

# An Exploration of Water Resources Futures under Climate Change Using System Dynamics Modeling

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## Abstract

Results from an integrated assessment of water resources in the Okanagan Basin in south-central British Columbia, Canada, show that climate change will both reduce water supply and increase water demand, leading to more frequent and more severe water shortages than in the recent historic record. Competing uses of water are primarily agricultural irrigation (orchards, cropland, pasture, and vineyards), residential, and ecological (includes salmonids). The region is semi-arid and the agriculturally-based economy is particularly sensitive to the effects of climate change. The model characterizes a region that is 7500 km<sup>2</sup> and simulates using a monthly timestep. Scenarios are derived through 2069 using downscaled climate model results coupled with watershed modeling studies, as well as studies that linked crop water and urban demands to climate. The

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model enables users to explore plausible future supply and demand scenarios (agricultural, residential and instream flow demands) while evaluating strategies for adapting to future climate change. In the simulated worst case scenario, the combined effect of future climate change and population growth could cause annual water deficits (historically experienced once every 10 years) to become increasingly frequent by the 2050's time period—perhaps every 2 out of 3 years annually. During the dry month of August, when demand is high, shortages could occur every 1 out of 2 years. An adaptation scenario with moderate levels of conservation is tested and shows minor improvements from the no adaptation scenario. Further study is required to explore the potential of adaptation on reducing future water deficit.

**Keywords:**

## 1 Climate Change and Water Resources Planning

Are water managers prepared for operating under future climate conditions? Water managers have always worked towards reducing risk and increasing system capacity to handle ever-widening extreme conditions, so some argue that they are ready for climate change. [Stakhiv \(1996\)](#) states that society is constantly adapting in incremental steps and that climate change will simply be an additional stressor to which we must adapt. However, these “common-place adaptations” that have been part of daily management practices assumed that climate was relatively stable, varying around a stable mean ([de Loë & Kreutzwiser, 2000](#)). It is unknown whether future climate changes will occur gradually, over several decades, or if there will be sudden shifts. [Kashyap \(2004\)](#) suggests that climate change adaptation is not comparable to historic adaptation, because the environmental changes will be more rapid and intense than in the past. However, most climate modeling characterizes climate change as occurring slowly and gradually, justifying a reactive or “wait-and-see” approach. Regardless, the conventional practice of relying on historic data to estimate future conditions is inadequate. New methods for assessing the future are necessary to maintain the reliability of water resource systems over the long term. Certainly the future contains many unknowns, so an effective assessment needs to integrate all known stressors on the system and support the development of strategies that are flexible and resilient, under a wide range of future conditions. In many regions, climate change will be a significant stressor, so it must be included in any planning initiative. Unfortunately, this is not common practice today. For example, in 2005, only four U.S. states included climate change in their water resources planning initiatives ([Viessman & Feather, 2006](#)).

For water managers to incorporate climate change issues into their planning processes, climate change information must be translated into terms that are relevant to their concerns. Two current challenges are the level of uncertainty in climate change estimates and the mismatch of both spatial and temporal scales.

While current global climate models provide information at large geographic scales and low spatial resolution, managers handle small geographic areas and require data with relatively high spatial resolution (Lins et al., 1997). A third challenge is that of translating climate change data into terms of hydrologic impacts. The presence of these issues has, to date, deterred practitioners from bringing climate change into the water management forum. Unfortunately, projections of future conditions that do neglect climate change could be grossly inaccurate, and managers who rely on this information may be unwittingly and unnecessarily allowing vulnerabilities in their systems. While a community can often endure single-year events without permanent losses, a prolonged deficit in the water balance could deplete water storage in reservoirs and groundwater aquifers, and even collapse industries dependent on water.

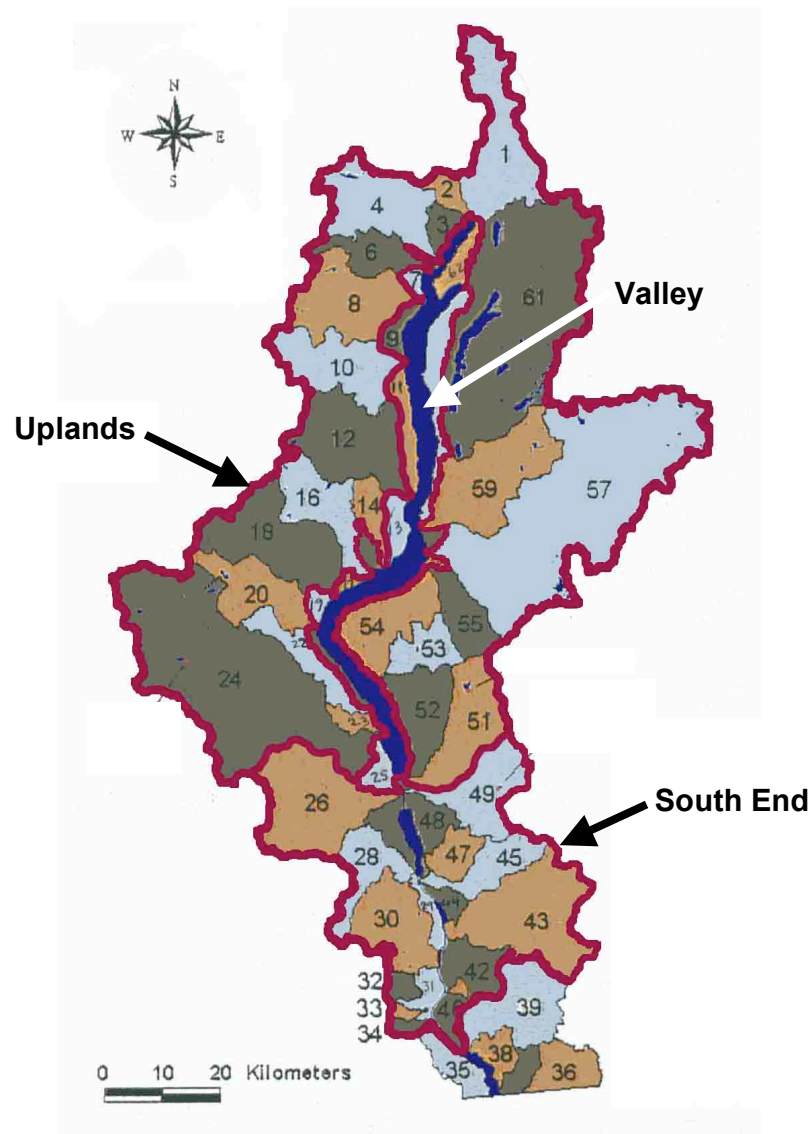
## 2 The Okanagan Basin Study Area

The Okanagan Basin in south-central British Columbia is one of the most arid regions in Canada, with annual average precipitation ranging from less than 300 mm to 450 mm. The long, narrow basin extends 182 km from the Canada-U.S. Border and covers an area of 8200 km<sup>2</sup> (See [Figure 1](#)). The major economic industries in the basin are agriculture, forestry and recreation. Agriculture accounts for approximately 70 percent of annual water use in the basin. The Okanagan River is one of the only tributaries to the Columbia River that still supports viable salmon populations.

