimum withdrawal formulation in Equation (2), the system performance considering different conservation limits are summarized in Table 2. For the scenario of having a 50% conservation limit in Table 2, the total water withdrawal by all consumptive users can be reduced to 1,967.5 Mm^3 from 3,467.6 Mm^3 in the baseline scenario, which is a 43.3% conservation. The irrigation water withdrawal accounts for 1,463.7 Mm^3, which is 74.4% of the total water withdrawal. However, irrigation contributes 97.6% of the total water conservation. The remaining 2.4% conservation comes from the MI users, whose withdrawal reduces to 503.8 Mm^3 from 540.3 Mm^3 in the baseline scenario. These findings imply that the same level of economic benefits can be produced by utilizing much less water, with conservation from both the irrigation and MI sectors. Irrigation contributes a majority of the total water usage reduction, whereas the MI usage seems hard to be significantly reduced. In an extreme scenario of having no conservation limit, the MI users even take more water than their initial allocation, thereby making irrigation's contribution more than 100%. An important indicator for system performance is the overall water productivity. As can be seen from the last row in Table 2, the overall productivity increases from 0.44 to 0.77 $/$m^3$, a 75% improvement, between the scenarios of baseline and 50% limit, and can increase more under higher conservation limit scenarios.

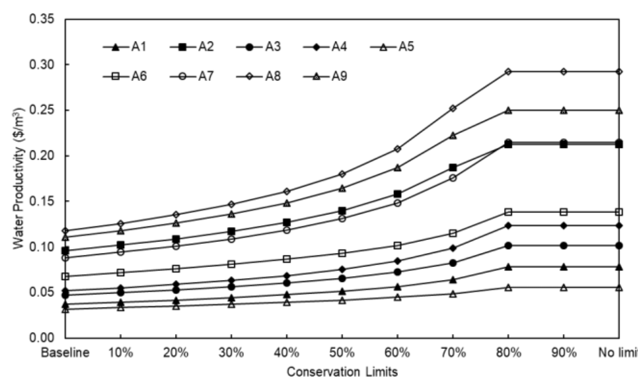

Figure 4. Productivity of irrigation users under the scenarios of different conservation limits and minimum withdrawal formulation.

In terms of the water consumption level of each individual user, Figure 3 depicts the change patterns of irrigation users. As major conservation contributors, irrigation's water consumption level change with respect to water conservation limit is obvious, as indicated in Figure 3. Specifically, all irrigation users are reducing their water usage, including the unsatisfied ones in the baseline scenario, until they reach their conservation limits under all scenarios. After the limit of 80%, the consumption level for each irrigation user remains the same because there is a minimum demand requirement equivalent to 20% of one's maximum demand. However, the water productivity of each irrigation user shows an upward trend, as depicted in Figure 4. For example, A3's productivity increases from 0.05

$/m^3 in the baseline to 0.07 $/m^3 under the 50% limit scenario, and to 0.10 $/m^3 under the no limit scenario.

In contrast, the responses of MI users are quite diversified. As can be seen in Figure 5, more water is utilized by G2 and I2 along with the increase of the conservation limit, whereas other MI users reduce their water usage to a certain level and then start to increase their usage. It is believed that marginal net benefit is the key factor influencing all MI users' responses, as it is clearly indicated in Figure 6 that all MI users' marginal net benefits are merging to the same value.

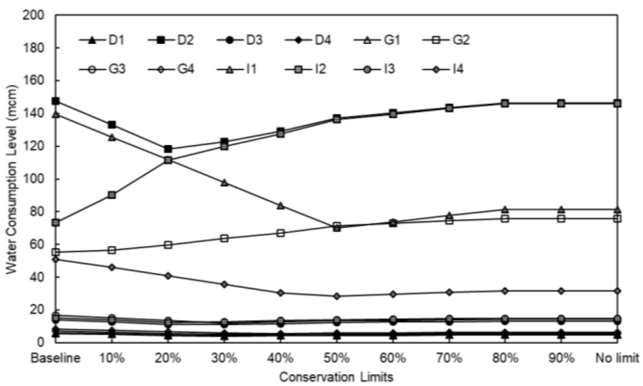

Figure 5. Water consumption level of MI users under the scenarios of different conservation limits and minimum withdrawal formulation.

