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Future Water Supply and Demand in the Okanagan Basin, British Columbia: A Scenario-Based Analysis of Multiple, Interacting Stressors

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Abstract Surface water is critical for meeting water needs in British Columbia's Okanagan Basin, but the timing and magnitude of its availability is being altered through climate and land use changes and growing water demand. Greater attention needs to be given to the multiple, interacting factors occurring and projected to occur in this region if water is going to be sustainably provisioned to human users and available for ecosystem needs. This study contributes to that goal by integrating information on physical, biological and social processes in order to project a range of possible changes to surface water availability resulting from land-use, climatic and demographic change, as well as from Mountain Pine Beetle infestation. An integrated water management model (Water Evaluation and Planning system, WEAP) was used to consider future scenarios for water supply and demand in both unregulated and reservoir-supported streams that supply the District of Peachland. Results demonstrate that anticipated future climate conditions will critically reduce streamflow relative to projected uses (societal demand and ecological flow requirements). The surficial storage systems currently in place were found unable to meet municipal and instream flow needs during "normal" precipitation years by the 2050s. Improvements may be found through demand reduction, especially in the near term. Beyond the implications for the District of Peachland, this work demonstrates a method of using an accessible modeling tool for integrating knowledge from the fields of climate science, forest hydrology, water systems management and stream ecology to aid in water and land management decision-making.

Keywords Water supply and demand · Integrated water resource model · Climate change · Reservoir management · Instream flows · Mountain Pine Beetle

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1 Introduction

Although Canada has 20% of the world's freshwater stocks, a popular misperception of an abundance of *renewable* freshwater has inhibited integrated planning for water management (Sprague 2007). Many parts of Canada may not be prepared to face changes brought about by depletion of non-renewable sources, a changing climate, and increased demands for clean water (Sprague 2007). The Okanagan Basin, located in south-central British Columbia, has had a similar culture of assumed abundance, but is unique in Canada in that it has a semi-arid climate, a small catchment for renewable water, and is undergoing population growth amidst land-use change and increasing climatic variability (Taylor and Barton 2004; Okanagan Basin Water Board 2008). Thus, the region is in greater need of developing a strategy for meeting its water needs.

Surface water sources are of major importance in the Okanagan Basin, contributing 67% of the annual water demand (Okanagan Basin Water Board 2010). Precipitation occurs primarily as winter snowfall and summers tend to be warm and dry (Merritt et al. 2006). Due to these conditions, as agriculture increased in the basin in the 1940s, reservoirs were constructed in the high elevation plateaus to capture water and store it for summer irrigation (Symonds 2000). Since that time water managers have relied upon expanding surface storage in order to meet expanding water demands (Canada-British Columbia Okanagan Basin Agreement 1974; McNeill 2006).

As with many areas around the world, the paradigm of increasing storage in the Okanagan will not be sufficient to meet future water needs (Gleick 2000; Land and Water British Columbia 2004). Most locations suitable for the construction of reservoirs have either been used for that purpose or otherwise developed; filling deeper chasms for water storage remains a more complicated and expensive option (McNeill 2006). The annual snowpack has also historically served as a natural water reservoir. Over the past century however, the winter daily maximum temperature has increased by 2.4°C, decreasing the depth and duration of the snowpack (Taylor and Barton 2004). If the trend of warmer temperatures in the winter and summer continues as predicted (Cohen and Kulkarni 2001; Merritt et al. 2006) that reservoir may become increasingly unreliable in the future.

Adding to the hydrological implications of a changing climate in the region is hydrologic variation resulting from the ongoing Mountain Pine Beetle (MPB) infestation and associated salvage harvesting. Historically, forest management has only been found to significantly impact seasonal and annual water yields once over 30% of the watershed area had been harvested (Winkler et al. 2008). The MPB infestation has the potential to cause severe (>30%) forest mortality over extensive subbasins of the Okanagan where lodgepole pine (*Pinus contorta*), the primary host of MPB, dominates (Aukema et al. 2006; MacLauclan et al. 2008; Ministry of Forests and Range 2008). The large scale of these changes may cause unprecedented alteration of the timing, magnitude and quality of surface runoff (Redding et al. 2008), changes which are of particular concern to water managers in the Basin (Uunila et al. 2006).

Along with changes in water supply, many changes in water demand are predicted for the Okanagan Basin. Greater population and economic growth, spurred by the region's relatively warm climate and suitability for agriculture, are predicted to bring increased demand for water, especially in the summer months when the natural supply is lowest (Okanagan Basin Water Board 2008; Merritt et al. 2006). Greater demand for water when the margin of available water is at a minimum implies an increase in the vulnerability of the water users to smaller fluctuations in hydrology.

Fluctuation in flow relative to historic levels also has implications for aquatic life. It has been widely recognized that maintenance of flow regime is vital for the proper functioning of aquatic and riparian species (Poff et al. 1997). Climate alone is likely to alter flow regimes in this region (Miles et al. 2000; Merritt et al. 2006; Field et al. 2007). It is important to understand how changes in climate and land cover interact with increasing demand in order to determine subsequent impacts on stream flow and therefore integrity of aquatic ecosystems (Meyer et al. 2000; Palmer et al. 2008; Nelson et al. 2009).

In order to determine how the multiple and interacting factors that influence water supply and demand in the region may affect water availability in the future, we applied, calibrated and evaluated an integrated water resource model (Water Evaluation and Planning system, WEAP; Stockholm Environment Institute 1997) for a subwatershed within the Okanagan Basin. The WEAP model was employed to meet the following study objectives: (i) quantify potential changes to magnitude and timing of streamflow for a range of climate and land cover change scenarios, (ii) combine those scenarios with several water management and water use scenarios, and finally (iii) evaluate the scenarios in terms of stress on water supply for human use and aquatic life.

2 Methods

2.1 Study Area

The District of Peachland (49.78° N, 119.72° W) and the watersheds providing the majority of its water were chosen as the study area (Fig. 1). This small but growing municipality of 5,200 residents is supplied by Peachland Creek, a regulated stream (e.g. containing a

