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SYSTEM DYNAMICS MODELLING FOR AN URBAN WATER SYSTEM: NET-ZERO WATER ANALYSIS FOR PEACHLAND (BC)

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Abstract: A Net-zero water (NZW) community limits the consumption of freshwater resources and returns water back to the same watershed, so as not to deplete the groundwater and surface water resources of that region in quantity and quality over the course of a year. A NZW study includes the analysis of various combinations of water supply sources, water conservation, and reuse over time. Such dynamics can be modelled by using system dynamics. This article aims to develop a system dynamics model (SDM) to achieve NZW at the urban community level. The SDM was developed by including all life cycle stages of urban water using STELLA® software. The developed SDM was validated using the historical data of Peachland water consumption (BC). Moreover, the model was applied to analyze NZW of the Peachland community during 2015-34 by considering six different scenarios. In the base case scenario, two thirds of the supplied water will be used for irrigation and will not be directly available to the community for reuse. As the community is in a semi-arid region, the Peachland community can only achieve NZW or even net-plus water for the initial five years by considering Peachland as a typical urban community without agriculture, and by implementing various water efficiency improvement measures. However, due to the projected increase in water demand, the NZW cannot be achieved after 2019.

1 INTRODUCTION

1.1 Urban Water Systems and Peachland

The world's urban population is more than half (~54%) of the total population and is expected to increase rapidly (UN DESA 2014). In Canada, the urban population is very high (~ 81%) and is growing (Statistics Canada 2014a). The growing population requires a large volume of water served by the urban water supply. Urban water processes, such as water abstraction, treatment, distribution, wastewater treatment, disposal, and stormwater drainage are essential in any urban area. They are necessary for the human consumption of safe water and reduction of environmental impacts due to wastewater discharge (Termes-Rifé et al. 2013). These human regulated urban water processes constitute a *human hydrologic cycle* (Bagley et al. 2005), or simply an urban water system (UWS).

The District of Peachland (DoP) is located in the Okanagan Valley, British Columbia (BC), Canada. The DoP covers an area of 17.98 square kilometres (DoP 2008). The estimated population of the DoP is 6320 in 2014 with an annual population growth of 6.5% (Statistics Canada 2014b). The public water is supplied from two creeks (Trapanier Creek and Deep Creek), Okanagan Lake, and two Ponderosa wells (groundwater) (DoP 2007). Major consumers of the municipal water are residential (indoor and outdoor) buildings, agriculture, public parks, golf courses, and commercial and institutional sectors. The wastewater generated from the water use is treated at the Westside Regional Wastewater Treatment Plant and then discharged to Okanagan Lake.

1.2 System Dynamics Model (SDM) for Urban Water Systems

System dynamics is a well-established methodology to quantify complex feedbacks in system interactions (Forrester, 1961; Forrester, 1968). The system dynamics model (SDM) is often used to quantify system behaviors with feedback loops for more accurate projections (Qi and Chang 2011). The model allows for the effective trade-off analysis of multi-scenarios and the multi-attributes of UWSs over time (Sehlke and Jacobson 2005). A SDM can help users better understand and express how complex systems function through visualization and computer simulation (Sehlke and Jacobson 2005). System dynamics involves the construction of "causal loop diagrams" or "stock and flow diagrams" to mimic a dynamic system. System dynamics has not been explored much in water demand estimation studies (Qi and Chang 2011; Zarghami and Akbariyeh 2012)**.**

1.3 Net-Zero Water (NZW) Analysis

The concept of net-zero water (NZW) is similar to the carrying capacity of a system (Holtzhower et al. 2014). NZW refers to the balance of water demand and supply within a given areal boundary (Holtzhower et al., 2014). The US Army states that "net-zero water limits the consumption of freshwater resources and returns water back to the same watershed so not to deplete the groundwater and surface water resources of that region in quantity or quality over the course of a year" (US Army 2011). The central theme of NZW emphasizes a balance so that the sum of all input water is offset by comparable output water (Joustra and Yeh 2014). NZW presupposes that a community system can secure an adequate water supply within its boundaries, typically from surface water, groundwater, reclaimed water, and rainfall (Holtzhower et al. 2014). Achieving net-zero water similar to the natural cycle requires both the conservation of water and the creation of balanced water feedback loops (Joustra and Yeh 2014).

