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# Water Supply-Demand Management under Climate Change

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## Abstract

This study aimed to investigate optimal multiple reservoir operations and water demand management considering climate change impact. In this study, conditional density estimation network creation and evaluation (CaDENCE) method was used for downscaling precipitation, and support vector machine (SVM) was used for downscaling temperature. The Bayesian neural network (BNN) model was applied to simulate the monthly reservoir inflows, which was used as the input to the optimization model. A multi-reservoir system was used for methodology demonstration, where three reservoirs were delivering water to an urban area. Several water-saving measures including long-term and short-term measures were involved in the optimization model to mitigate water shortage problem. The model aimed to maximize the total revenue obtained from water release of three reservoirs subject to constraints of available water supply, demand of water users, and cost of water demand management. The optimal water release schemes and adoption of water-saving measures under current and future climate-change conditions were obtained. The results showed that the water releases would increase at spring and decrease at winter under HadCM3 A2 emission scenario compared to the current condition.

**Keywords:** climate change, downscaling, reservoir operation, water supply-demand management

## Introduction

Climate change impact on water resources has been recognized as a serious concern for many countries. A warmer climate could potentially influence the regional precipitation pattern and river runoffs, and make current water management systems less effective as expected (Milly et al., 2008). This is especially true for planning of reservoir operation, as it is significantly influenced by river inflows and water users, where both may subject to climate change impact. In recent years, various researchers made a lot of efforts in investigating the potential effect of climate change on water resources management. For examples, Eum and Simonovic (2010) studied the optimal reservoir operation considering the potential impact of climate change by using an integrated water resources management model; Islam and Gan (2014) assessed the future outlook of water resource management of the South Saskatchewan River Basin of Alberta under climate change. However, there are relatively limited studies on the coupling of climate change study and optimization of a water supply-demand system. Therefore, the objective of this study is to advance a water supply-demand management model and apply it to a study case in Canada. With the aid of downscaling tools, the change of rainfall patterns under future conditions will be reflected in the variations of river flows, and then the projected flow conditions will be used as important parameters to be embedded in the water management model.

## Study Area

The studied water supply-demand system is adapted from a real-world case (Greater Vancouver Regional District, GVRD) located in the south part of the Georgia Basin, Canada. The area currently has a population over 2 million, receiving water supplies from Capilano, Seymour, and Coquitlam reservoirs (as shown in Figure 1) (Huang et al., 2006). A variety of hydrological factors are affecting the reservoir inflows, including precipitation, snowpack and temperature (BC Hydro, 2005). Due to population growth, the water supply systems in the GVRD under future climate change conditions may not be able to meet the demands. Adaptation strategies that emphasize on utilizing existing resources more efficiently are important for better supply and demand management. In this study, several long-term and short-term water-saving measures are considered. The short-term ones include replacement of water-saving facilities and installation of outdoor water-saving kits; the long-term measures include education, metering, and leak detection (as shown in Table 1). The related cost and efficiency of each water-saving measure are mainly referred to BC Ministry of Community & Rural Development (2009).