In recent decades, rapid development combined with natural hydrologic variability increased concern among water resource managers. In the twenty years between 1978 and 1998 the population in the Central Okanagan Regional District doubled and the rest of the basin also experienced rapid growth that far exceeded projections (BC Stats, 2006; Canada-British Columbia Consultative Board, 1974). Drought conditions in the summers of 2003 and 2004 caused water shortages and major fires, leading to a public review of emergency preparedness (Filmon & Review Team, 2004).

## 3 Project History

Several previous research initiatives focusing on both the physical and social aspects of the system established a sound foundation on which to build this project. Stakeholder dialogue activities between 2001 and 2004 began communications and developed trust with parties responsible for or interested in water management in the Okanagan. In addition, these activities increased awareness and concern about potential climate change impacts as well as adaptation opportunities (Cohen & Kulkarni, 2001; Cohen et al., 2004, 2006). As a result, one Okanagan community included climate change scenarios in their water resources planning document (Summit Environmental Consultants, 2004).



**Figure 1:** Okanagan Basin Map, showing the delineation of watersheds into three model regions (based on Merritt & Alila, 2004).

[Taylor & Barton \(2004\)](#) statistically downscaled six global climate models to create a range of plausible scenarios for the Okanagan. These climate scenarios show mean temperature increases between 1.5 and 4 degrees Celsius throughout the year, and generally wetter winters and drier summers. [Merritt & Alila \(2004\)](#) and [Merritt et al. \(2006\)](#) incorporated these climate scenarios within simulations by the UBC Watershed stream flow runoff model ([Quick, 1995](#)) to generate hydrologic scenarios. The results show significant changes to the annual hydrograph from the historic period (1961–90) to the period between 2010 and 2100. All scenarios show a reduced snowpack, an earlier onset of the spring freshet by as much as four to six weeks in the 2080's, and decreases in summer precipitation. Some scenarios also show more intense spring freshets. [Neilsen et al. \(2004, 2006\)](#) used the climate scenarios to model the impact on agricultural crop water demand. Higher temperatures increase both evapotranspiration and the length of the growing season—two factors which increase crop water demand. As a result, crop water demand could increase by 12 to 61 percent, as climate change intensifies through the decades. Furthermore, [Neale \(2005, 2006\)](#) correlated residential outdoor watering with temperature and detached dwellings for several Okanagan communities, showing that water demand in the residential sector will also increase under climate change, in the absence of conservation measures. Each of these results on its own provides important information, but only reflects part of the picture. By considering these impacts together—in the system context—we can determine the increased risk to the water resource system in the future.

## 4 Methodology

The purpose of this initiative was to enable and support the Okanagan Basin's water resources community in incorporating climate change projections into their planning and policy development and in evaluating their water resources within a system context. This was conducted through a participatory integrated assessment centered around the development of a system dynamics model. The products of this process were:

1. A simulation model of the water resource system, incorporating future projections of climate change and population growth, as well as adaptation options
2. A shared learning experience for both the participants and the research team. This paper describes the model structure and an analysis of model output, while the shared learning process is described in [Langsdale et al. \(2006\)](#).

The model was created to investigate several questions:

- (a) What is the current state of the system?
- (b) What effect will climate change and population growth have on the future water supply and demand balance?

- (c) What role could adaptation measures have on improving or maintaining water resource system reliability despite increased stress from climate change and population growth?

Following a brief introduction to “participatory modelling,” this paper presents quantitative results for (a) and (b) and discusses insights related to point (c). The model was constructed as a high level scoping model, with greater emphasis on capturing the structure of the system, rather than on calibrating data. This is appropriate to the objectives, as the model results have not been and will not be used for designing new infrastructure nor operating rules. The significance of the results presented here is provided in the general trends, rather than in any specific numerical values.

#### 4.1 Participatory modelling

Participatory modelling is a recently established approach for conducting integrated assessment but it has already been applied to a variety of fields such as policy analysis and organizational learning, as well as environmental resource applications such as water resources and land management. Participatory modelling is founded on the belief that mental models of system behaviour are based on numerous unstated assumptions, so often contain gaps and inconsistencies. The process of sharing these mental models exposes points of agreement and points of conflict. Effective conflict negotiation illuminates hidden assumptions so that they may be clarified and challenged (Fisher & Ury, 1981). Participatory model development can focus on characterizing system structure, while model simulations reveal system behaviour, which is less intuitive and often the source of confusion (Forrester, 1987; Vennix, 1996). The model can then be used to explore a range of future conditions or assumptions. Participants may engage directly in the modelling process, or the model may be developed in an iterative process with regular opportunities to contribute (van Asselt & Rijkens-Klomp, 2002).

#### 4.2 System dynamics

Models used for collaborative modeling in water resources applications include system dynamics platforms like STELLA™ (Cardwell et al., 2004; Costanza & Ruth, 1998; Langsdale et al., 2006; Palmer et al., In press), and Studio Expert (Tidwell et al., 2004). Other types of models which have been used include MIKE-BASIN (Borden & Spinazola, 2006; Borden et al., 2006); the Water Evaluation And Planning system model (WEAP) (Jenkins et al., 2005); and OASIS with OCL (Hydrologics, 2003). System dynamics software packages are blank slates and can be applied to any problem, while MIKE-BASIN, WEAP, and OASIS are all limited to water resources applications.

System dynamics was developed for the purpose of characterizing complex, non-linear systems through capturing interrelations, feedback loops and delays. Modern system dynamics software packages are ideal for use with a participant

group of varying levels of technical proficiency because of their graphically-based model level and user interface. These models can easily manage both clearly-defined and poorly-defined components in the same model. Similarly, they can capture quantitative, physical parts of the system, such as hydrology, as well as intangible parts of the system, such as policies and human responses, so they are quite appropriate for participatory modeling applications.

Case studies where the system dynamics approach was applied to environmental issues include: the Louisiana coastal wetlands, the South African fynbos ecosystems and the Patuxent River watershed in Maryland, USA (Costanza & Ruth, 1998); water resources management in Switzerland, Senegal and Thailand, and vegetation management in Zimbabwe (Hare et al., 2003); water allocation issues in the Namoi River, Australia (Letcher & Jakeman, 2003); transportation and air quality in Las Vegas, USA (Stave, 2002); and Patagonia coastal zone management (van den Belt et al., 1998).

## 5 Description of the Actual and Modeled System

The Okanagan Sustainable Water Resources Model (OSWRM) simulates future conditions by projecting current conditions and overlaying the effects of population growth and climate change on water supply and demand. The purpose of the model is primarily for supporting stakeholder dialogue surrounding the issue of how climate change could play a role in future water management and is not intended to optimize design or guide real-time operation. The model can help dialogue participants to learn about the complexities of managing water resources for multiple uses, simulate a range of plausible water resources futures, assess adaptation strategies (and portfolios of strategies), identify data gaps, and prioritize areas of future research.

Here, we provide detail about the Okanagan water resources system and how it was characterized in OSWRM using a STELLA™ platform. First, major features and components of the model are described. Then, relationships between these components, which provide more insight into behaviour, are described through the use of a Causal Loop Diagram.