A recent report published by the US National Research Council showed that "The use of reclaimed water to augment potable water supplies has significant potential for helping to meet future needs, …." and also recommended potable reuse with or without an environmental buffer as an alternative water management approach (National Research Council 2012). Similarly, water recycling for the augmentation of drinking water supplies has been promoted by the Australian government, who published guidelines for reclaimed water quality management (EPHC/NHMRC/NRMMC 2008). Also, in Canada, the provincial government of British Columbia has planned for the mandatory construction of dual water-plumbing (additional purple pipes for reclaimed water flow) in new buildings (MoE 2008). These initiatives show an increasing aspiration for reclaimed water use. This research develops a system dynamics model for the urban water system of Peachland and analyze its potentiality to achieve NZW.

2 METHODOLOGY

The system dynamics model for the UWS of Peachland was developed by using STELLA® software (Karamouz et al., 2012; Qi and Chang, 2011). The SDM includes three sub-models: population, water, and wastewater sub-models. These sub-models and NZW analysis method are described below:

a. Population Sub-model

The population dynamics of the District of Peachland was analyzed using the population growth equation as given in Equation 1 (Nasiri et al. 2013). The data required for the population sub-model, such as base population, population growth rate, and dwelling size were obtained from Statistics Canada (2014b).

[1] $N_t = N_0 e^{r\,t}$

where N_t = population in a month, N_0 = Base population, r = population growth rate (monthly), t = time duration in months

b. Water Sub-model

The water sub-model represents the flow of supplied water within the Peachland community. The water flow occurs through the urban water stages: abstraction, treatment, distribution, and use. The water use dynamics was modelled using Equation 2. The equation includes the water consumed by different activities of the urban sectors: residential; industrial, commercial, and institutional (ICI); agricultural; public parks; and golf courses over time.

[2] $(\text{Water use})_t = (\text{Residential water use})_t + (\text{Agricultural water use})_t + (\text{Institutional water use})_t + (\text{Commercial water use})_t + (\text{Industrial water use})_t + (\text{Parks and golf courses water use})_t$

where '"t" refers to a month

The rates of water consumption by different residential indoor activities were obtained from modified Mayer et al. (1999). The extensive study on the end uses of residential water also included Canadian cities. The efficiencies of conventional and efficient water fixtures and appliances were obtained from Mayer et al. (1999), ENERGY STAR (2014a), and ENERGY STAR (2014b). The rate of irrigation demand for different land covers such as agriculture, lawns, community parks, and golf courses of the Okanagan valley (OBWB 2010) was used for Peachland. The agricultural land area (121.6 ha) was estimated from the land use map of Peachland (DoP 2008). The average maximum site coverage of lot area is 48% for different types of residential buildings with an average lot size of 1178 m^2 in the district (DoP 1996). The site not covered by building structures or paved areas is required to be landscaped. Based on these requirements, the average lawn area per dwelling unit was considered as 50% of the average lot size. In addition, the area of community parks is 14.49 ha and new neighbourhood development is required to maintain a community park of 3.04 ha per 1000 population (DoP 2014a). Also, a golf course of 0.6 ha is located in Peachland (Ponderosa Golf 2015). The rates of commercial and institutional (CI) water use were obtained from the CI water use studies by US EPA (2009) and Dziegielewski et al. (2000). The data on the present industrial, commercial, and institutional floor space and their future growth were obtained from (DoP 2012). However, Peachland has no major industries (DoP 2012).

c. Wastewater Sub-model

The wastewater dynamic was modelled in the wastewater sub-model. This sub-model includes wastewater (WW) collection and its treatment for residential and ICI sectors.

[3] $(\text{WW})_t = (\text{Residential WW})_t + (\text{Industrial WW})_t + (\text{Commercial WW})_t + (\text{Institutional WW})_t$

Where '"t" refers to a month

d. Net-Zero Water Analysis

The potentiality of Peachland to achieve net-zero water was analyzed using the developed SDM. Equation 4 was used for the analysis.

[4] $(\text{Net water})_t = (\text{Water use})_t - (\text{Rooftop rainwater harvested})_t - (\text{Greywater reused})_t - (\text{Reclaimed water use})_t - (\text{Stormwater harvested})_t$

Where '"t" refers to a month

The average monthly rainfall data of the past 35 years (1980 to 2014) of the nearby meteorological stations of Penticton and Kelowna (Government of Canada 2015) was used for the estimation of rooftop rainwater harvesting and stormwater harvesting potential.

Prior to the development of a complete SDM, a causal loop diagram (CLD) was developed. A CLD is a foundation of a SDM, and is used to identify relationships between individual system components and to show feedback loops that affect system regulation (Nasiri et al. 2013). The CLD of the SDM of the Peachland UWS is given in Figure 1. In the CLD as shown in Figure 1, a "+" sign indicates a positive (reinforcing) relationship between two variables. An increase in the arrow tail variable causes an increase in the arrow head variable. A "-" sign indicates a negative (balancing) relationship between two variables. An increase in the arrow tail variable causes a decrease in the arrow head variable (Nasiri et al. 2013). Based on the CLD, a SDM was developed. The SDM was validated using the historical monthly data of municipal water consumption by Peachland from 2010 to 2014.