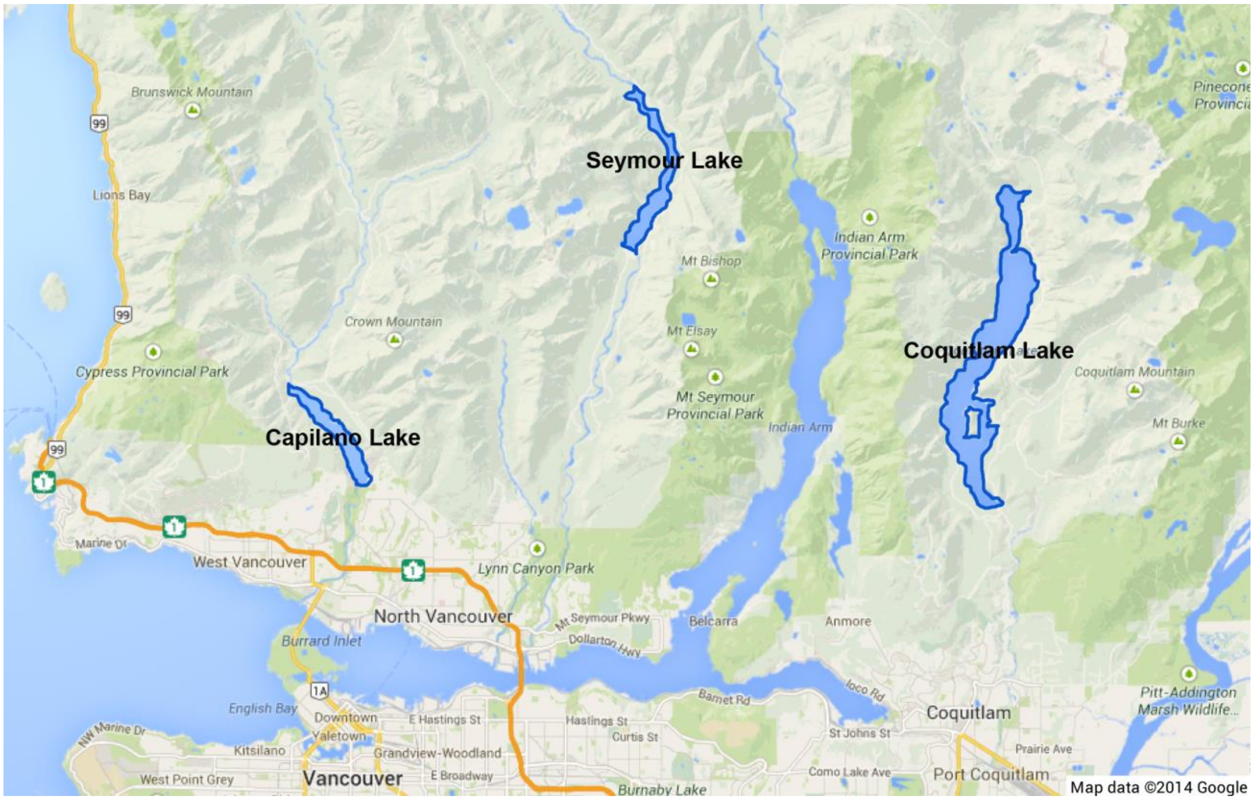

**Figure 1**. Map of study area (adapted from Google Map).

**Table 1.** Unit costs and efficiencies of long-term and short-term conservation measures

| Long-term Measures | Unit cost (CAD $/m$^3$) | Efficiency (%) | Short-term Measures | Unit cost (CAD $/m$^3$) | Efficiency (%) |
|---|---|---|---|---|---|
| Education | 1.06 | 20% | Showers | 2.38 | 3% |
| | | | Toilet | 1.85 | 10% |
| | | | Faucet | 1.44 | 3% |
| Metering | 0.68 | 20% | Laundry | 12.97 | 2.5% |
| | | | Dishwasher | 14.61 | 0.15% |
| | | | Outdoor water kits | 0.058 | 9.5% |
| Leakage detection | 1.27 | 10% | Sprinkling bylaw | 0.031 | 3% |
| | | | Rainbarrel program | 1.42 | 8% |

Source: BC Ministry of Community & Rural Development (2009)

## Model Formulation

The water supply-demand model can be formulated as follows:

$$Maximize\ \sum_{t=1}^{T}\left(BR\cdot WR_t+BI\cdot WI_t+BC\cdot WC_t\right) \tag{1}$$

Subject to:

$$ST_{it}=ST_{it-1}+Q_{it}-X_{it}-E_{it}\quad \forall i,t \tag{2}$$

$$ST_{it}\leq ST_i^{\max}\quad \forall i,t \tag{3}$$

$$\delta_t=\max\left(0,DM_t-\sum_{i=1}^{I}X_{it}\right)\quad \forall t \tag{4}$$

$$\sum_{i=1}^{I}X_{it}=WR_t+WI_t+WC_t\quad \forall t \tag{5}$$

$$DM_t\cdot\left(\sum_{k=1}^{K}Y_{1k}\cdot\eta_{1k}+\sum_{s=1}^{S}Y_{2st}\cdot\eta_{2s}\right)\geq\delta_t\quad \forall t \tag{6}$$

$$\sum_{k=1}^{K}\sum_{t=1}^{T}Y_{1k}\cdot\eta_{1k}\cdot DM_t\cdot LC_k+\sum_{s=1}^{S}\sum_{t=1}^{T}Y_{2st}\cdot\eta_{2s}\cdot DM_t\cdot SC_s\leq BGT \tag{7}$$

$$WR_t\geq WR_t^{\min},WI_t\geq WI_t^{\min},WC_t\geq WC_t^{\min}\quad \forall t \tag{8}$$