In this text, the term “demand” refers to the volume of water requested by a user group for consumptive or non-consumptive use. “Demand” is not synonymous with water rights, nor is it always the amount allocated. Demands for agricultural or residential diversions are based on current use patterns in the absence of conservation measures or any water shortage restrictions and are referred to as “maximum demand.” The maximum demand is not the maximum possible, but is simply the current trajectory based on normal year conditions. Instream demand and conservation targets are defined by policies with fixed monthly targets. When shortages occur, allocations will be less than maximum demand.

Residential demand includes domestic and other municipal demands. Most

out-of-stream water use in the Okanagan can be classified as either agricultural or residential applications. Water to support non-domestic municipal use, such as watering of parks or golf courses, is either averaged into per capita residential use values, or counted as agricultural use. Industrial use is very low in the region, and therefore was not separated from residential use in this study. The terms “municipal” and “urban” are less representative because of the water allocation structure in the Okanagan: municipalities frequently serve both residential and agricultural customers.

## 5.1 Components of the Okanagan Sustainable Water Resources Model

### 5.1.1 Spatial Scales

OSWRM describes nearly the entire basin, from the northernmost extent to the mouth of Osoyoos Lake (see [Figure 1](#)). As most people work at the community or regional level, they are typically not aware of whole-basin issues, or how their area interacts with the larger scale. A comprehensive study in the 1970’s recommended basin-scale management of the water resource ([Canada-British Columbia Consultative Board, 1974](#)). Except for the formation of the Okanagan Basin Water Board, which until recently has had limited scope and influence, there has been little progress on realizing basin-scale management. Modeling the entire basin provides an avenue for exploration and discussion of the larger perspective.

This area was divided into three major regions ([Figure 1](#)) according to water source type: all of the tributary watersheds to Okanagan Lake on which there are human controls (Uplands), Okanagan Lake as well as all unmanaged (small) watersheds contributing to the lake (Valley), and all watersheds that contribute to the mainstem downstream of the Okanagan Lake dam at Penticton (South End). These major sub-basins have areal extents of 5200, 800, and 1500 km<sup>2</sup> respectively, and have distinct climates, topography, and water use patterns. Feedback between these sub-basins is minor, limited to some water cycling by return flows. Otherwise, the relationship between these areas is defined by water that flows through from Uplands, to Okanagan Lake, and finally into the South End.

This paper describes results for water supply and use from the Uplands. The Uplands region comprises 70 percent of the total land area modeled, so results for the Uplands dominate in an aggregation of results for the basin. Also, because water is used multiple times through the basin, an analysis of the Uplands provides a clear and accurate picture of the relative magnitudes of instream and out-of-stream demands.

### 5.1.2 Time Scales

OSWRM simulations use monthly timesteps in thirty-year blocks of either a historic period (based on 1961–90 data) or one of two future periods (2010–



2039 or 2040–2069). The data gap between 1990 and 2010 was a consequence of our reliance on data from established climate models and previous work that predetermined our simulation periods. The future periods, referred to as the 2020's and 2050's by climate modelers, and the historic years, were those used by researchers in the previous phases of this project (see [Merritt & Alila, 2004](#); [Taylor & Barton, 2004](#)). Monthly timesteps were chosen to capture the seasonal climate shifts while maintaining simulation efficiency.

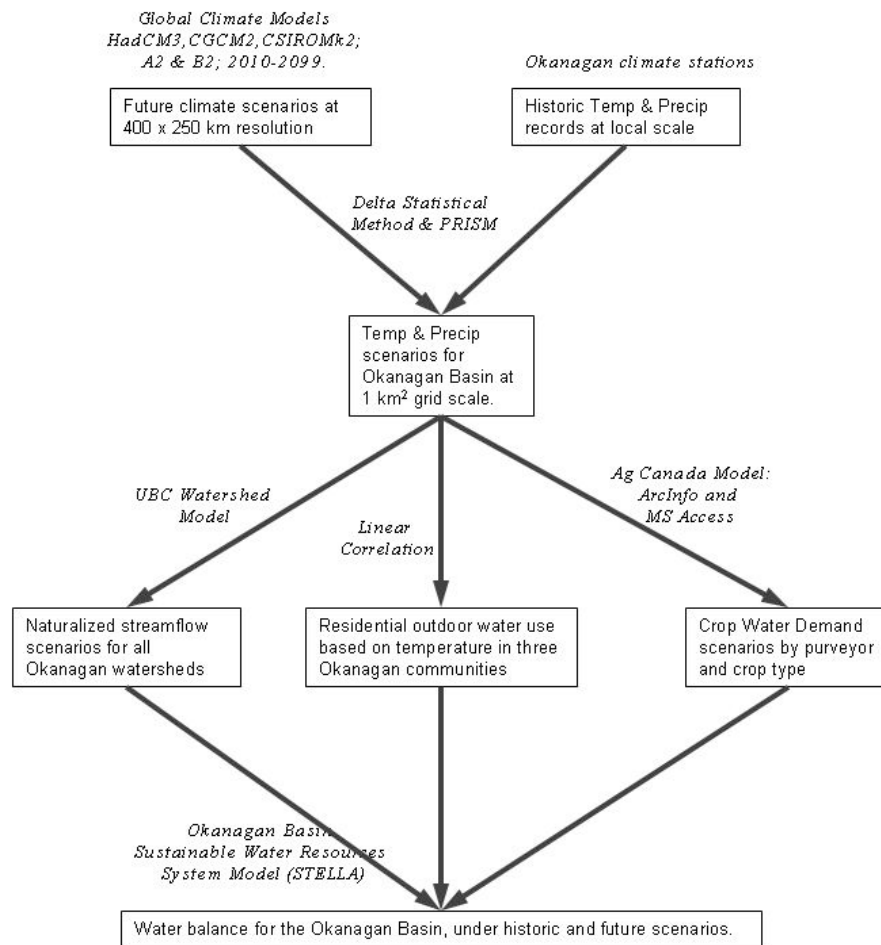
### 5.1.3 Hydrology

[Figure 2](#) summarizes how climate change information was translated into hydrologic impacts that were directly relevant to the balance of water resources and use in the OSWRM. [Taylor & Barton \(2004\)](#) statistically downscaled three global climate models (HadleyCM3, CSIRO Mk2, and CGCM2) and two emissions scenarios (A2—high growth in global greenhouse gas emissions; B2—moderate growth in emissions) using local temperature and precipitation data. [Merritt & Alila \(2004\)](#) and [Merritt et al. \(2006\)](#) generated hydrologic streamflow scenarios for these six climate scenarios. Because all future scenarios are adjustments to the 1961–1990 historic climate data, the pattern is repeated in each time block ([Figure 3](#)). Included in OSWRM are three climate scenarios, referred to as Hadley A2, CSIRO B2, and CGCM B2, for the 2020's and 2050's time blocks. These scenarios were selected because they provided the widest range of behaviour, and thus the widest range of possible future conditions among the scenarios that Taylor and Barton developed. Generally, future climate scenarios predict an annual streamflow hydrograph that has an earlier, flashier spring freshet than in the historic record.