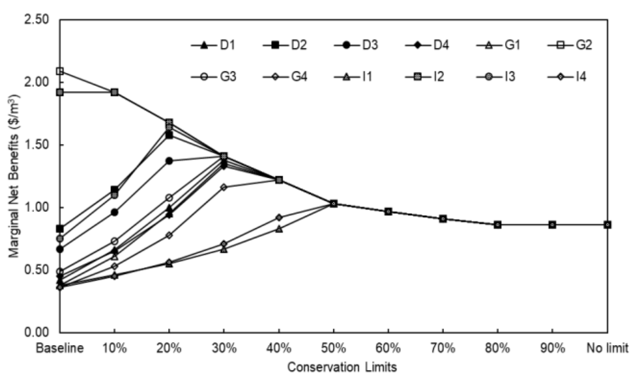

Figure 6. Marginal net benefit of MI users under the scenarios of different conservation limits and minimum withdrawal formulation.

As portrayed in Figure 6, in the baseline scenario, G2 and I2 possess higher marginal values than the other MI users. The values are 2.09 $/m^3 for G2 and 1.92 $/m^3 for I2, whereas the values of the other MI users range from 0.36 to 0.83 $/m^3. Consequently, all other MI users are reducing their water usage and their marginal values are increasing. G2 and I2's marginal values merge the earliest under the 10% limit scenario with a merged value of 1.92 $/m^3. For the other MI users, if one user's marginal value is still less than the merged value, the user will continue to reduce its water usage until its marginal value grows to the same level as the merged value. It can be seen that all MI users' marginal values become identical under the 50% limit scenario and afterwards. This implies that after the 50% limit scenario all MI users are equally efficient in terms of benefit generation. In other words, they are able to produce the same amount of net benefits with every additional unit of water, and they would increase their water usage in a proportional manner if more net benefits need to be produced.

5.2.2. Results under the Minimum Consumed Formulation

When the minimum water consumed by all users is set as the objective function following Equation (3), the resulting system performance under different conservation limit scenarios are as summarized in Table 3. Again, consider a 50% limit scenario as an example, for which the total water consumed by all users can be reduced from 2,254.3 Mm^3 in the baseline scenario to 1,153.0 Mm^3, which is a 48.9% water conservation. Water consumed by irrigation accounts for 1,097.7 Mm^3, and 55.3 Mm^3 is consumed by MI users. The share of irrigation in the total water consumed is 95.2%, but irrigation contributes 99.7% of the total water conservation. These two high percentages imply that irrigation is not only the dominant water consumer but also the major water contributor in the basin, whereas the MI users make a very minor difference in terms of water conservation. This finding is in accordance with the implication in the previous formulation, but irrigation is much more influential in this case. Since the same level of economic benefits (1,512.7 million dollars) is produced under all scenarios, it can be calculated that the overall productivity increases from 0.67 to 1.31 $/m^3 between the scenarios of baseline and 50% limit, as shown in the last row in Table 3, which makes a 95.5% improvement.

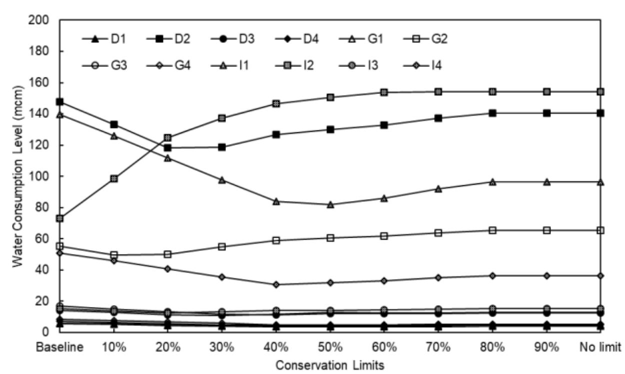

Figure 7. Water consumption level by MI users under the scenarios of different conservation limits and minimum consumed formulation.

At the individual level, the water consumption levels of the irrigation users are identical as drawn in Figure 3. The irrigation users' water productivities also show a similar upward trend in this case as in the previous formulation. This indicates that the only effective constraint for irrigation users is the conservation limit restriction. However, there are substantial differences with respect to the reactions of MI users, as depicted in Figure 7. More specifically, I2 is the only one who consumes more water under all scenarios, and reaches its maximum demand under the 60% limit scenario. In contrast, G2, which

Table 3. System Performance under the Scenarios of Different Conservation Limits and Minimum Consumed Formulation