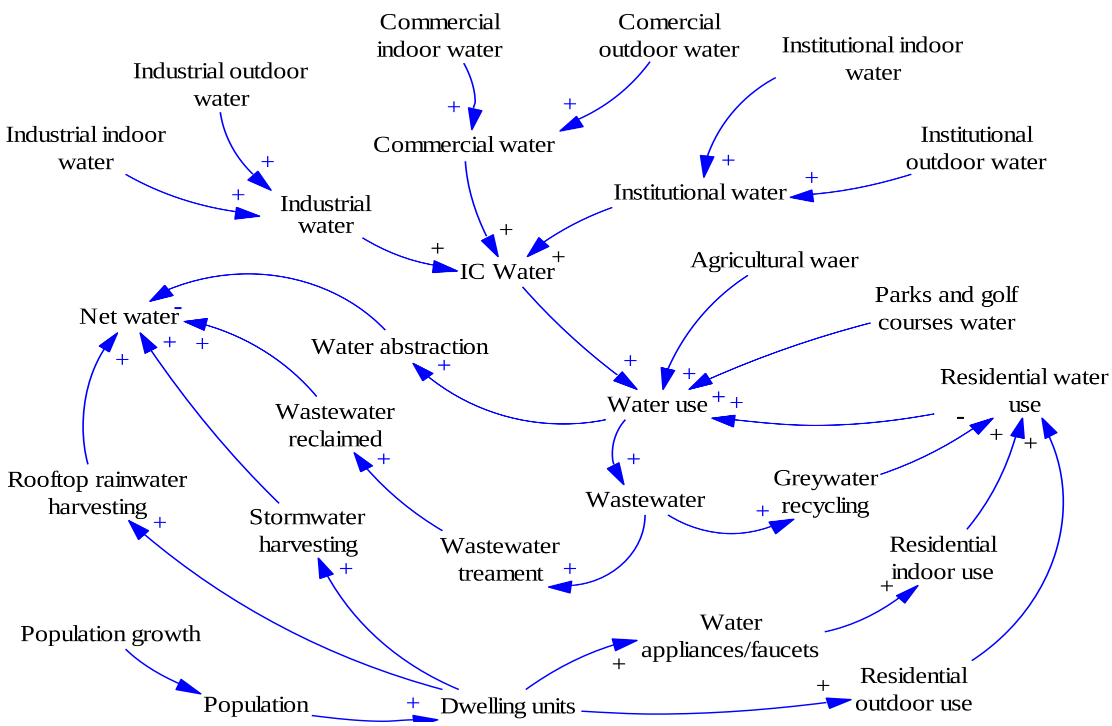

Figure 1: Causal loop diagram of the urban water system of Peachland

3 RESULTS AND DISCUSSION

3.1 System Dynamics Model for the Peachland UWS

The monthly water consumption of Peachland was simulated for five years from 2010 to 2014. The result was compared with the historical data of Peachland (DoP 2015) and is shown in Figure 2. The coefficient of determination (r^2) of the model is 0.85, which is high and is acceptable. Both historical data and SDM result showed an equal average water consumption of Peachland: 1104 L/capita/day for the five-year duration. In particular, the average residential water consumption of Peachland from 2010 to 2014 was 711 L/capita/day based on the SDM. The residential water consumption of Peachland is very high compared to the Canadian average of 343 L/capita/day (Environment Canada 2014), British Columbia average of 490 L/capita/day, and Okanagan valley average of 675 L/capita/day (OBWB 2011). The important causal factor for high residential water consumption by Peachland may be a low density residential neighbourhood with a large area of outdoor landscaping. For example, a minimum lot size of a single family residential building is 1350 m^2 (0-25% slope) to 4000 m^2 (≥ 35% slope) in an area without sewer connection and is 830 m^2 in an area with sewer connection and can have a maximum site coverage of 40%. Also, a site not covered by building structures or paved areas is required to be landscaped (DoP 1996). In addition, neighbourhood developments are required to maintain the standard of 4.04 ha parks per 1000 population (neighbourhood parks of 1.01 ha and community parks of 3.04 ha) (DoP 2014a).