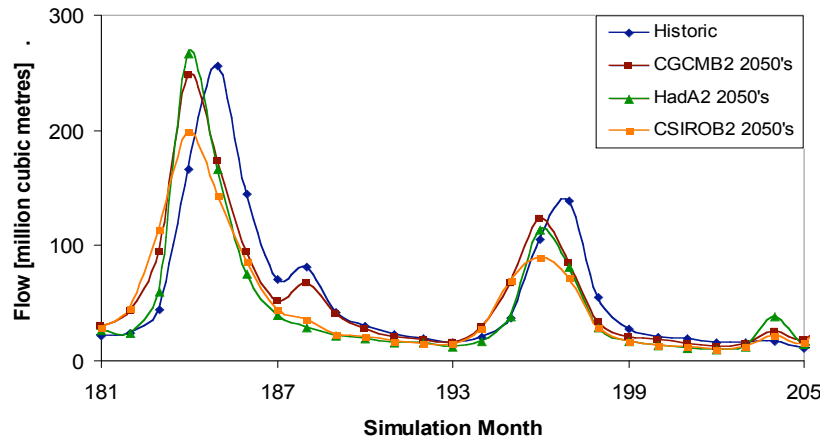
### 5.1.4 Agricultural Demand

Agricultural water demand was based on [Nielsen et al. \(2004, 2006\)](#). The model described therein generated estimates for crop water demand for major water purveyors by relating demand to climatic and location-based factors. In OSWRM we aggregated this output according to water source and normalized by area and by crop type. Each water source region has a single average per land area irrigation demand profile for each crop and each climate scenario. The normalization of the data allowed us to create options for users to simulate changes both in total land in production and in crop type mix. Efficiency factors are applied.

The values for agricultural demand were derived by applying water delivery factors on the crop water demand estimates. [Nielsen et al. \(2004, 2006\)](#) assumed that an additional 33 percent above crop water demand is required for transporting water through the soil medium. Thus, irrigating with a rate that is 133 percent of crop water demand is considered the minimum required to satisfy crop needs. This rate is theoretically possible if maximum efficiency can be achieved through technologies like drip irrigation combined with irrigation scheduling. To estimate actual, current irrigation rates, an additional factor of



**Figure 2:** Flow chart illustrating the progression from climate models and local records to supply and demand inputs to the Okanagan Sustainable Water Resources System Model. (Cohen et al., 2004; Neilsen et al., 2004, 2006; Merritt et al., 2006; Neale, 2005, 2006).



**Figure 3:** Upland streamflow for historic and 2050's climate scenarios. Two years are shown: 1976–77 for the historic scenario, and 2055–56 for the 2050's scenarios. Note the repeated use of the historic climate pattern, as well as the earlier annual peak flow.

30 percent was applied to account for losses from irrigation technologies such as overhead sprinklers and unlined ditches (van der Gulik & Stephens, 2005). These factors combine to a total of 173 percent of crop water demand.

### 5.1.5 Residential Demand

Residential demand, based on work by Neale (2005, 2006), uses correlations of temperature and outdoor water use, average residents per dwelling, proportions of detached and multi-unit dwellings, as well as average savings realized by a number of demand side management strategies (discussed in detail below). Data generated for selected communities was extrapolated to OSWRM's regions.

### 5.1.6 Instream Flow Demand and Conservation Flow Targets

Instream flow requirements are included in both the tributaries to Okanagan Lake and the mainstem lakes/river chain south of Penticton. Because water is diverted out of the tributary streams, we assume that instream flow demands downstream cannot be satisfied by water earmarked for diversion. Instead, instream flow demands are exclusive from the out-of-stream demands.

In the tributaries to Okanagan Lake, conservation flow targets defined for several streams as monthly percentages of mean annual discharge (Northwest Hydraulic Consultants, 2001) were extrapolated to all tributaries. The "normal" conservation flow target is automatically modified in dry years when not enough

water is present in the system to satisfy the target. “Normal” instream demand remains constant because it is based on established policy parameters; however, in practice, this target is modified during droughts.

### 5.1.7 Adaptation and Policy Options

A variety of water conservation measures for the agricultural and residential sectors are included, such as metering, xeriscaping, and technology upgrades. Policy options are provided for drought management, enabling the user to select different priorities for water allocations. Some of the policy options included on the basic user interface include:

- Implementing agricultural conservation and selecting a level of efficiency.
- Implementing residential conservation strategies, including public education, xeriscaping, plumbing retrofit, and metering.
- Modifying residential development patterns, including housing occupancy rate and the ratio of apartments to multi-unit dwellings.
- Modifying sector allocation rules applied during water shortages.
- Implementing a policy to satisfy all Upland water shortages with Okanagan Lake water.

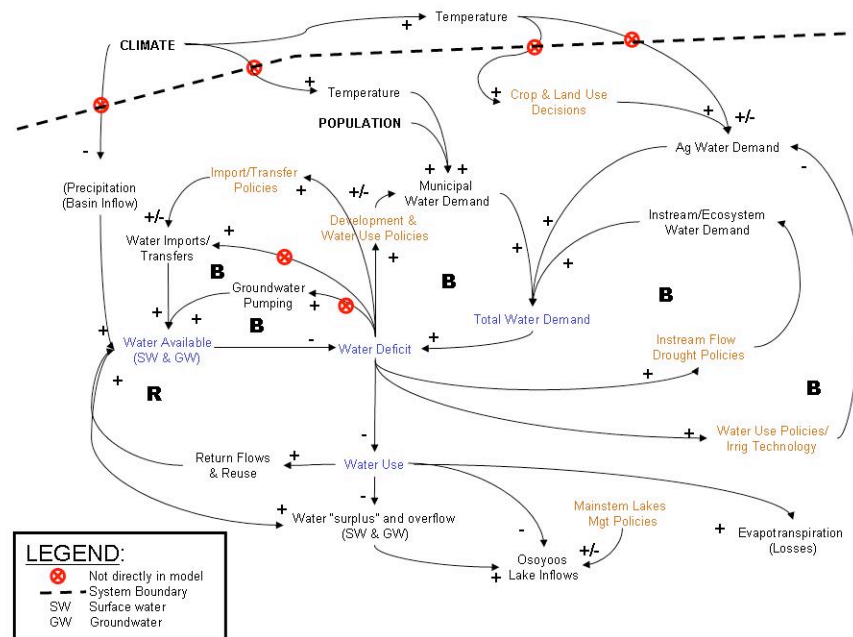
Advanced options include increasing the capacity of storage in the Uplands and adjusting the irrigated land area for each crop type. A complete list of adaptation and policy options is available in [Langsdale et al. \(2006\)](#).

## 6 Dynamics of the system

Here we describe the actual and modeled system through key linkages that define the behaviour of the aspects of interest. Since our main objective is to explore the balance between supply and demand, we characterize the aspects that will increase or decrease the supply and/or the demand.

### 6.1 The Causal Loop Diagram

One tool for illustrating a complex system is a “Causal Loop Diagram” (CLD, [Figure 4](#)). CLD’s are particularly useful for identifying feedback loops and for clarifying the factors that control system behaviour. Since one purpose of OSWRM was to gain a better understanding of the water balance under a variety of times and conditions, we chose “Water Deficit” as the state variable to indicate the condition of the system. “Water Deficit” is directly influenced by “Water Available” and “Total Water Need.” The arrows that connect these elements show the relationship, and the +/- signs indicate the direction of influence. For example, the positive link from Total Water Need to Water Deficit means that as Total Water Need increases, Water Deficit will also increase. The negative



**Figure 4:** Causal Loop Diagram of the actual Okanagan Basin water resources system.

link from Water Available to Water Deficit means that as the amount of Water Available increases, the Water Deficit decreases; there is an inverse relationship. Similarly, as the Water Deficit increases, Water Use is forced to decrease.