Scenarios:	Baseline	10%	20%	30%	40%	50%
Total Water Consumed (Mm^3)	2254.3	2030.5	1808.3	1589.1	1371.1	1153.0
Irrigation Water Consumed (Mm^3)	2195.5	1975.9	1756.4	1536.8	1317.3	1097.7
MI Water Consumed (Mm^3)	58.8	54.6	51.9	52.3	53.8	55.3
Irrigation Consumed Percentage (%)	97.4	97.3	97.1	96.7	96.1	95.2
Total Water Conservation (%)	-	9.9	19.8	29.5	39.2	48.9
Irrigation Conservation Contribution (%)	-	98.1	98.5	99.0	99.4	99.7
Overall Productivity ($/m^3)	0.67	0.74	0.84	0.95	1.10	1.31
Scenarios:	60%	70%	80%	90%	No limit	
Total Water Consumed (Mm^3)	934.7	717.4	544.7	544.7	544.7	
Irrigation Water Consumed (Mm^3)	878.2	659.3	485.4	485.4	485.4	
MI Water Consumed (Mm^3)	56.5	58.1	59.3	59.3	59.3	
Irrigation Consumed Percentage (%)	94.0	91.9	89.1	89.1	89.1	
Total Water Conservation (%)	58.5	68.2	75.8	75.8	75.8	
Irrigation Conservation Contribution (%)	99.8	99.9	100.0	100.0	100.0	
Overall Productivity ($/m^3)	1.62	2.11	2.78	2.78	2.78	

Table 4. A Comparison of Water Withdrawal by MI Users between two Formulations (Mm^3)

Scenarios:	Baseline	10%	20%	30%	40%	50%	60%	70%	80%	90%	No limit
D1	0.00	0.00	0.00	-0.08	-0.17	-0.41	-0.44	-0.42	-0.40	-0.40	-0.40
D2	0.00	0.00	0.00	-3.91	-3.60	-7.44	-6.99	-6.35	-5.78	-5.78	-5.78
D3	0.00	0.00	0.00	-0.05	-0.02	-0.64	-0.72	-0.66	-0.61	-0.61	-0.61
D4	0.00	0.00	0.00	-0.05	-0.22	-0.53	-0.57	-0.55	-0.53	-0.53	-0.53
G1	0.00	0.00	0.00	-0.08	-0.55	-0.77	-0.80	-0.78	-0.77	-0.77	-0.77
G2	0.00	-6.75	-9.85	-8.64	-8.73	-10.86	-10.73	-10.51	-10.29	-10.29	-10.29
G3	0.00	0.00	0.00	-0.38	-1.25	-1.97	-2.06	-2.02	-1.97	-1.97	-1.97
G4	0.00	0.00	0.00	0.00	-0.57	-1.17	-1.22	-1.21	-1.20	-1.20	-1.20
I1	0.00	0.00	0.00	0.00	0.00	13.72	12.89	14.28	15.47	15.47	15.47
I2	0.00	8.33	13.83	17.08	18.19	14.39	14.67	10.97	7.95	7.95	7.95
I3	0.00	0.00	0.63	0.92	0.91	0.27	0.20	0.26	0.31	0.31	0.31
I4	0.00	0.00	0.00	0.00	1.90	4.20	3.93	4.33	4.68	4.68	4.68

shares the same pattern as I2 in the previous formulation, reacts differently. G2 only starts to increase its water usage when the limit is larger than 20%. The industrial users I1, I2 and I4 start to increase their consumption levels at the scenarios of 50, 20 and 40% limits, respectively. All of the other MI users are generally reducing their water usage to a certain level and then turn to increasing their water usage.

Meanwhile, the differences among MI users can also be observed in their various marginal net benefits as shown in Figure 8. Unlike the results of the same marginal value for all MI users after the 50% limit scenario in the previous formulation, marginal values in this case tend to merge based on the types of users. The general users possess the highest average marginal value, domestic the second highest, and industrial the lowest in this formulation. This is because more water is distributed to industrial users, as industrial users have the lowest consumption ratio and general users the highest. The fact that the industrial users have a favorable position is very sensible in the formulation which is targeted on minimizing water consumed by all users because industrial users consume the least percent of their water diversion among all users.

5.2.3. Comparisons and Discussions of the Formulations

The results of the two formulations provide some similar findings and also some different outcomes. Similar findings include: (a) a substantial amount of water can be conserved while producing the same level of economic benefits; (b) irrigation is the largest water contributor while MI users make a small difference in water conservation; (c) MI users make economic contributions in order to maintain the same level of aggregated benefits; and (d) overall water productivity can be considerably improved.