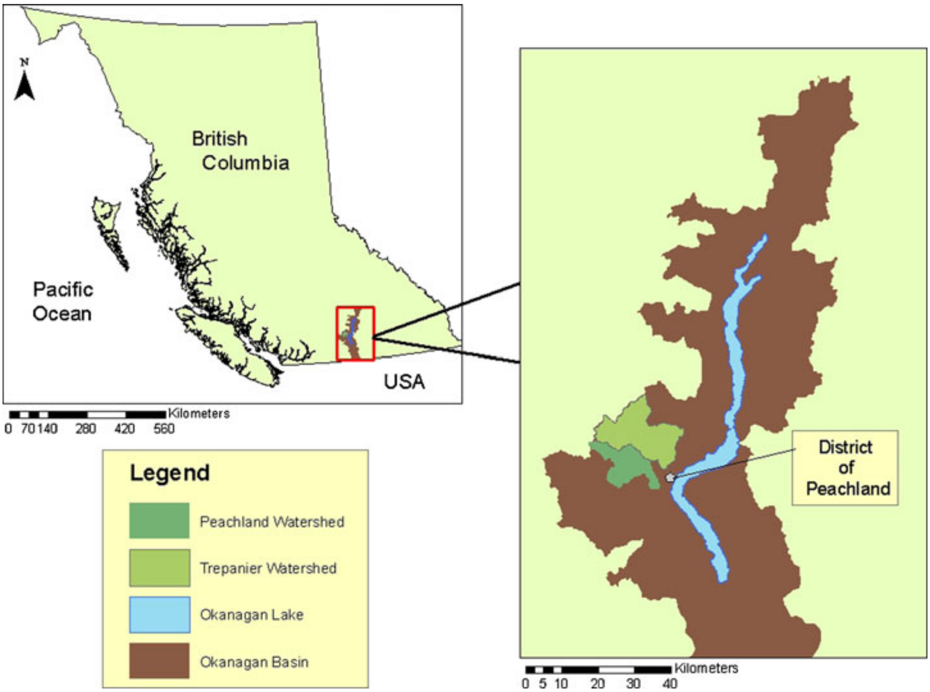

Fig. 1 Study area location

reservoir), and by Trepanier Creek, a barrier-free "natural" stream. Collectively, the two streams drain an area of 380 km^2. Historically, the combination of natural flow and reservoir storage has provided "just enough" water to meet municipal demands and instream flow needs during the low precipitation summer months (Dobson 2006). The combination of Peachland's reliance on surface water sources and its potential vulnerability to change led to its selection for a study of the impact of changing climate and land use on water resources.

The two creeks each serve a separate water system in Peachland, each with approximately half the population, so the impacts of changes in hydrology and demand in the two systems were examined separately in this study. Impacts on aquatic life in each creek were also examined separately. Withdrawals for municipal and agricultural use in the District are upstream of the major spawning and rearing habitats of the salmonids in these creeks (Kokanee (*Oncorhynchus nerka*) and Rainbow Trout (*Oncorhynchus mykiss*)), so the combined impacts of hydrological change and change in municipal demand are the greatest for the stream reaches with the greatest habitat requirements. Only preliminary work has been done on determining flow-habitat relationships in Okanagan streams (Summit Environmental 2004). The regional-scale B.C. Modified Tennant method (Ptolemy and Lewis 2002) was used for determining instream flows needed for optimal ecologic condition for Peachland Creek and Trepanier Creek (Northwest Hydraulic Consultants 2001).

2.2 Model Development and Implementation

The Water Evaluation and Planning system (WEAP; Stockholm Environment Institute 1997) was chosen as the modeling framework for the study because it integrates both hydrologic modeling and a decision support system, which allows for concurrent examination of scenarios for environmental change and water management decisions. WEAP simulates water's movement through bio-physical system components in a semi-distributed hydrologic model and then allows for comparing options for storing, allocating and delivering water for human consumptive purposes and evaluating subsequent impacts on aquatic ecosystems (Yates et al. 2005a). WEAP also accounts for water use patterns by including economic, technological and demographic variables.

The utility of WEAP as the modeling framework for this study is demonstrated by the fact that it has been applied in other areas facing challenges similar to the Okanagan Basin. It has been applied extensively in California's Sierra Nevada region to examine the impacts of climate change on downstream water users (Young et al. 2009; Purkey et al. 2007; Mehta et al. 2011), tradeoffs between agriculture and instream flow needs (Yates et al. 2005b) and to explore options for how water purveyors can meet water needs over the next century (Huber-Lee et al. 2006). Most users of WEAP have chosen this tool for its ability to pair supply and demand within a single model and to provide a practical way to examine future water resource management options (Hall and Murphy 2010; Höllermann et al. 2010; Mutiga et al. 2010; Purkey et al. 2007; Yilmaz and Harmancioglu 2010).

WEAP represents hydrologic processes through a rainfall-runoff algorithm by calculating the water balance for user-defined areas of similar hydrologic properties, or hydrologic response units (HRUs). The model was developed in this study through categorizing the study area into 39 hydrologic response units (HRUs), based on combinations of elevation, slope, aspect, land cover, and soil type. Water in each HRU at each time step is either stored in the soil, evaporated using the Penman-Monteith equation, or contributes to streamflow. Details of WEAP algorithms and variables are given in Yates et al (2005a), Young et al (2009), Hall and Murphy (2010), and the WEAP user's manual

(Stockholm Environment Institute 2007). Model structure as it applies to this study is shown in Fig. 2.

Daily streamflow data for the period 1973–2007 were obtained from the Water Survey of Canada's hydrometric database (HYDAT, Environment Canada 2007). The period from October 1983 to October 1993 has the most complete daily record for flow data, as well as temperature and precipitation data for climatic data discussed below. Thus, the study period was chosen as October 1983 to October 1993.

Landscape data, including soil type, contour lines, and vegetative land cover, were obtained as GIS files (Ministry of Agriculture and Lands 2003; Ministry of Forests and Range 2008; Ministry of Energy, Mines and Petroleum Resources 2009) and were field-verified where possible. GIS input data was processed using ArcGIS 9.0. Water infrastructure and allocation information was obtained through interviews and review of agency and consultant documents. Water use information was obtained through review of agency reports, consultant reports, and interviews.

Hydrological processes, water demands and the meeting of instream flow targets were evaluated using a daily time step. This was chosen in order to closely represent the hydrologic scale of the study watersheds, which have a time of concentration, or the time it takes a drop of water to reach the watershed outlet (Loucks et al. 1981), of approximately one day. The daily time step is also appropriate given that climate input data are available as daily averages and expected streamflow responses to precipitation events are on the scale of days, rather than weeks or months. Note that in application of WEAP to larger watersheds,

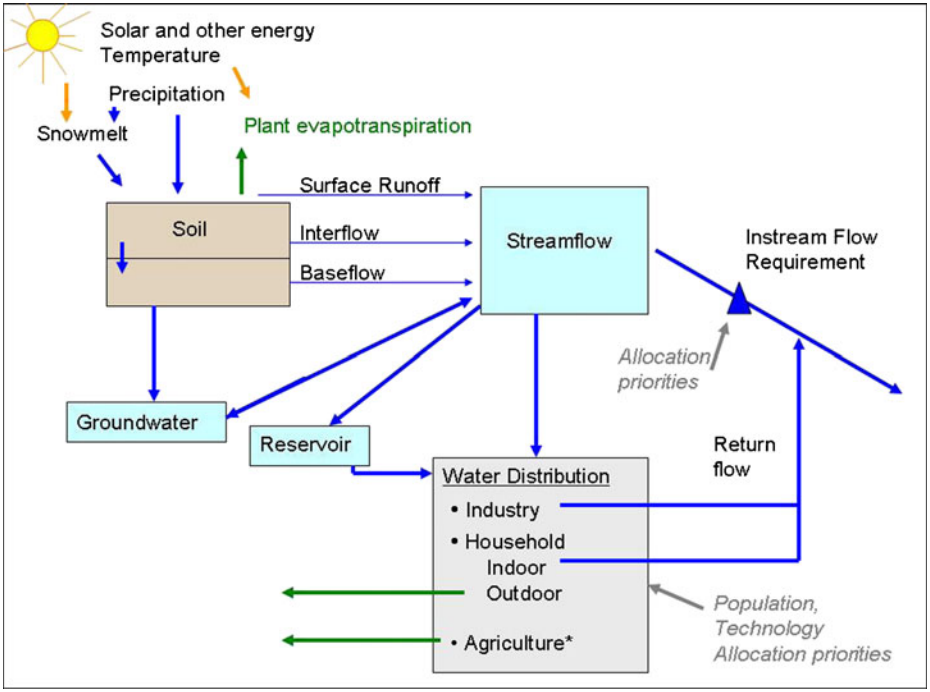

Fig. 2 WEAP functional schematic as applied in present study. Many additional components beyond those implemented in this study are available in WEAP

monthly time steps have been used (Purkey et al. 2007; Hall and Murphy 2010; Yilmaz and Harmancioglu 2010).