## 6.2 Water Deficit

The Water Deficit is the shortage in water relative to water demand. In the CLD, the Water Deficit represents an aggregate for the whole basin. The parameter is always zero or positive, as states of water surplus are ignored. More severe deficit conditions are represented by larger magnitudes.  $\text{Water Deficit} = \max[\text{Maximum Water Demand} - \text{Managed Supply}, 0]$

“Managed Supply” aggregates surface water, groundwater, and water diverted from adjacent river basins, and includes the delay created by reservoirs. “Maximum Water Demand” aggregates the basin’s agricultural, residential, and ecological demands. Forest evapotranspiration is captured as land cover in the UBC watershed model, so is already subtracted from streamflow.

### 6.3 Balancing Feedback Loops

There are several balancing loops that work to alleviate Water Deficit either by increasing supply or by reducing demand. Supply is increased through additional imports and/or groundwater pumping. In the actual system, we know basin residents have supplementary groundwater wells. However, these are unregulated and there is little information on the magnitude, location, or frequency of use. It should be noted that, although groundwater pumping increases supply in the short term, it is probable that surface water and groundwater are closely linked; therefore, groundwater pumping may reduce the amount of surface water available over the longer term. In OSWRM, only certain communities rely on these supplemental sources, and their contribution increases only as the populations in the communities increase. This supplementary supply–drought feedback is not captured.

When deficit is present, mechanisms exist for reducing allocations to each of the three use sectors. Decisions about prioritizing water use and thus, implementation of these mechanisms, is decided at the local scale, often by individual purveyors. Extended periods of water deficit may encourage implementation of conservation measures.

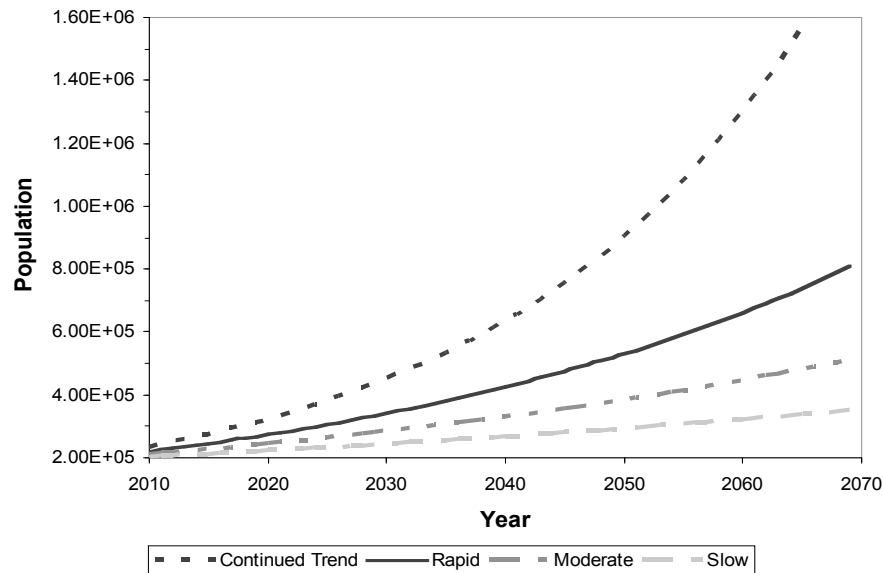
### 6.4 A Reinforcing Feedback Loop

Water is reused multiple times on its journey between precipitating onto the ground and exiting to Osoyoos Lake. This phenomenon is captured by a weak reinforcing loop. Water is returned to the system post treatment, or through irrigation returns. Several communities reclaim treated water from residential sources and use it for watering golf courses and municipal parks. The increase in water available reduces the water deficit, which allows for increased water use. Additional water consumption increases the volume of water returned to the system. The reinforcing strength of this loop is highly limited by exit pathways, such as flows downstream, and losses to evapotranspiration or to deep aquifers.

### 6.5 External Drivers—Climate and Population

Without external drivers, the system could achieve dynamic equilibrium. However, the external influences of a climate change and population growth disrupt the system. Climate change can affect the water deficit through multiple influence points—decreased precipitation reduces streamflow, and increased temperatures increase agricultural irrigation requirements and residential outdoor watering. In this analysis, we assume population is affected only by factors outside of our system and that it will continue to increase over time. Therefore, without significant water reduction or conservation strategies, residential water demands will continue to increase.

Residential growth rate projections used in this work are based on community and regional plans. These rates are significantly lower than the growth rates of recent decades. [Figure 5](#) compares the population projections based



**Figure 5:** Population projections for the Uplands water users. Continued trend uses growth rates realized between 1961 and 1990. Rapid, Moderate, and Slow growth rates are based on Community Plans.

on the three growth rates defined by the community plans (rapid, moderate, slow) with the population based on growth rates under recent history (continued trend). The historic growth rate was significantly higher than projections, so the future estimates of population growth may also be underestimated. For that reason, we emphasize the rapid growth scenario in the results presented in this paper.

## 7 Results

The results presented in this paper all focus on the Uplands portion of the basin, defined primarily as the managed tributaries to Okanagan Lake and users of this water source. [Subsection 7.1](#) describes projections of maximum future demand compared with managed supply, at a number of scales from thirty-year aggregations, to monthly averages. [Subsection 7.2](#) shows feasible allocations associated with the amount of supply available in these future scenarios. Finally, [Subsection 7.3](#) discusses the role of adaptation as a means to making a smooth transition to the future as described by these plausible scenarios.

## 7.1 Managed supply versus maximum demand

**Figure 6** compares the total managed supply with the total maximum demand in the Uplands Region of OSWRM from the historic to the future simulations. These results are aggregated and reported as annual averages, with one value for each of the three thirty-year simulation periods. **Figure 6** presents both rapid (a) and slow (b) growth rates to show the sensitivity of the system to population growth. The remaining figures present only the rapid growth scenario unless otherwise noted.

“Managed supply” combines stream flow in the tributary streams with the supplemental supplies and return flows, and includes timing adjustments from the reservoirs. The “No Climate Change” scenario supply data lines show a slight increase over time. This increase can be fully attributed to these supplemental sources and return flows, which are dependent on population. Note that all three climate scenarios contain these minor increases in supply, although they are superimposed by the more dominant decreasing trend that is a direct result of the decrease in basin precipitation due to climate change.