$$X_{it},WR_t,WI_t,WC_t\geq 0\quad \forall i,t,k,s \tag{9}$$

where $i$, $t$, $k$, and $s$ are index of reservoirs, months, long-term measures, and short-term measures, respectively; $BR$, $BI$, and $BC$ are revenues per unit water consumption from residential region, industry, and commerce, respectively; $WR_t$, $WI_t$, and $WC_t$ are water distributed to residential region, industry, and commerce, respectively; $ST_{it}$ is final storage of reservoir $i$ at month $t$; $Q_{it}$ = reservoir inflow of reservoir $i$ at month $t$ (Mm$^3$); $X_{it}$ = water release from reservoir $i$ at month $t$ (Mm$^3$); $E_{it}$ is monthly water volume released for fishery use; $\delta_t$ is water deficit amount (Mm$^3$);

$DM_t$ is minimum water demand amount of each month $t$; $\eta_{1k}$ and $\eta_{2s}$ are efficiency of long-term water-saving measure $k$ and short-term measure $s$, respectively; $LC_k$ and $SC_s$ are unit cost of long-term measure $k$ and short-term measure $s$, respectively; $BGT$ is allowed budget for water-saving measures; $Y_{1k}$ is binary variable, where $Y_{1k} = 1$ if long-term measures are adopted; $Y_{1k} = 0$ if otherwise; $Y_{2st}$ = binary variable, where $Y_{2st} = 1$ if short-term measures are adopted; $Y_{jst} = 0$ if otherwise.

## Climate Change Impact Assessment

Figure 2 shows the flow chart of the procedures to conduct a climate-change impact assessment. Firstly, statistical downscaling is carried out to obtain future weather conditions (i.e. rainfall and temperature). The Conditional Density Estimation Network Creation and Evaluation (CaDENCE) method is used for monthly precipitation downscaling (Cannon, 2012). The predictor selection is based on the Spearman correlation coefficient between monthly precipitation and large scale predictors. In this study, 20 ensembles are used for projecting future conditions. Then, the monthly temperature downscaling is carried out using support vector machine (SVM) (Tripathi et al., 2006), which is conditioned upon precipitation. NCEP reanalysis data (i.e. 1997-2003) (Kalnay et al., 1996) is applied for calibrating the downscaling models and the HadCM3 A2 scenario (Gordon et al., 2000; Pope et al., 2000) is used for generating climate scenarios for future periods 2011-2099. In this study, the Bayesian Neural Network (BNN) model is applied for the monthly flow data simulation. The observed weather (including precipitation, Tmin and Tmax at monthly scale) and hydrological data (i.e. monthly average runoff), with time period from 1997 to 2006, is used for training BNN model and then the downscaled climate data is used as inputs to the trained BNN model to generate runoffs under future conditions (2011-2099). More technical details of the assessment methodology can be referred to Lu et al. (2014). It is noted that we only select HadCM3 A2 scenario in this study for the methodology demonstration, other GCMs and scenarios could also be used by the proposed method.

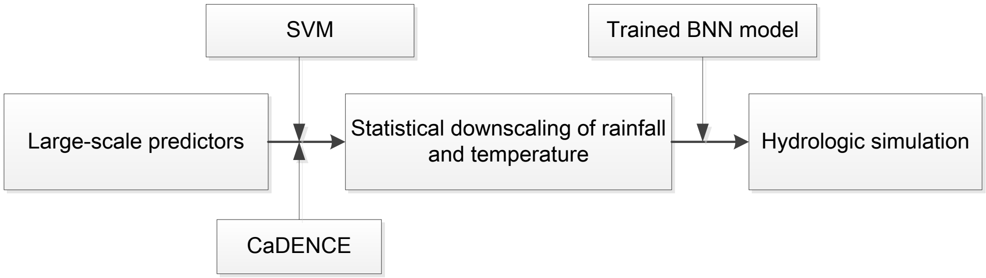

**Figure 2**. Flow chart of methodology.

## Result Analysis

The precipitation from downscaling showed that the precipitation would increase from March to August, and would decrease from November to February. For example, compared to current condition the average precipitation of April at Capilano reservoir during period 1 to 3 would increase by 23.6%, 28.2, and 11.9%, respectively, and at November would decrease by 20.1%, 26.5%, and 27.8%, respectively. The result also showed the temperature would increase in the spring under future condition. For example the Tmax of February at Capilano reservoir would increase by 17% to 24%, and the Tmin of February would also increase by 10.2% to 58.4% in the next three periods. Based on the inflow results simulated by hydrological model, the average inflow amount would increase from February to July, but decrease from August to January. For example, compared to current inflow, the average inflow of Capilano reservoir at March during period 1 to 3 would increase by 64.9%, 56.8%, and 71.4% respectively, and in October would decrease by 46.7%, 53.7%, and 33.9%, respectively. This is because the precipitation would increase in spring and decrease in winter. The increase of temperature during spring would also cause snow smelt in spring and lead to increase in inflow.