2.2.1 Climatic input data

Temperature and precipitation data were obtained from Environment Canada (2009) for a lower elevation climate station (Peachland, BC; 345 meters above sea level (m.a.s.l.), 49.78° N, 119.72° W) and a higher climate station (Brenda Mines, BC; 1520 m.a.s.l., 49.87° N, 120.00° W). Temperature and precipitation inputs were derived for each HRU from the climate station data based on a daily lapse rate (temperature) and monthly lapse rate (precipitation). Daily temperature data available from Brenda Mines and Peachland climate stations were used to determine the lapse rate each day of the period of record using the equation:

$$LR_T = \frac{T_U - T_L}{E_U - E_L} \tag{1}$$

where T_U is the temperature at upper station; T_L is the temperature at lower station; E_U is the elevation at the upper station and E_L is the elevation at lower station. For comparison,—0.0065°C m^{-1} is the global mean lapse rate (Dodson and Marks 1997). The average lapse rate calculated using Eq. 1 for the study period was −0.0064°C m^{-1}. The LR_T rate was used at each timestep to calculate temperature values at the mean elevation (T_E) for each HRU as:

$$T_E = T_L + LR_T(E - E_L) \tag{2}$$

where T_E is the temperature at the desired elevation, T_L is the lower station temperature value; LR_T is the temperature lapse rate determined at the time step from Eq. 1; E is the median elevation of the HRU; and E_L is the lower station elevation. For most of the study period, T_E was derived from Peachland. However, there were a few months during the study period for which the temperature data at Peachland (T_L) were not available. To determine T_E for those periods, the mean temperature lapse rate was applied to the Brenda Mines station, with T_E solved as:

$$T_E = T_U - 0.0064(E - E_U) \tag{3}$$

The low and high elevation climate stations were used to calculate a lapse rate for precipitation, LR_P. However, since precipitation did not occur every day, nor did precipitation occur on the same days at high and low elevations, an average lapse rate over each month was calculated and then applied daily precipitation data (G. Jost, personal communication). This was developed as:

$$LR_P = \frac{P_U - P_L}{P_U/(E_U - E_L)} \tag{4}$$

Where LR_P is the precipitation lapse rate; P_U is the monthly mean precipitation at the upper station; P_L is the monthly mean precipitation at the lower elevation station; E_U is the upper station elevation; and E_L is the lower elevation station elevation.

Since it more frequently at the higher elevation station relative to the lower elevation station, adding the lapse to the lower station data resulted in an excessive bias onto the days that it rained, so instead the inverse of the precipitation lapse rate was applied to the higher station to determine values for the lower elevations. This method was deemed appropriate since the mountainous conditions of the upper station were representative of larger areas of the study area than the lower elevation station.

The equation for determining daily precipitation for each HRU was then determined as:

$$P_{ED} = P_{UD}(1 - LR_P(E - E_u)) \tag{5}$$

where P_{ED} is the daily precipitation at median elevation of HRU; P_{UD} is the daily precipitation at the upper climate station; LR_P is the precipitation lapse rate; E_U is the upper station elevation and E is the median elevation of the HRU.

Data for relative humidity and wind speed are required as forcings for the model algorithms, and were only from the Kelowna, BC weather station, located at 429 m.a.s.l.; latitude: 49.96° N, longitude: 119.38° W) near the study watershed. Hourly data were aggregated to determine daily averages. Where no data were available for any hour in a day, the average of the preceding day was used to fill in the missing values.

2.2.2 Snow Processes Representation

Within WEAP, the parameter used to specify the temperature at which precipitation forms as snow was set at the default value of 0°C. A melting point value of 4 or 5°C has been used in other WEAP implementations to show that snow does not start to melt as soon as air temperature is greater than 0°C (Young et al. 2009). Setting the melting point above 0°C accounts for the model representation of the snowpack whereby the temperature of the entire snowpack has to be brought to the melting point before melt can occur. A value of 4°C was chosen for use here.

An additional physical representation of the snowmelt process is provided through a decaying albedo parameter that represents "ripening" of the snow surface of old snow. A daily albedo decay rate was applied to dynamically decay albedo on the daily time step in this model, implemented within WEAP as a "user-designed variables". Here, an albedo decay rate of 0.019 day^{-1} was used. This is the approximate rate of decay determined based on research by the U.S. Army Corps of Engineers (1956) and approximately the same rate as found from measurements in B.C. forests and clearcuts (Boon (2009) reports a change in albedo from 0.8 on April 1 to an albedo of 0.2 on May 1, which is equivalent to a daily decay rate of 0.0194 d^{-1}).

To account for the fact that sometimes snow fell after the albedo already began to decay, the snowmelt routine was modified so that additional snow less than 10 mm did not bring the albedo value up to the high value (0.85) but kept the albedo at the value of the previous day before the snowfall.

2.3 Model Calibration and Evaluation

Calibration and validation periods were selected from within the 1983–1993 period for which hydrologic and climatic data were most complete. Separate three-year periods were used for calibration and validation, with performance of the calibrated model then assessed across the whole time series. The calibration and validation period were chosen for time periods where complete daily data were available for temperature and precipitation at both the Peachland and Brenda Mines climate stations, stream flow (Gauge 041 in Trepanier Creek, and Gauge 173 in Greata Creek in the Peachland Creek basin (Environment Canada 2007)), and snow water equivalent (SWE) (River Forecast Center at Brenda Mine (Station 2 F18, 1520 m.a.s.l.) and MacDonald Lake (Station 2 F23, 1780 m.a.s.l.) (Ministry of Environment 2009).

Calibration and validation period were selected from the 3-year blocks where data were most complete. For Trepanier Creek this was Oct 1983–Sept 1986 (calibration) and Oct 1990–Sept 1993 (validation). For Greata Creek this was Oct 1973–Sept 76 (calibration) and Oct 1983–Sept 1986 (validation). The mid 1970s and 1980s were appropriate as a calibration periods given land use conditions: less than 2% of the watersheds had been harvested (Ministry of Forests and Range 2008), meaning the hydrology reflected mostly "natural" land cover conditions. Landscape parameters in GIS were adjusted as necessary in order to reflect the addition of some clearcuts present during the validation period without adjusting calibrated model hydrologic response parameters. Additionally, the validation period was adjusted relative to the calibration period to reflect changes in interbasin diversions at the Brenda Mines site.

For calibration, the modeled snowpack was first adjusted to match historic SWE data (Ministry of Environment 2009). The model was then calibrated to optimize the best fit for timing of snowmelt against date of depletion data from aerial surveys (Dobson 2003). Final calibration of the melting rates required beginning albedo decay 5 days earlier than generated by the model. Soil and vegetation data were utilized for calibration of nine landscape parameters in WEAP. Final adjustment of all parameters assured that modeled streamflow most closely approximated measured streamflow data.

The calibration resulted in a model that neither under nor over-predicted annual streamflow volumes (10-year measured vs. modeled water balance differed by −1%), produced a good representation of baseflow, and adequately represented the storm events and spring snowmelt over the hydrograph as a whole (Fig. 3). The Nash-Sutcliffe Efficiency index of hydrologic model performance was calculated on natural log-transformed values (NSE_{ln}), and ranged from 0.66 to 0.76 on an annual basis.