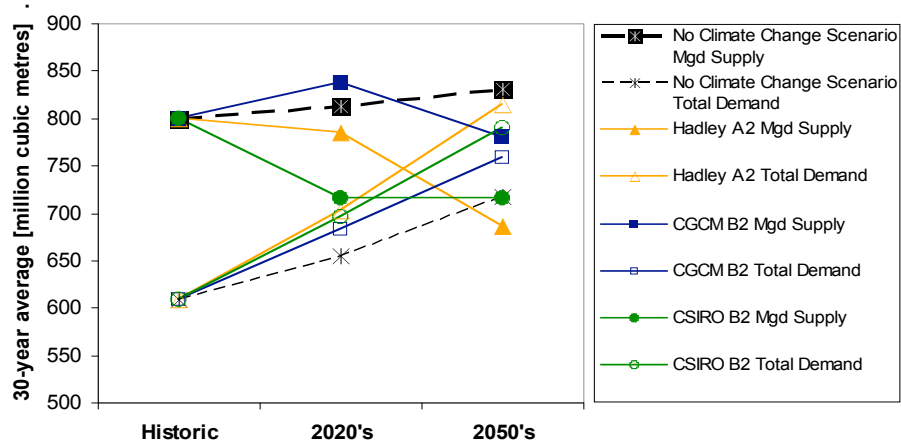
In **Figure 6**, “Total demand” includes the three major sectors: agricultural, residential, and conservation flows. The maximum demand values are based on projections of current use patterns and do not assume any increases in efficiency such as implementation of conservation measures. Maximum demand is independent of supply and may be greater than available supply, even in the historic period. In all of these scenarios the conservation flow target remains constant through time, so changes in demand are all a result of changes to residential and agricultural demands. Agricultural land under production and crop types are also assumed to be constant; thus, any simulated increase in agricultural demand is due to climate change.

In the historic period, the average managed supply in the Uplands exceeded the average maximum demand. All of the future scenarios in **Figure 6** show decreases in supply and increases in demand over the long term. The CGCM B2 scenario does show an increase in supply in the 2020’s, but the large decrease in supply in the 2050’s still leads to a decrease overall. Average annual demand exceeds supply by the 2050’s in the Hadley A2 and the CSIRO B2 scenarios, for both the rapid and slow growth scenarios. The CGCM B2 scenario is the least severe, but still shows a smaller gap between supply and demand in the 2050’s.

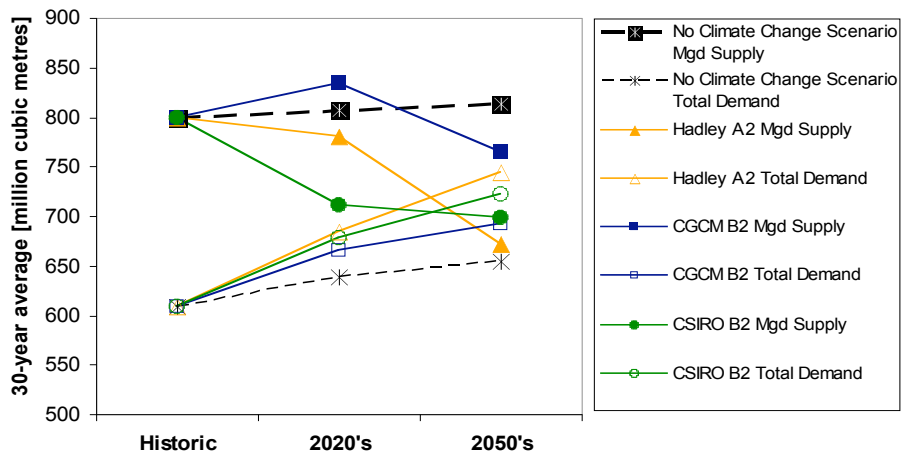
### 7.1.1 Annual Variability

The thirty-year annual averages shown in **Figure 6** show the long-term trends, but conceal the presence of shortages due to annual climate variability. **Figure 7** and **Table 1** show annual variability which reveals the magnitude and frequency of annual water shortages. The scatter plot (**Figure 7**) presents managed supply versus maximum demand for each year of simulation from the historic period through the 2050’s for a single climate scenario (Hadley A2). The dashed line represents the supply-demand equality, which is approximately the location of the threshold between water deficit and surplus; points located above this



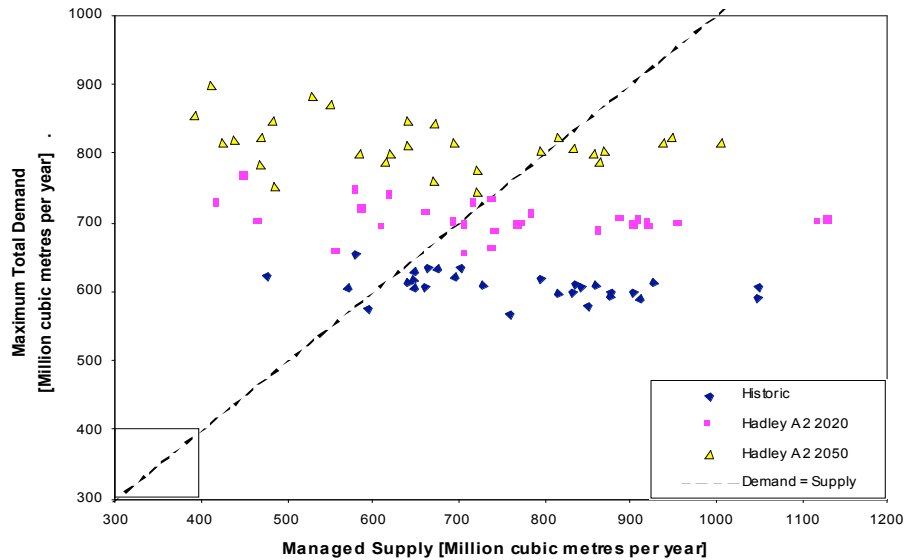


(a) Rapid Population Growth



(b) Slow Population Growth

**Figure 6:** Thirty-year annual averages of total managed supply and maximum demand from the Uplands, showing trends through time for multiple climate scenarios with (a) rapid population growth, and (b) slow population growth.



**Figure 7:** Annual total managed supply and total maximum demand for the Hadley A2 climate scenario and rapid population growth among Uplands water users.

threshold represent a deficit in the annual water budget. In the thirty-year historic period, there are three years in deficit (one out of ten). By the 2050's, both the Hadley A2 and the CSIRO B2 scenarios show a deficit frequency of about two out of three years, whether population growth is slow or rapid. CGCM B2 is less severe. [Table 1](#) summarizes the years in deficit for each of the scenarios and time periods. By the 2050's period, the climate change scenarios estimate shortages occurring every 14 to 22 years out of 30 if rapid population growth occurs. Slow population growth has little effect, with shortages still occurring every 11 to 21 years out of 30.

### 7.1.2 Intra-annual Variability

Water supply and demand in the Okanagan are unequally distributed through the year, so some of the years that are not in deficit overall may still experience summer shortages. [Figure 8](#) shows supply and demand by month, including a breakdown of the three major demand sectors. Managed water supply currently peaks in March as a result of the spring freshet. Total demand also peaks in March; however, out-of-stream demands peak in July and August. Instream conservation flow targets roughly follow the historic natural pattern of supply, and the monthly targets are held constant each year. In all of the future climate change scenarios, the spring freshet occurs slightly earlier in the 2020's and 2050's. Managed supply reflects this, as is shown by the increases in April supply through time. Because the conservation flow targets are based on the historic peak flow, a slight offset in timing of peak flow emerges. Future residential and

**Table 1:** Summary of deficit years as defined on the scatter plot (Figure 7) for multiple climate scenarios.

(a) Rapid Population Growth Scenarios			
	No. of years (out of 30) where demand equals or exceeds supply		
	Historic	2020's	2050's
No CC	3	6	10
Hadley A2	–	11	22
CGCM B2	–	8	14
CSIRO B2	–	14	21
Hadley A2 Mod Adapt	–	9	19

(b) Slow population growth scenarios			
	No. of years (out of 30) where demand equals or exceeds supply		
	Historic	2020's	2050's
No CC	3	5	6
Hadley A2	–	9	19
CGCM B2	–	7	11
CSIRO B2	–	14	21

**Table 2:** Allocations as a percent of demand, shown as annual totals and for August, the month with the greatest deficit in the future scenarios.