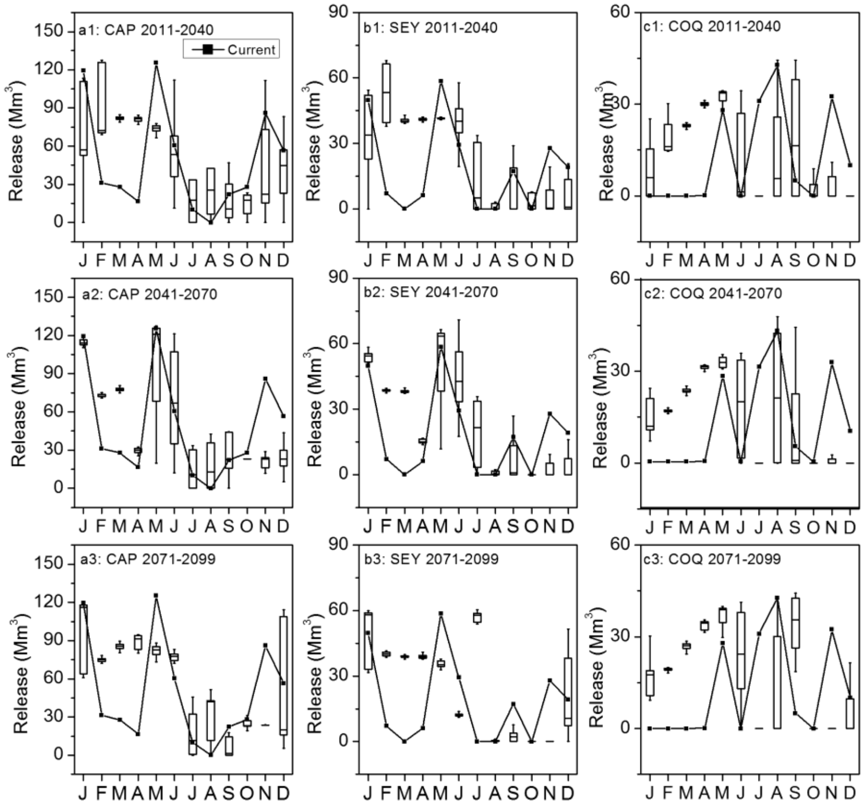

**Figure 3**. Water release of each reservoir under A2 Scenario during different periods.

Figure 3 shows the water release of each reservoir under A2 emission scenario during periods of 2011-2040, 2041-2070, and 2071-2099, based on the solutions from 20 ensembles. It is found that, under the current condition, the water release from Capilano reservoir is generally higher than that of other reservoirs. It may because the inflow of Capilano reservoir is the highest. It also shows that the Coquitlam reservoir would release more water during July and August which is the most drought period. The comparison of the water release between current and future conditions shows that the water releases are still low during summer period (July to September); the water release amount would increase during spring (from February to April), but decrease during winter (October to December). For example, the median value of water release from Capilano reservoir at February during periods 1, 2 and 3 would increase by 32.2%, 31.6%, and 40.9% compared to that under current condition, respectively. The median value of water release from Capilano reservoir in December during periods 1, 2 and 3 would decrease by 20.6%, 59.1%, and 64.7%, compared to that under current condition, respectively. This may because, under A2 scenario, there could be a higher rate of snowmelt from spring to early summer and higher precipitation, and thus a higher increase of inflow during this period. However, the inflow during late summer and early winter could decrease. Generally, the results show that the shortage problem may extend to winter under the projected future condition.