2.4 Scenario Development

The nine years of the daily time series (1983–1993) served as the "baseline" scenario in this study. The longest time series for which precipitation data were available for the high elevation climate station (1973–1993) was used to determine the relative precipitation regimes in this baseline period. The total precipitation data for each year were divided by

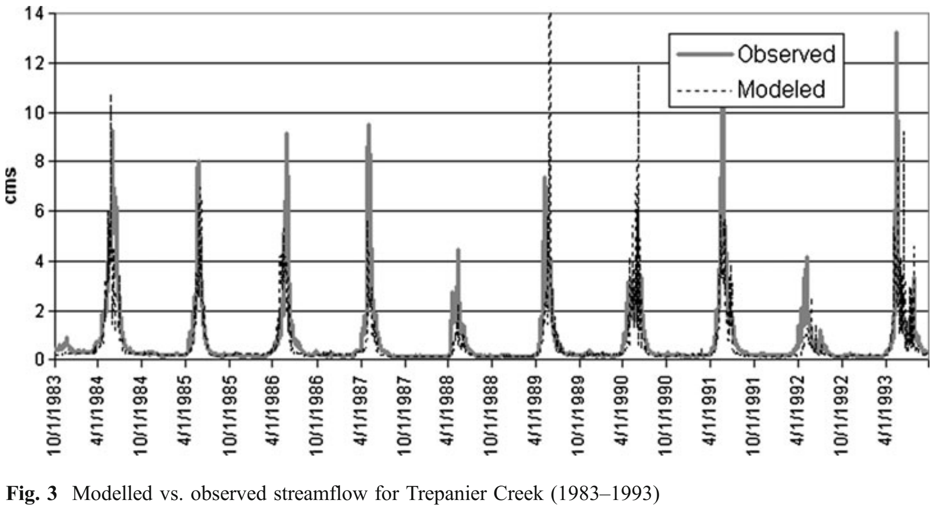

Fig. 3 Modelled vs. observed streamflow for Trepanier Creek (1983–1993)

quintile, with the highest values representing "very wet" years, and the lowest representing "very dry." All five precipitation quintiles were found within the nine-year baseline series. The climate scenarios utilized in this study were then built as perturbations of the baseline time series, and therefore also capture a range of climatic conditions. Climate and land use scenarios were also paired with two water use estimates and two reservoir release scenarios. The full suite of scenarios evaluated is listed in Table 1, and is described in detail in the following sections.

The hydrologic changes were evaluated using paired *t*-tests between annual streamflow for baseline vs. scenario conditions. Monthly variation was assessed using paired *t*-tests and the Indicators of Hydrologic Alteration software (Richter et al. 1996) in order to assess how the changes would affect aquatic life.

2.4.1 Climate Change Scenarios

Climate change scenarios were developed using two global climate models (GCMs), CGCM2 and HadCM3, for two time periods (2020s and 2050s). Both GCMs were applied to the study area using the A2 emissions scenario. The Canadian Global Coupled Model, version 2 (CGCM2) provided the most conservative estimates of impacts of climate change in a modeling study by Merritt and Alila (2004) showing slight increases in summer mean temperatures and an increase in summer precipitation, and the HadCM3 showed greatest increase in summer mean temperatures and greatest decreases in summer precipitation. Therefore, these two models were deemed appropriate show a wide range of possible impacts. Selection of an emission scenario was based on a desire to show the more extreme impacts possible under future climate change. The A2 SRES scenario represents a mid- to high-range projection for CO_2 emissions (Nakicenovic et al. 2000) and thus was chosen to examine what may happen to water resources under more extreme climatic conditions.

Precipitation projections were derived from the GCM grid over the Okanagan (CCIS Project 2003). Temperature data were obtained from the Climate BC project (Wang et al. 2006) which adjusted PRISM derived temperatures (Daly et al. 2002) to elevation. In order to downscale the regional precipitation data to the study area HRUs, the "delta" method

Table 1 Summary of scenarios evaluated

Theme	Description	Scenario
Climate Change	2020s - CGCM2	2020s CGCM2
	HadCM3	2020s HadCM3
	2050s - CGCM2	2050s CGCM
	HadCM3	2050s HadCM3
Drought	Prolonged drought (3 years like 2003) occurring under 2020s climatic conditions (CGCM2, 2020s)	Drought+ 2020s
Mountain Pine Beetle	MPB attack affecting all mature pine in HRU	
	During baseline climate conditions	MPB Only
	In context of climate change (CGCM2, 2020s)	MPB+ 2020s
Water Use	Activity-based (derived from use per activity)	Lower estimate
	Extraction-based (derived from source extraction metering)	Higher estimate
Reservoir Release	Low initial volume, baseline release rate	Low release
	High initial volume, lower release rate	High release

was used whereby each daily value was perturbed by the percentage of change projected (Loukas et al. 2004). For precipitation values, each day with precipitation was adjusted by the average percent change value given for each month. This method creates a scenario where only total volume of precipitation differs between baseline and future climate scenarios, not number of days with precipitation. However, since dry periods are expected to become longer and drier under future climate change (Field et al. 2007), drought scenarios were also developed as one way to explore acute changes in precipitation regimes. For the drought series, precipitation data were used from 2003, a recent and severe drought year in the study area was utilized for the 4th, 5th, and 6th years of the 9-year scenario. For the remaining years, precipitation data was altered by the CGCM2 (2020s) GCM downscaled to each HRU.

2.4.2 Land Cover Change Scenarios

The Mountain Pine Beetle (MPB) scenarios were designed to characterize the hydrologic response that might be expected from an insect outbreak similar to what has occurred in extensive areas of British Columbia. Due to the slow death and loss of limbs of beetle-attacked trees, the greatest hydrologic impacts are expected to occur 15 to 20 years post-attack (Huggard and Lewis 2007). Therefore, MPB simulations were set to begin 15 years post-outbreak for HRUs with lodgepole pine stands. One scenario was developed for baseline climate conditions in order to examine the impacts of the MPB attack alone, and a second scenario was developed for MPB occurring under simulated climate of the 2020s.

Forest conditions after a MPB attack lead to a reduction in interception of precipitation by the tree canopy, a faster snow melt rate, and a reduction in evapotranspiration (Redding et al. 2008; Spittlehouse 2006; Winkler et al. 2009). Reduced interception was represented in WEAP by increasing incident precipitation such that snow accumulation represented by the model corresponded to the difference in snow accumulation between forested and open areas in the study region, as reviewed by Winkler et al. (2009). The snowmelt rate of forested areas was increased to achieve expected rate of melt under open areas (Winkler et al. 2009) by increasing the values of within model parameters (e.g. the Rnet_other variable as described in Young et al. 2009). Evapotranspiration was reduced through reduction of the values of the Kc variable in WEAP, which modifies the Penman-Monteith equation (Stockholm Environment Institute 2007).

For the MPB in the 2020s climate scenario, precipitation values were determined by first altering precipitation based on projected climate change influence (based on the CGCM2 2020s A2 GCM downscaled to the study area), which were further adjusted for each HRU to account for reduced interception of an open area vs. a forested area. Temperature values from the CGCM2 2020s scenario were used in place of baseline values in this scenario.