The water consumption levels of the MI users are different between the two formulations. These differences are calculated by using the results of the minimum consumed formulation minus that of the minimum withdrawal formulation, and are summarized in Table 4. These findings indicate that more water is distributed to industrial users. I2 is the water consumer with the largest increase when the conservation limit is 60% or less while I1 has the largest increase when the conservation limit is 70% or higher, as underlined in Table 4. Other MI users, especially G2, tend to consume less water under the minimum consumed formulation.

Table 5. A Comparison of Water Conservation Percentages among Different Formulations (%)

Scenarios:		10%	20%	30%	40%	50%	60%	70%	80%	90%	No limit
Min Withdrawal Formulation	All Users	9.1	18.0	26.6	35.1	43.3	51.3	59.3	65.6	65.6	65.6
	MI Only	0.8	1.4	1.8	2.1	2.3	2.4	2.4	2.4	2.4	2.4
Min Consumed Formulation	All Users	9.9	19.8	29.5	39.2	48.9	58.5	68.2	75.8	75.8	75.8
	MI Only	0.2	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4

Table 6. Key Indicators of Performance Obtained from Fractional Optimization

Scenarios	Baseline	10%	20%	30%	40%	50%	60%	70%	80%	90%	No limit
Total Net Benefits (Million $)	1512.7	1668.03	1652.5	1634.6	1614.1	1590.4	1557.9	1512.7	1512.7	1512.7	1512.7
Total Water Withdrawal (Mm^3)	3467.6	3262.03	2959.9	2656.6	2352.2	2046.4	1733.4	1411.9	1192.7	1192.7	1192.7
Water Productivity ($\$/m^3$)	0.44	0.51	0.56	0.62	0.69	0.78	0.90	1.07	1.27	1.27	1.27

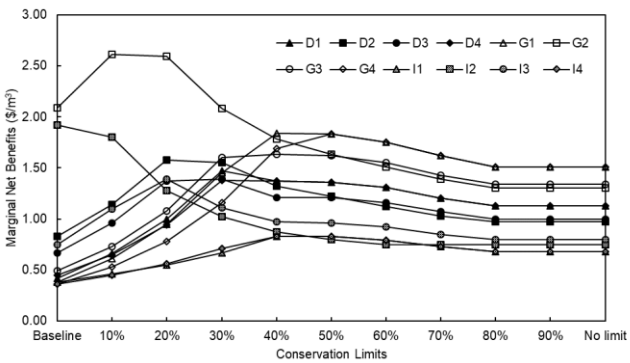

Figure 8. Marginal net benefits of MI users under the scenarios of different conservation limits and minimum consumed formulation.

It is interesting to note that a large portion of the conserved water from irrigation is not utilized by MI users, because MI users are also reducing their usage in most scenarios. This portion of water is stored in reservoirs or instream flows, and can be used to meet the requirements of ecosystem protection, fisheries or recreation. In addition, if more benefits are required from the system, the stored water can be released to consumptive users as well. It is estimated that the total net benefits can be improved by 11% when all MI users consume water to their maximum demand.

Nevertheless, this finding may raise another question: is it necessary to involve irrigation users if their conservation is not utilized by MI users? To address this question, another case, in which only MI users are involved, is built and tested by using the two formulations. Water conservation percentages under both formulations are as listed in Table 5. As can be seen in the table, if only the MI users are involved, at most 2.4% of the water withdrawal can be conserved under the minimum withdrawal formulation, and 0.4% of water consumed under the minimum consumed formulation. As a result, it is necessary to include irrigation users because both percentages are much less than those in the cases for which all users are involved. This conclusion can also be supported by the finding in the previous sections that MI users only make a small contribution to water conservation.