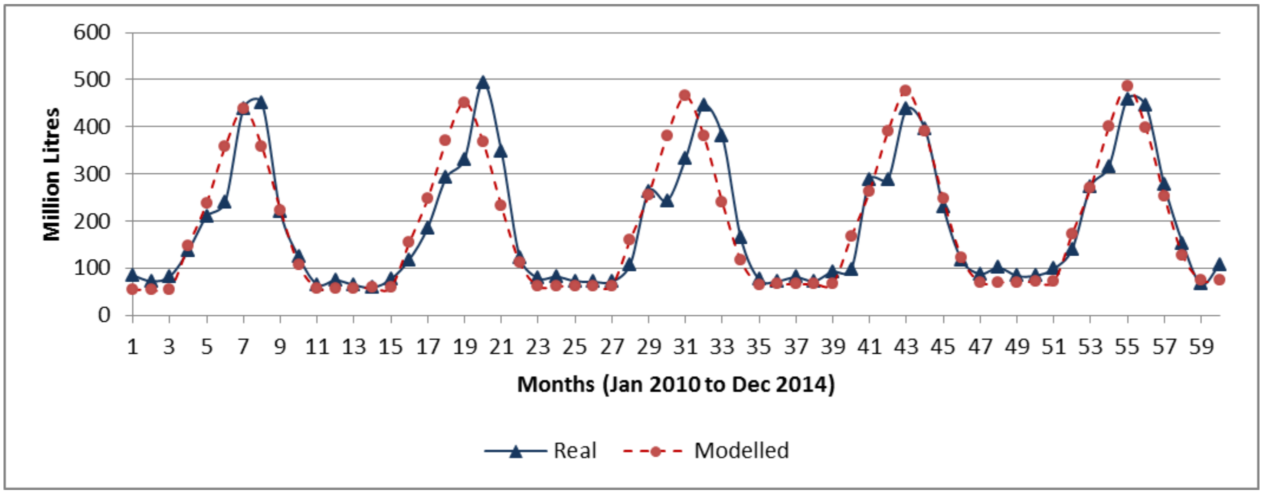

Figure 2: Comparison of historical (real) and modelled data of monthly water consumption from January 2010 to December 2014

Furthermore, the slight variation of the peak water use in the real and modelled data (Figure 2) could be due to the difference in irrigation water demand. Due to the lack of the monthly irrgation pattern of Peachland, the SDM model used the monthly irrgation rate derived from combining the total annual irrigation rate of the Okangan valley and the monthly irrigation pattern of British Columbia (BC). The monthly irrigation pattern of Peachland may be different from that of the BC avearege. The accuracy of the model can be improved by using the location specific irrgation rate of Peachland. However, the model's generalizability will be decreased.

The sectorial water consumption of Peachland from 2010 to 2014 estimated by the SDM is shown in Figure 3. As shown in the Figure, the major water consumer was the residential sector consuming about 65 % of the total water supply. In this sector, approximately 37% of the total water was used for irrigating outdoor lawns. The next dominant water consumer was agriculture with about 25% of water consumption. The remaining water was used by ICI sector (5.7%) and community parks and golf courses (4.8%). The ICI sector also includes water uses such as firefighting, street sweeping, system flushing, sewer flushing, and culvert flushing.