Percent of Demand Met (Allocations/Demand)	Annual Totals		August Only	
	2020's	2050's	2020's	2050's
CGCM B2	93%	82%	84%	59%
Had A2	90%	74%	79%	50%
CSIRO B2	76%	72%	49%	45%
Had A2 Mod Adapt	86%	78%	81%	55%

agricultural demands increase through the irrigation months (March—October). By the 2020's, the thirty-year averages of demand in July, August, and September exceed available supply. By the 2050's, the deficit during these months is exacerbated, and extends between June and October.

In [Figure 8](#), conservation demand remains constant through the future periods (because it is defined by policy). Agricultural demand increases with climate change, and residential demand, which historically was rather minor, becomes a more notable—although still small portion of the profile by the 2050's with rapid population growth.

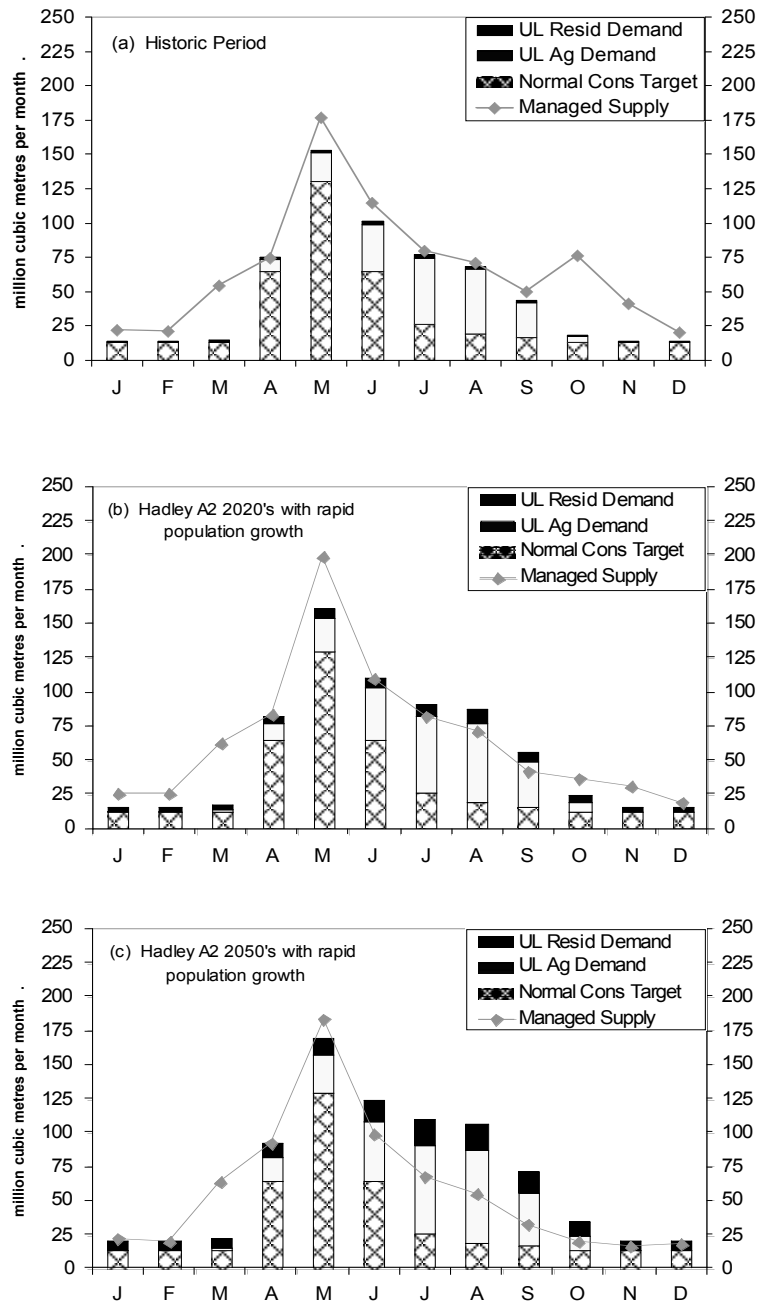
## 7.2 Maximum demand versus total allocation

The volume of water that can be allocated to meet demands is limited by the amount of managed supply available each month. When water shortages occur, water allocations are determined by drought policies and management decisions. The graph in [Figure 9](#) shows maximum demand and total allocation over the thirty-year simulation period for several scenarios.

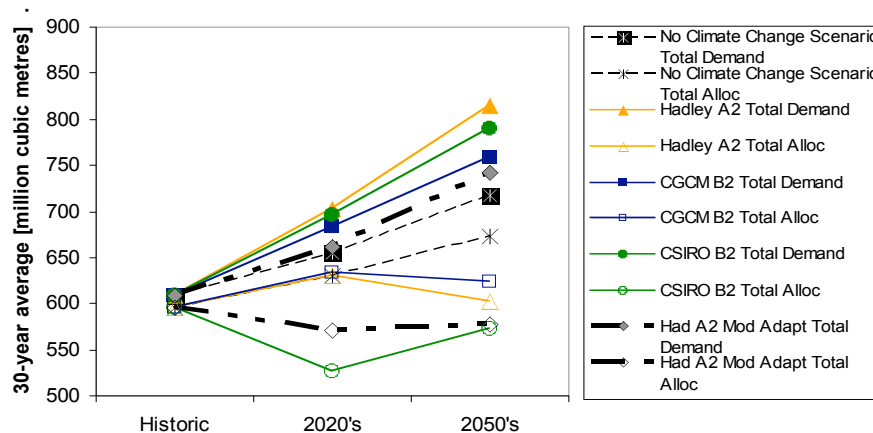
OSWRM allocates water to the three sectors based on interpretations of the current drought policies and management practices that were described to us by the local stakeholders who participated in the model building sessions. For example, residential outdoor watering restrictions are standard practice in the region, so it is the first sector to be cut. On average, percent reductions across sectors are similar, with a slight priority granted for conservation flows and slightly greater reductions in the residential sector.

In the future climate change scenarios, both agricultural and residential demand levels during the summer increase. At the same time, supplies are generally decreasing overall. Spring melt occurs earlier, and summers are drier, which makes meeting summer and fall demand even more challenging. Critical months by the 2050's extend from June through October, with August becoming the most severe.

The difference between the allocation curves and the demand curves in [Figure 9](#) shows how much demand can be satisfied. This is expressed in [Table 2](#) as percentages of the demand met (through allocations) for both annual totals and August values. In the historic simulation, 98 percent of annual demand was



**Figure 8:** Thirty-year average monthly managed Uplands supply and maximum demand profiles with demand from the three major sectors revealed.