2.4.3 Water Use Estimates

Water use is not metered in most municipalities in the Okanagan Basin, including the District of Peachland (Maurer 2010; Dobson 2006). Thus, the model could not be populated with data on water use by sector. To account for the most likely range of possible water use values, two estimates of water use were developed. The first method, referred to here as the "activity-based" estimate, was developed by using population data from 2008 (Economic Development Council 2009) combined with an extrapolation of the expected amount of water use per capita based on several consultant reports (Summit 2004; Urban Systems

2005). The second method developed is referred to as the "extraction-based" estimate and was derived values from metering that did occur for water extracted from Peachland and Trepanier Creeks over the period from 1999 to 2002 (Urban Systems 2005). As the usage estimates differed by over 60%, they were utilized in model scenarios as high (extraction-based) and low (activity-based) values for water use. The activity-based approach resulted in an estimate of 3.24 million m^3 of water demand per year, with the extraction-based approach estimating 5.31 million m^3 per year for the baseline period.

For future projections based on the activity-based estimates (e.g. low demand), projected increases were set by population growth estimates based on the community build-out projections (Summit 2004) multiplied by use rates for domestic indoor and outdoor use, agriculture, commercial, industrial, and parks described in consultant reports (Summit 2004; Urban Systems 2005; Dobson 2006). Increases in evaporative demand due to climate change were accounted for by increasing outdoor and agricultural use rates by expected percent use increases (Neilsen et al. 2006). For the extraction-based (e.g. high demand) water use values, it was not possible to differentiate future increases by sector. Thus, modifications were made to account for increases in household demand as a function of extraction rates in the winter months, and in irrigation demand as a function of historic summer extraction rates and projected increase in evaporative demand due to climate change (Neilsen et al. 2006).

2.4.4 Reservoir Operations

WEAP enables water management simulations based on priority rankings for allocations. WEAP was programmed to mimic Peachland Reservoir releases based on historic operating practices (Ministry of Water, Land and Air Protection 1999). The highest priority set for reservoir operations was to release water from the reservoir to meet the daily demands by the District of Peachland. The next highest priority was set to fill the reservoir in order to save for the next year's water needs. Finally, reservoir releases were programmed to meet instream flow needs. In one scenario, the model pulled water from the reservoir to meet a water license held by the Ministry of Environment (Ministry of Water, Land and Air Protection 1999). In the second scenario, reservoir levels were initially higher and releases set below historic rates.

3 Results

3.1 Climate and Land Cover Impacts on Streamflow

The two GCMs used in this study resulted in different directions of change in annual total streamflow in the near term: the CGCM2 scenario shows an increase in the 2020s and the HadCM3 scenario shows a decrease (Table 2). In the longer term (2050s), both climate scenarios indicated a decrease in annual streamflow (Table 2). Median flows in the summer months (June–August) decreased in the near and long term, with significant decreases in monthly flow volume (m^3) in August and September for the 2050s (Table 2).

The Mountain Pine Beetle scenarios (MPB+ baseline climate and MPB+ 2020s climate) each exhibited significant increases in annual mean and monthly median stream flows (Table 3). There were significant differences between MPB under baseline climate versus MPB in the context of climate change. Mean annual streamflow is significantly lower in the

Table 2 Change in stream hydrology metrics for climate change scenarios. Change designated as scenario conditions compared to baseline conditions in Trepanier Creek, averaged across the 9 scenario years. Streamflow volumes in million m^3 (Mm^3), with monthly m^3/second (cms) in parentheses. Seasons defined as: winter = December to February; summer = June to August. Freshet defined as highest 7 days of flow (Mm^3)

Metric	Unit	2020s		2050s	
		CGCM2	HadCM3	CGCM2	HadCM3
Annual streamflow volume	Mm^3	+2.7$^{\triangle}$	−2.4 $^{\triangle}$	−1.7 $^{\triangle}$	−7.7 $^{\triangle}$
Winter streamflow	Mm^3 (cms)	+0.311 (0.103)	+0.419 (0.140)[a]	+0.625 (0.208)[a]	−0.145 (0.048)
Spring freshet	Days	9 days earlier	2 days earlier	16 days earlier°	14 days earlier°
Freshet volume	Mm^3	+0.731	−0.366	−0.183	−0.876
Summer streamflow	Mm^3 (cms)	−2.13 (0.709)	−2.76 (0.919)	−4.80[b] (1.60)	−5.74[b] (1.90)

$^{\triangle}$ denotes significance at $p<0.1$ for mean annual data; [a] significance difference in monthly median flow (cms) as determined with the Indicators of Hydrologic Alteration software (Richter et al. 1996). ° denotes significantly earlier date of maximum flow; [b] denotes cumulative monthly flows significantly lower ($p<0.1$) in August and September.

MPB Only than the MPB+ 2020s scenarios ($p<0.001$). The higher winter temperatures (average increase of 2°C) of the 2020s climatic conditions was found to offset some of the increase in maximum snow accumulation due to canopy loss in the MPB scenario, and led to a greater impact on date of snow depletion than MPB conditions alone. The MPB+ 2020s scenario led to a greater shift in timing of freshet (an average of 11 days earlier) than either climate change or Mountain Pine Beetle conditions on their own.

3.2 Supply Change Scenarios Paired with Reservoir and Water Use Scenarios: Impacts on Human and Aquatic Ecosystem Users

Taken on their own, the climate and land cover scenarios revealed a range of possible changes to streamflow, yet these changes will not happen in isolation. For example, climate

Table 3 Change in stream hydrology metrics for Mountain Pine Beetle attack scenario. Change designated as scenario compared to baseline conditions in Trepanier Creek. Monthly streamflow volumes in million m^3 (Mm^3), with monthly m^3/second (cms) in parentheses. Seasons defined: winter = December to February; summer = June to August. Freshet defined as highest 7 days of flow volume (Mm^3)

Metric	Unit	Mountain Pine Beetle Attack	
		Present Climate	2020s CGCM2
Annual streamflow	Mm^3	+16.3[a]	+19.9[a]
Winter streamflow	Mm^3 (cms)	+0.719 (0.240)[a]	+1.15 (0.382)[a]
Spring freshet	Days	5 days earlier	11 days earlier
Freshet volume	Mm^3	+2.34	+3.10
Summer streamflow	Mm^3 (cms)	+2.68 (0.893)[a]	+1.60 (0.533)[a]
June streamflow	Mm^3 (cms)	+0.513 (0.238)	+0.011 (−0.202)

[a] denotes significance at $p<0.1$ for mean annual data, and significance in monthly median flow (cms) as determined by the Indicators of Hydrologic Alteration software (Richter et al. 1996).

change will also affect outdoor irrigation demand, which in turn affects water available for instream flows. Population growth simultaneously increases water use and drives how much water is released from reservoirs, subsequently impacting reservoir levels. This section presents the range of possible impacts from the climate and land use scenarios when combined with varying water use and reservoir management in terms of stress on human water users and aquatic life. The following is a description of patterns present across all scenarios.