Table 2 lists the probabilities of adopting short-term measures during different periods. The probability is calculated based on the frequency of occurrence of the measures in 20 groups of solutions. The short-term measures would only have probability to be adopted during July to January under future condition; while under current condition the short-term measures would not be adopted (i.e. the value of $Y_{2st}$ under current condition are zero), which indicate that the shortage would be more serious during summer and winter under future condition. It is also found that the shortage period is the longest during period 1, which is from July to January. Moreover, it shows that the probability of the adoption would be influenced by the cost and efficiency of the measures. For example, it is found that during period 1 at July, the probability of displacing laundry and dishwasher is 0.15 and 0.25, respectively, which is less than other measures. This may because of the high cost and low efficiency of these measures. For long-term measures, the probabilities of adopting education, metering, and leakage detection would be (i) 0, 0.1, and 0.1 for current period, (ii) 0.4, 0.15, and 0.2 for period 1, (iii) 0.25, 0.3, and 0.05 for period 2, and (iv) 0.4, 0.3, and 0.05 for period 3. It is indicated that the probability would increase in the future compared to that under current condition due to the serious shortage caused by climate change. The adoption of leakage detection would have relatively low probability during periods 2 and 3 (i.e. 0.05), which is due to its higher cost and lower efficiency.

**Table 2**. The probabilities of adopting short-term measures during different periods

| Period | Measures | JUL | AUG | SEP | OCT | NOV | DEC | JAN |
|---|---|---|---|---|---|---|---|---|
| 2011-2040 | Showers | 0.25 | 0.3 | 0.2 | 0.3 | 0.25 | 0.15 | 0.2 |
| | Toilet | 0.3 | 0.15 | 0.25 | 0.35 | 0.3 | 0.15 | 0.1 |
| | Faucet | 0.4 | 0.3 | 0.35 | 0.4 | 0.35 | 0.25 | 0.1 |
| | Laundry | 0.15 | 0.15 | 0.05 | 0.2 | 0.15 | 0 | 0 |
| | Dishwasher | 0.25 | 0.2 | 0.1 | 0.25 | 0.15 | 0.15 | 0 |
| | Outdoor water kits | 0.3 | 0.45 | 0.45 | 0.45 | 0.25 | 0.5 | 0.2 |
| | Sprinkling bylaw | 0.45 | 0.35 | 0.3 | 0.5 | 0.2 | 0.55 | 0.25 |
| | Rainbarrel program | 0.4 | 0.25 | 0.2 | 0.3 | 0.2 | 0.15 | 0.05 |
| 2041-2070 | Showers | 0.35 | 0.6 | 0.4 | 0.55 | 0.5 | 0.3 | 0 |
| | Toilet | 0.2 | 0.1 | 0.2 | 0.5 | 0.3 | 0.35 | 0 |
| | Faucet | 0.4 | 0.2 | 0.45 | 0.45 | 0.4 | 0.5 | 0 |
| | Laundry | 0.3 | 0.2 | 0.1 | 0.1 | 0.25 | 0.15 | 0 |
| | Dishwasher | 0.1 | 0.3 | 0.2 | 0.2 | 0.3 | 0.25 | 0 |
| | Outdoor water kits | 0.25 | 0.4 | 0.4 | 0.5 | 0.65 | 0.75 | 0 |
| | Sprinkling bylaw | 0.35 | 0.4 | 0.45 | 0.35 | 0.6 | 0.7 | 0 |
| | Rainbarrel program | 0.35 | 0.25 | 0.45 | 0.4 | 0.45 | 0.5 | 0 |
| 2071-2099 | Showers | 0.1 | 0.4 | 0.25 | 0.4 | 0.4 | 0.05 | 0 |
| | Toilet | 0.1 | 0.15 | 0.3 | 0.4 | 0.45 | 0.25 | 0 |
| | Faucet | 0.25 | 0.4 | 0.4 | 0.75 | 0.6 | 0.4 | 0 |
| | Laundry | 0 | 0.2 | 0.25 | 0.05 | 0.05 | 0.1 | 0 |
| | Dishwasher | 0.05 | 0.2 | 0.2 | 0 | 0.3 | 0 | 0 |
| | Outdoor water kits | 0 | 0.5 | 0.45 | 0.55 | 0.7 | 0.55 | 0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sprinkling bylaw | 0.05 | 0.55 | 0.4 | 0.65 | 0.55 | 0.4 | 0 |
| Rainbarrel program | 0.05 | 0.3 | 0.2 | 0.45 | 0.65 | 0.15 | 0 |

## Conclusions

A water supply-demand model was proposed and applied to a multi-reservoir system for seeking optimal water release strategy and demand management options. The climate change impact on water supply-demand management was also considered. CaDENCE was used for precipitation downscaling, and SVM was used for temperature downscaling. BNN model was applied to simulate the monthly inflows of three reservoirs under future climate change condition. The monthly inflow data was used as the input to the optimization model. The results showed that, under future condition (i.e. HadCM3 A2 emission scenario), the water releases would increase at spring and decrease at winter in comparison to those at the current condition.

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