**Figure 9:** Thirty-year average annual summary comparing demand (all three sectors) and total water allocated in the Uplands for the rapid population growth scenarios.

satisfied, while 95 percent of August demand was satisfied. All of the future scenarios show reduced capacity of the system to meet demand.

### 7.3 Deficit and adaptation

Reductions in demand can be forced during dry years, which will occur with increasing frequency and severity, or they can be voluntary and anticipatory, through the use of anticipatory conservation strategies. Various conservation and adaptation strategies that reduce consumption could decrease the total demand as shown, and may help to lessen the frequency and severity of forced allocation reductions.

The scenarios described thus far include several assumptions. First of all, the future “maximum” demand assumes that no additional conservation strategies will be implemented. Furthermore, the scenarios assume agricultural demand will continue to increase as a function of crop water demand, without regard to water rights limitations. Residential water demand will continue to increase as a function of the exponentially increasing population. Therefore, conservation measures and/or regard for legal limits may reduce the severity and frequency of deficit.

Figure 9 and Table 2 include the results of a “moderate adaptation scenario.” This scenario takes some of the current adaptation trends in the region, and extends them to the entire basin. Residential demand management includes public education and metering with charges by increasing block rate. Combined, the strategies may slow residential demand by about 40 percent (Neale, 2006). The moderate adaptation scenario also includes a reduction in all agricultural demand, by six percent. These reductions are not from current levels, but are

reductions from the future scenarios without adaptation, as shown in [Figure 9](#). Note that future average allocations are also slightly reduced in the adaptation scenarios, compared with allocations in the associated (Hadley A2) no adaptation scenarios. The decrease in average allocation is partly due to the decrease in managed supply and partly to the decrease in demand. The decrease in managed supply is due partly from the decrease in return flows from residential indoor use and partly from storage release adjustments. The wastewater return flows are significant, so as residents use less, the return flows are much less. The remaining supplementary sources are minor. As a result, the reliability of meeting demand in the future does not increase significantly. In fact, it appears to drop slightly in the 2020's, but shows a slight improvement from the no adaptation scenario in the 2050's.

Alternate ways of allocating water to the three main sectors are nearly limitless. OSWRM provides an opportunity for users to explore this feasibility space through numerous optional settings, as described in [subsection 5.1.7](#). [Cohen & Langsdale \(2006\)](#) show simulation results from a number of adaptation scenarios, providing some insight into the effectiveness of a range of options available. It is theoretically possible to define this feasible region (i.e. the range of possible combinations of adaptation measures that would produce satisfactory results); however, the boundaries of the region are subjective, dependent on both opinion and irrigation technology. Therefore, defining boundaries would be quite challenging. This task is beyond the scope of this project, but is recommended for future work. The purpose of this modeling initiative, couched in a participatory process, was not to find “the” solution, but to help the Okanagan’s water resources community reflect on what they value and explore what policies would be effective both in reducing future vulnerabilities and in creating a desired future for the region.

#### 7.4 Implications for future management

All future climate change scenarios, from 2010 through 2069, show a significant decrease in water supply from the 1961–1990 condition. This decrease may be slightly offset by additional groundwater pumping and diversions from adjacent river systems; however, the limitations of these sources are currently unknown. Simultaneously, out-of-stream (agricultural and residential) demands are projected to increase significantly. Residential water demand is more sensitive to population growth than to climate change, although climate change does accelerate the effect of an increasing population. In contrast, the area of agricultural land in production is quite stable in the Okanagan (in part due to the provincial Agricultural Land Reserve), but crop water demand is highly sensitive to changes in climate, so irrigation may intensify. It is possible that either market conditions or climate shifts could force changes in crop types, which would change irrigation needs. Conservation flows are policy-based, and are assumed to remain constant throughout the simulation time period.

All of the climate scenarios show that the long-term average allocations may remain close to the levels in the historic simulation. This is because in

wet years, allocations increase to match the increased demand, while dry years become more frequent and intense, so allocations in dry years are less than present levels. Even though historic and future allocations are comparable, the reliability of the water supply to meet demand decreases from a historic rate of 98 percent to 72–82 percent in the 2050's. Most of this future deficit is due to the impacts of climate change. Population growth contributes to only a small portion of this reduced reliability, as is evidenced by the “no climate change” scenario. Future simulations without climate change result in allocations that are 94 percent of maximum demand in the 2050's.

Satisfying demand during the dry season, when irrigation demand peaks, becomes increasingly difficult. August may be the worst month, with allocations reducing from 95 percent in the historic simulation, to 45–59 percent of demand in the 2050's. Conservation measures may reduce this deficit, however, the “moderate adaptation scenario” which incorporates some of the adaptation measures currently being implemented in the region and extrapolates them for the whole region, does not significantly reduce the deficit. The potential effectiveness of the conservation measures may be slightly dampened by the feedback loop created by the residential water consumption that provides return flows back to the system. Indoor water use is, in effect, not a consumptive use. Stricter conservation measures, limiting future residential development, and limiting increases in agricultural demand, may be required to prevent future water conflicts. The agricultural sector may be forced to implement efficient irrigation technologies, change crop types, and/or reduce land under production. As a complement to conservation measures, expansion of supplies may play a role. [Cohen & Langsdale \(2006\)](#) showed that expanded use of Okanagan Lake may be feasible, if care is taken to avoid depleting this resource. Expanding groundwater use has not been fully explored. Caution should be applied with expansion of either groundwater or Okanagan Lake as they are not new resources, but are hydrologically connected to current sources.

## 8 Conclusions

OSWRM is a highly aggregated scoping model intended for the purpose of exploring a variety of future scenarios. Analyzing the results of these scenarios helped to illuminate dominant and controlling system characteristics, such as feedback loops. Identifying parameters to which the system is sensitive also helps to select priorities for future research. For example, reductions in residential water use caused a notable decrease in wastewater return flows (from residential indoor water use). Refining the portion of residents on sewer, and the portion of water which is returned may increase the accuracy of model results.

Because the modeling exercise was primarily focused on qualitative characterization as opposed to quantitative calibration, it is important to focus more on the general trends of the future scenarios than on specific values. OSWRM is useful for quickly testing a number of different climate change, population growth, and adaptation scenarios; however, when the Okanagan community is



ready to move toward design and policy-setting, then more detailed studies are recommended.

The results presented in this paper focus on the Uplands portion of the basin for clarity of presentation. At the outset of this work, the common belief was that the dry southern portion of the basin, downstream from more than half of the basin's population, would be most vulnerable to all stressors on the water resources. Intuitively, one would expect that water shortages in the upstream end of the basin would increase in severity as you move downstream. However, to date, watersheds in the Upland tributaries have proven to be most sensitive to drought. The 2003 drought caused severe conflict and resulted in the development of an operating agreement in the Trout Creek watershed, while the South End felt little or no impact. One reason for the lack of sensitivity is that the South End community's two main water sources are quite buffered from climate variation. Surface water supplies used for irrigation are managed to a large extent through operation of the dam on Okanagan Lake, and groundwater used for domestic purposes is typically a stable resource, not immediately impacted by drought. However, the question still remains whether long-term strains in the Upland region will eventually trickle down to the South End. Current research on the characterization of the groundwater aquifers will provide some clues to this puzzle. Ultimately, it will be the decisions that the residents and water managers make that will have significant influence over the future of water resources in the Okanagan Basin.

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