In the near term (2020s), if the projections of the CGCM2 climate model downscaled to this basin develop as expected and are paired with the range of water use volumes examined here, there will be no significant water deficit present for users in the District of Peachland (Table 4). Even under the higher reservoir release scenario (in combination with both high and low water demand levels), there is a greater volume of water remaining in the reservoir at the end of the dry season in six out of nine years under the 2020s CGCM2

Table 4 Metrics of stress to human and ecological water users. Values shown are for Peachland Creek and the water system drawing from Peachland Creek. L = lower; H = higher. Average length of deficit calculated during years with deficit only. Average values for Drought+ 2020s (for all but "years with a deficit") calculated for 3 drought years only; all other average values based on 9 scenario years. Instream flow statistics averaged over a "normal", "very wet" and "very dry" year (3×365=1095 days total)

Supply Change Scenario	2020s CGCM2		2020s HadCM3		2050s CGCM2		2050s HadCM3		Drought+ 2020s	
Water Use Value	L	H	L	H	L	H	L	H	L	H
Peachland Creek—Higher reservoir release										
Years with deficit in Peachland (no., out of 9)	0	0	1	2	1	2	2	6	3	4
Average length of deficit (days per year)	na	na	62	100	62	130	111	109	62	90
Percent of demand met during period of deficit (average)	na	na	82	64	88	60	62	56	43	35
Net change in days instream flow target met (out of 1095 days)	−104	−66	−112	−114	−143	−162	−481	−413	−377	−453
Days with no flow (average number per year)	0	0	0	0	0	58	48	124	61	120
Peachland Creek—Lower reservoir release										
Years with deficit in Peachland (no., out of 9)	0	0	0	0	0	0	0	0	0	0
Net change in days instream flow target met (out of 1095 days)	−276	−207	−274	−266	−302	−383	−540	−567	−683	−406
Days with no flow (average number per year)	0	0	0	0	44	80	73	110	41	91

scenario, indicating a low probability of a deficit occurring if the climate remains at the conditions anticipated for the 2020s by CGCM2.

The 2020s HadCM3 scenario resulted in moderate deficits, with up to two out of nine scenario years experiencing a deficit depending on water demand and reservoir management. Even during years with a deficit, between 64% and 82% of demands were met (Table 4).

The 2050s HadCM3 climate change scenario combined with higher water use and higher reservoir release resulted in the highest impact in terms of meeting the District of Peachland's needs from Peachland Creek: six years out of nine experience a water deficit (Table 4). Yearly deficits last from 50 to 168 days, with only 38% to 71% of municipal and agricultural demands met (an average of 56% met, Table 4) during that time.

Streamflow during the 2050s scenarios across the nine scenario years resembled streamflow for drought conditions under the 2020s climate. The net reduction in meeting instream flow targets in July through October in a "very wet", "normal" and "very dry" year in the 2050s (HadCM3 model) were within 10% of the values obtained for the three-year drought for the 2020s climate. These are the result of net changes summarized across both Trepanier and Peachland Creek, for both high and low water use values. This suggests that the lower flows anticipated by mid-century (even taking into account inter-annual variability) could lead to stress to aquatic life similar to a drought occurring during the 2020s.

The Mountain Pine Beetle scenarios developed here led to the greatest increase in streamflow across all metrics, and led to the lowest constraints on meeting Peachland's water needs. Instream flow targets, however, are less frequently met relative to baseline in some months under the MPB scenario in the context of climate change in the 2020s (Fig. 4). This results from reductions in flow due to hydrological changes and increases in

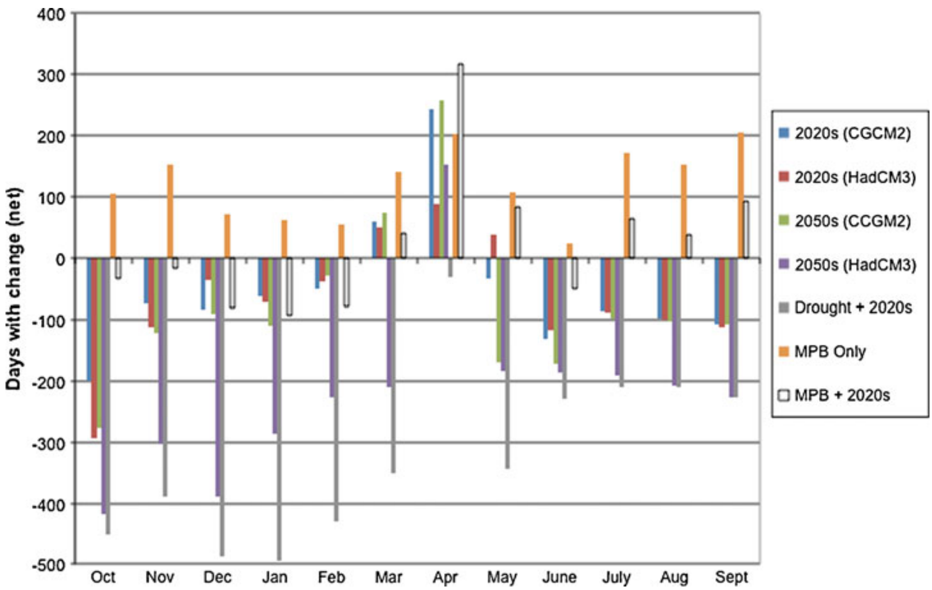

Fig. 4 Difference in meeting instream flow targets between baseline and scenarios. Values represent "net change" (sum of increases and decreases) in number of days that instream flow targets were met between scenario and baseline. Number of days are aggregated across both creeks, both water use estimates, and both reservoir management scenarios, in a "normal", "very wet" and "very dry" year (18 years total)

demand occurring during these months. Across the nine-year MPB+ 2020s scenario run, June flows were generally lower than baseline and July and August flows are no different from baseline conditions for flows in Trepanier Creek above the withdrawal point. Earlier snowmelt and earlier peak and recession of the freshet contribute to lower June flows. Below the withdrawal for Peachland, flows are lower in June of some scenario years, contributing to instream flow targets being met to lesser extent than baseline for up to 15 days. With the higher water use in the "very dry" year, July instream flow targets on Trepanier Creek are also met to a lesser extent. Thus, even with generally increased flows due to a MPB attack, the hydrological changes due to climate change can result in a reduction in meeting downstream water needs for portions of the year.

3.2.1 Patterns Across Multiple Scenarios

For Peachland's water system drawing water from Peachland Creek, deficits were always found to be present in the 2050s with the higher reservoir release rate after two consecutive "very dry" years (e.g. precipitation within the driest quintile of the 30-year period of record), as well as after the first drought year in the Drought+ 2020s scenario. Under these conditions, deficits occur with both high and low demand levels, but are more pronounced for the higher demand value. For these scenarios, deficits occurred, at minimum, during all of July and August.

In all future climate and drought scenarios, there was a net reduction in meeting instream flow targets across all precipitation regimes, including the wetter years (Table 4), and in all months but April (Fig. 4). The greatest reduction in meeting instream flow targets was in the summer months. All climate change, reservoir management and water use scenarios led to reductions, but no increases, in meeting instream flow targets in June through September. These changes were influenced by reduced inflow to the reservoir due to reduced precipitation, the earlier freshet recessions on Trepanier Creek, and higher demands during summer months. Across all scenarios, the ability to meet instream flow targets is reduced during very few days in the "very dry" years due to the fact that targets are not met in either baseline "very dry" years, or future scenarios.

4 Discussion

An integrated approach towards assessing streamflow and water availability is critical for assessing future water management strategies (Kundzewicz et al. 2007). Before assessing the management implications of the results, discussion is warranted regarding the influence of the model on outcomes and the confidence in the results from the different supply and demand forcings.