Furthermore, one may also be interested in assessing the maximum value of water productivity under different scenarios. To solve this problem, a fractional optimization program is designed in which the main objective is to maximize the water productivity expressed in Equation (1). Specifically, the aggregated net benefits of all of the consumptive users are considered as the numerator and the total water withdrawal is treated as the denominator. A summary of the results from the fractional optimization is listed in Table 6. As can be seen from this table, the value of the total net benefits is greater than the baseline value (1,512.7 million dollars) in some cases, but the values are decreasing along with the increase in the conservation limit until the total net benefits drop to the baseline value when the conservation limit is 70% or more. Meanwhile, the total water withdrawal also shows a descending trend, but is higher than the value reported in Table 2 under each scenario except for the cases having conservation limits of 70% or more. In fact, irrigation users still choose to conserve as much water as they are allowed under all scenarios. The differences appear on the water consumption of MI users who have slightly higher water consumption. This is also the reason for a higher value of total net benefits. In terms of water productivity, the values in Table 6 are higher than those in Table 2 under each corresponding scenario. For example, under the scenario with a 20% conservation limit, the value of water productivity from the first formulation reported in Table 2 is 0.53 $\$/m^3$, while the maximum value is 0.56 $\$/m^3$, as shown in Table 6. However, the differences in water productivity between the two sets of results are shrinking until equalizing when the conservation limit is 60% or more.

A publication on investigating water availability for future growth and economic development in southern Alberta has recently appeared. Specifically, by analyzing historical data during the past decade using a statistical method, Bennett et al. (2017) investigated the amount of unused licensed water from irrigation districts, major urban and rural communities, and transferred water. They found that on average 54.5% of the licensed allocation of irrigation districts, and 56.1% of the licensed allocation of major urban and rural communities have not been utilized during the last ten years. Hence, it was concluded that there is sufficient water for meeting future increaseing demand. However, in this study it is argued that it may be difficult to conserve more than half of their initial allocation unless the conservation limit is set to a value greater than 60%, as can be seen in Tables 2 and 3. Based on the finding that irrigation users always choose to conserve water up to the conservation limit, a high limit such as 60% means that all irrigation users utilize 60% less of their initial allocation, which is a difficult task in the real world.

However, there are two major distinctions between this study and that of Bennett et al. (2017). Firstly, their study was carried out based on licensed allocation and this investigation is founded based on initial allocation. It is argued that the initial allocation under a given water availability scenario constitutes a more sensible baseline scenario for WDM because initial allocation indicates the actual amount of water under one's control while licensed allocation only implies the maximum amount of water one can withdraw. In water shortage cases, a user with high licensed allocation may not be able to obtain any water since there are other senior users possessing higher priority for water diversion. Therefore, an initial allocation step, which may be executed by using the various allocation approaches proposed by Wang et al. (2007), is necessary before the implementation of WDM. Secondly, hydrological considerations are not entertained in their study, which may lead to an overestimation or underestimation of water availability for future needs. For instance, water in one tributary (sub-basin) is physically unavailable for users in another tributary (sub-basin) if there is no connecting conduit, and failing to consider this may result in an overestimation. In addition, return flows from upstream users can be a source of water for downstream users, and an underestimation may occur if return flow is not taken into account.

6. Conclusions

Two versions of a basin-wide hydrologic-economic optimization method are developed to estimate the minimum water requirement to produce no less net benefits under different conservation limit scenarios. The minimum requirement with a given conservation limit can be considered as an achievable conservation target for WDM. It is found for the SSRB basin that irrigation is the largest water consumer and can be the greatest contributor in water conservation, and should be the first place to investigate. MI users' main contribution is on the economic side rather than the water side, even though their reactions regarding conservation limits are diversified depending on the formulation used. It is important to involve both the irrigation and MI users for the basin-wide WDM, because without irrigation users, MI users have limited effectiveness in reducing the overall water withdrawal or water consumed without sacrificing the overall net benefits. Therefore, it can be argued that any attempt of WDM strategies in a basin without considering irrigation users could hardly be successful to alleviate water stress faced by water managers and users. By the implementation of basin-wide WDM, the overall water productivity is considerably improved on account of the significant water conservation from the irrigation sector and the economic benefits produced from MI sectors.

Overall, this study presents a hydrologic-economic perspective to estimate conservation potential in a basin, and can be utilized to assist in designing better strategies for WDM. Even though great conservation potential is observed in the SSRB case, relatively low level of successful water transfer demonstrates that converting the potential to real exercises is not easy. There are still many obstacles that need to be overcome for promoting water transfer among users in a basin, especially within a priority-based water right system. Most importantly, proper incentive is necessary to be in place in order to motivate certain users to conserve water.

Acknowledgments. The authors would like to express their appreciation to three anonymous reviewers for their constructive comments which improved the quality of their paper. They would also like to thank the Natural Sciences and Engineering Research Council (NSERC) of Canada for its financial support. The first author gratefully acknowledges the China Scholarship Council for providing him with a scholarship to carry out his doctoral studies (No. 20120671-0003).

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