4.1 Model Influences

There are many considerations that need to be taken into account when using a semi-distributed model to represent changes to the hydrology of a watershed. According to a review of hydrologic models for forest management and climate change applications in British Columbia (Beckers et al. 2009), WEAP would classify as having useful features as well as structural limitations. WEAP has been successfully applied in a wide range of coupled climate change—water management studies (c.f. Young et al. 2009; Null et al. 2010; Vicuña et al. 2010 among others).

In terms of examining forest cover scenarios such as the Mountain Pine Beetle scenarios analyzed in the present study, lack of representation of a canopy layer necessitates incorporating user-defined adjustments available to account for this type of modification. Fully distributed, physically-based models would appear to be a more useful choice of model structure for explicitly capturing spatially-dependent land cover impacts. However, a more data-intensive, distributed model would have required more data than are available for the study area, resulting in omissions and inaccuracies in the model output. The ability of the WEAP model to represent watershed hydrology, reservoir storage and release operations, and downstream water use in an integrated platform was critical to addressing the full range of water balance questions.

Of all the types of uncertainty associated with scenario development—from the reliability of GCM outputs, to applying global climate projections to a local level, to calibrating the model to observed streamflow—the uncertainty associated with model calibration is likely of the least magnitude (Merritt et al. 2006). The user has the most control over reducing calibration error, as opposed to other kinds of error, and here, an adequate match between measured and modeled values was found, as presented in the Methods section. Uncertainty arising from climate models, demand data, and other inputs and forcings, would be the same regardless of category of hydrologic model applied.

4.2 Drivers of Change on Streamflow—Supply Side

Since there has been such a wide range in the precipitation projections produced by each Global Climate Model (GCM) and the likelihood of each occurring is deemed equally valid, the IPCC recommends that the results from more than one model be considered in conducting climate change impacts work (Kundzewicz et al. 2007). The two GCMs used here represent conservative (CGCM2) and more extreme (HadCM3) projections for summer temperature and precipitation impacts for the study region. Thus, uncertainty associated with a specific GCM was addressed by using two GCMs known to differ in order to characterize the range of possible climatic impacts. Figure 5 shows the differing ranges of variability in summer streamflow due to use of the two GCMs.

The range of values for decrease in monthly streamflow was greater with the HadCM3 climate model compared to the scenarios using the CGCM2 model, especially in July. The average change in both winter streamflow and summer streamflow was of the same

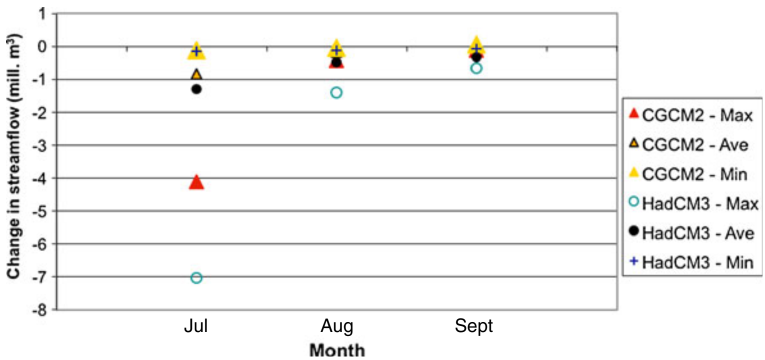

Fig. 5 Range of change in summer streamflow (across the 9 scenario years) relative to baseline, derived from the CGCM2 and HadCM3 climate models in the 2050s time slice

magnitude and direction for the 2020s period for both climate models (Table 2), increasing confidence that changes including increased winter streamflow and decreased summer flows are likely to occur. The climate scenarios using the two GCMs all indicated highly reduced summer streamflow under anticipated 2050s climatic conditions, but differed in the magnitude and direction of winter streamflow volumes for the 2050s. The divergence in winter streamflow predictions for 2050s is due to a much smaller freshet volume anticipated under scenarios using HadCM3 compared to freshet volume for scenarios using CGCM2. Both HadCM3 and CGCM2 predict a significantly earlier date for the spring freshet under 2050s, which contributes to the reduced summer streamflow volumes for that period.

The hydrologic responses to climate change in this study were consistent with other work done in the region. Merritt et al. (2006) modeled climate change impacts on streamflow in eight subwatersheds throughout the Okanagan Basin, also using the CGCM2 and HadCM3 climate models and A2 emissions scenario. The changes in mean annual flow volumes found in the present study show the same direction of change as those of the Merritt et al. (2006) study in both time periods. In both studies, use of the HadCM3 GCM results in reductions in flow volumes in July and August. Thus, there was a projected reduction in flow volumes in both studies at the time of highest water demand, leading to similar results during critical periods.

These results may be underestimates of the magnitude of potential change due to climate change, given recent research that suggests that the A2 emissions scenario for CO_2 emissions rates may be overly conservative. The A2 emissions scenario developed by the IPCC was intended to represent population increases but with slower economic growth and emissions rates than for the A1 “rapid growth, high emissions” scenario. Actual emissions during the early 2000s grew at a rate exceeding all scenarios envisioned by the IPCC (Raupach et al. 2007). The recent economic crisis of the late 2000s has resulted in annual emissions more in line with (although still slightly higher than) those anticipated by the A2 scenario (Le Quéré et al. 2009).

All indicators from the Mountain Pine Beetle scenario point to significant increases in annual and monthly median stream flows (Table 3). These results strongly suggest that increased flow will result from a MPB attack during the 15 year post-MPB stage modeled in the present study. These changes will result from reduced interception and sublimation losses as well as reduced transpiration, all of which result in increased water entering the pedosphere compared to under forested conditions.

The proportional increase in streamflow due to MPB attack in this study was on the high end of the range of results from other studies (Schnorbus et al. 2004; Spittlehouse 2006; Troendle and King 1987). A MPB attack is expected to result in less hydrologic impact than a clearcut (Winkler et al. 2009). Annual streamflow at the watershed outlet in the present study averaged 58% higher for the MPB Only scenario compared to the baseline scenario, and ranged from 43% to 84% higher for individual years. For reference, the highest value found in the literature was an average annual increase of 87% in streamflow for a catchment that was clearcut, with average increases for clearcut compared to uncut conditions closer to 50% (Spittlehouse 2006). Though differences between results are to be expected due to study location, time period, field vs. model-based study, etc., these higher results could mean that the assumptions used here regarding increase in water availability due to reduced interception and evapotranspiration may be overestimates.

A definitive result of the present study is that some of the negative climate-related impacts on water supplies may take place even when combined with the generally higher flows that are anticipated to accompany a Mountain Pine Beetle attack as in the results section. Given the likelihood of a future insect outbreak occurring in the context of climate change (Carroll et al. 2004); water managers should consider the combination of these perturbations on hydrologic change and on water users.

4.3 Drivers of Change on Streamflow—Demand Side

Lack of data on current water use is a constraint on projecting future water use throughout the Okanagan Basin. The two demand estimates used in this study reflect some of the uncertainty about actual water use in the study area since they were derived from two different studies with different methodologies and results. Neither of the estimates can be assumed to be more correct than the other, but rather represent a range of values of possible water use, with the extraction-based estimate (high) assuming 60% more use than the activity-based estimate (low) across the study area.

The relative importance of achieving an improved estimate of future water use can be determined by comparing the impacts of change in demand to the impacts of change in supply. Figure 7 shows that the change in streamflow due to consumptive water use was similar in magnitude and direction to the average changes in streamflow due to climate in August and September of the 2050s, CGCM2 scenario (Fig. 6). When supply and demand reductions in the HadCM3 scenario were compared, those due to water use (e.g. demand) tended to be small compared to climatic impacts (e.g. supply) for July, August and September (Fig. 7).

Figures 6 and 7 show that variability between demand projections—derived from two best estimates for baseline use—is low compared to variability between supply change projections due to climate change. This implies greater uncertainty about the changes in streamflow due to climate compared to uncertainty about projections for future water demand.

Given the magnitude of values in Figs. 6 and 7, changes in demand might be expected to have lower impacts on water users when compared to changes in supply. However, the effects of demand will be aggregated with changes in supply. During summer months, increased demand under conditions of reduced flow brings streamflow close to the threshold for meeting instream flow targets. Near that threshold, small changes in demand are important in terms of whether or not the instream flow targets can be met.

There were many instances where instream flow targets reduced under one water use scenario, but not the other. In particular, water use for the 2020s HadCM3 scenarios significantly constrained the meeting of instream flow targets, indicating that instream flow can be highly sensitive to demand. For the 2020s HadCM3 water use scenarios, the higher

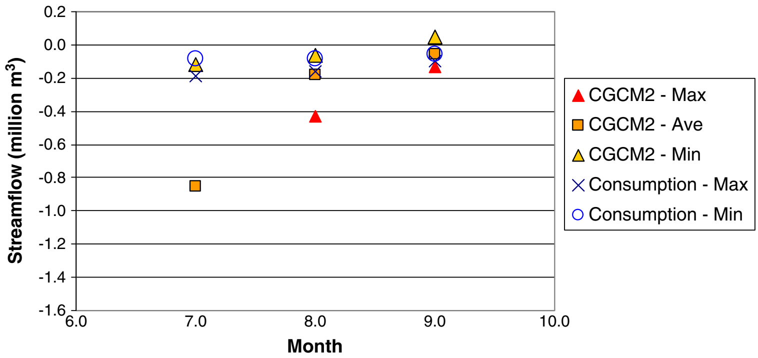

Fig. 6 Difference in monthly summer streamflow (m^3) between the CGCM2 2050s scenario and baseline due to climate-related impacts, and due to reductions through consumptive water use

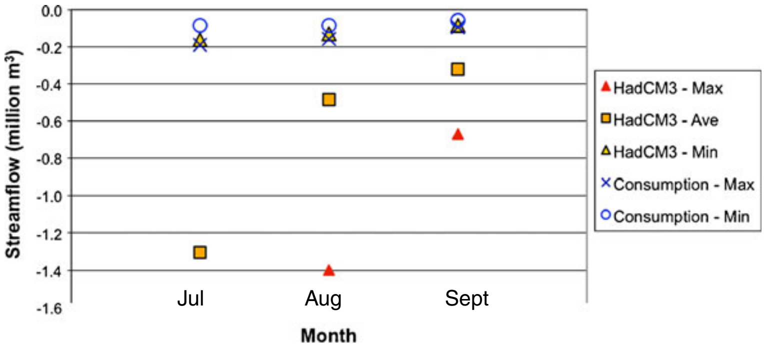

Fig. 7 Difference in monthly summer streamflow (m^3) between the HadCM3 2050s scenario and baseline due to climate-related impacts, and due to reductions through consumptive water use

demand value led to a month and a half of additional zero flow conditions for Peachland Creek relative to the same climate scenario using the lower demand value. Similarly, on Peachland Creek under the 2020s CGCM2 scenario, whereas low flows occur in July and August under the low water use value, the higher value leads to zero flows. In all scenarios, under all precipitation conditions, there were at least three months where more than 30% of days resulted in a differential ability to meet instream flow targets depending on water demand. These findings indicate a high degree of sensitivity for the aquatic ecosystem relative to Peachland's water use under climate change.

The results discussed here show the importance of the volume of water used by Peachland on instream flows for fish. This suggests that reducing demand would lead to further improvements in meeting instream flow targets. Increased efficiency, taking place largely in the outdoor watering sector, along with various planning and policy measures put in place in all water use sectors, could substantially reduce water use in the Okanagan (DHI 2010; Maurer 2010; Neale et al. 2007). In one study area in the Okanagan, Neale et al. (2007) found that by the 2050s, efficient water use, low population growth and the "best case scenario" for climate change, could reduce water use to below 2001 levels. Results from an Okanagan-wide study (DHI 2010) projected less substantial savings, but still suggested that if efficiency measures are put in place in all water use sectors, water consumption could be 35% less than without efficiency by the 2020s. Given that the lower water use value used here was 47% less than the higher value in the 2020s and 32% less in the 2050s, an additional 35% reduction could lead to even greater improvements for instream flows.

In summary: i) future climate change influences on streamflow are uncertain, but a range of variability is captured here and outcomes are validated through comparison to other studies; ii) future demand is also uncertain, but a high and a low value for demand allow for the evaluation of a range of water demands on instream flow targets; iii) reductions in streamflow due to increased demand may be low compared to changes due to future climate conditions, but since both of these changes impact the system, demand reduction will be a measure likely to improve instream flows for fish.

4.4 Water Management Implications

Our results do not point to precise conclusions regarding the timing of future reduction in streamflow or the magnitude of the deficit to the users. However, they do indicate the time periods where lower flows in conjunction with higher demand are likely to bring more water stress. Even with the more conservative climate model (CGCM2), reductions in streamflow are projected for the longer term. There are deficits in at least mid-July through August in the "dry" and "very dry" years in all but the MPB+ 2020s climate change scenarios on Trepanier Creek, showing that supply and demand changes will likely critically reduce the margin of available water in the summer months. Even with storage in place, municipal and instream flow needs cannot be fully met even in the "normal" years by the 2050s. This suggests that closer management of the reservoir and greater planning for reduced water availability will need to be an essential part of water management in this area in the future.

Given that the study watersheds have a snow-dominated hydrology with most of the water flowing downstream in the spring, the timing of spring peak flows is an important consideration for water management. When deficits are present on the Peachland water system drawing from the unregulated Trepanier Creek, they occur at the end of the spring freshet and resulted from both a reduction in flows and an earlier freshet recession (Tables 2 and 3 show the shift in timing of the freshet under the different scenarios). Efforts to reduce demand in order to fully meet water needs should consider the probable earlier timing of peak flows resulting from climate change and land use change.

Summer instream flow needs were always given lower priority in the model relative to consumptive uses and reservoir filling, which resulted in severe consequences for instream flow levels during June through September in all scenarios. This suggests that these consequences are likely to occur unless tradeoffs are considered between meeting municipal needs, filling the reservoir for later years, and meeting the optimal ecological condition in one season vs. another.

5 Conclusions

This study used an integrated water management model, WEAP, for hydrological modeling and scenario development to assess potential water futures in an arid watershed in southern British Columbia. From the study findings it can be seen that a "business as usual" strategy will not allow all demands for water to be met in the future in this watershed. Identifying optimal water management strategies in light of necessary tradeoffs will require discussions among stakeholders about their priorities for land and water use, economic and demographic growth, and the value of intact ecological systems.

Beyond its implications for the study area, this work demonstrates a method of using an accessible modeling tool for integrating knowledge from the fields of climate science, forest hydrology, water systems management and stream ecology to aid in water and land management decision-making. The methods developed here are relevant to water managers in other parts of Canada and the world facing similar challenges over increasing competition for water resources as flow regimes shift with climate and land use changes.

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