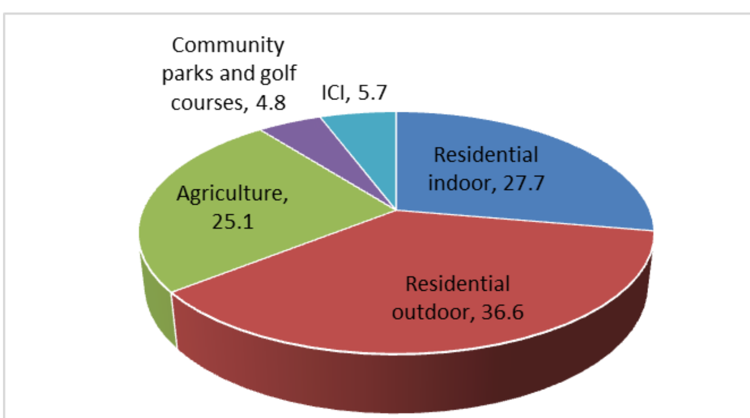

Figure 3: Water consumption by different sectors in Peachland 2010 to 2014

3.2 Applications of the Proposed SDM

3.2.1 Prediction of Water Demand

The SDM was applied for the prediction of water demand of Peachland. The total water demand under the base case scenario was simulated for 20 years from 2015 to 2034. The result of the simulation is shown in Figure 4. The total water consumption of 2,772.5 ML/year of 2015 will be gradually increased to 8,220.8 ML/year in 2034. In particular, a high population growth rate of 6.5% per year (Statistics Canada 2014b), a large area of landscaping requirement for residential buildings even in a semi-arid region, a rapid growth rate of 8.3% per year of the commercial and institutional sectors (DoP 2012), and 121.6 ha (6.8% of total land area) of reserved agricultural land (DoP 2008) will demand increased water in the future. In this period, approximately two thirds of water (66%) will be consumed by irrigation including residential outdoor lawns (39%), agricultural land (22%), and community parks (5%). This water is not directly available to the community for reuse. Water license is a permit issued to water users by government authority. The license permits water users to withdraw a given quantity of water in a specified time period (e.g. per year) at maximum from particular water bodies such as lakes, creeks and rivers. Although the District of Peachland has a water license of 17,587.0 ML/year from local lakes and creeks (DoP 2014b), which even exceeds the water demand of 2034, water demand is greatly increasing. In addition, the licensed volume of water does not guarantee the availability of water in sources and only indicates the maximum limit of water withdrawal. In turn, the water availability in the creeks of Peachland is decreasing (Harma, Johnson, and Cohen 2011). Therefore, Peachland needs to plan for sustainable urban water management.

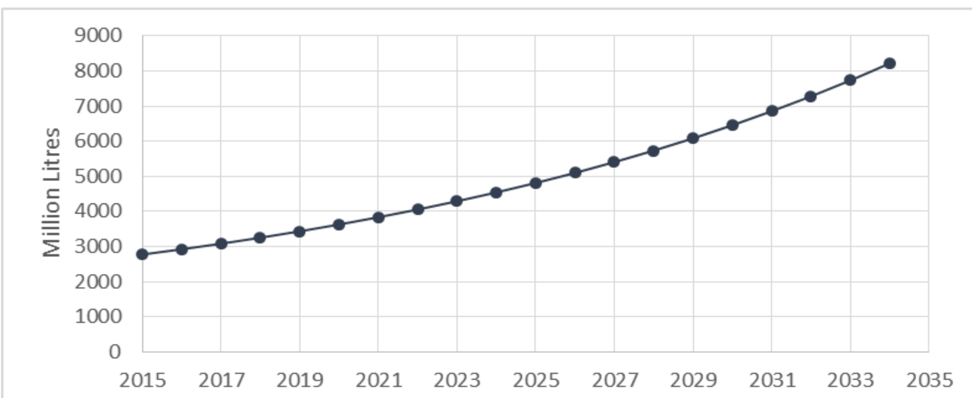

Figure 4: Water demand of Peachland from 2015 to 2034

3.2.2 Net-zero Water Analysis of Peachland

Peachland is located in a semi-arid region. The potentiality of Pechland to achieve NZW was analysed using the developed SDM. Six different scenarios were developed for the analysis. These scenarios are shown in Table 1.

Table 1: Scenarios for net-zero water analysis

Scenario	Community water features	Methods
1	Base case scenario	Future community water features similar to the present.
2	Scenario 1 with the efficient water fixtures	Efficient toilets, faucets, showers, dish washers, and cloth washers in all sectors with waterless urinals in CI sector.
3	Scenario 2 with irrigation demand reduction	Irrigation demand reduction by: 50% in residential lawns and 30% in agriculture and community parks/golf courses; use xeriscaping; water efficient crops, and efficient irrigation; 15% water conservation by behavioural change
4	Scenario 3 with rooftop rainwater harvesting and greywater recycling	Short term storage and use of harvested rainwater and recycled greywater
5	Scenario 4 with treated wastewater use	Use of treated wastewater (black water)
6A	Scenario 5 with stormwater harvesting and use	Stormwater harvesting of built up area (downtown, neighbourhoods, and residential areas) of 520 ha
6B	Typical urban setting of Scenario 6A	Scenario 6A without considering agricultural water use

The results of scenario analysis for achieving NZW from 2015 to 2034 are presented in Table 2 and Figure 5. As shown in Table 2, the average annual freshwater withdrawal of the UWS gradually decreases from Scenarios 1 to 6. The freshwater withdrawal and water use can be reduced by about 10% by using efficient water fixtures and appliances (Scenarios 1 to 2). However, water withdrawal and use can be reduced by 40% from Scenarios 1 to 3 by using efficient water fixtures and irrigation demand reduction. Peachland can reduce up to approximately 80% of freshwater withdrawal by using harvested rainwater, recycled greywater, treated wastewater (black water), and harvested stormwater (Scenario 6A compared to Scenario 1). Moreover, considering a typical urban setting without agriculture (Scenario 6B), Peachland can reduce up to 90% of water withdrawal by implementing similar measures to those of Scenario 6A.

Table 2: Average annual net water in six different scenarios for 2015 to 2034 period

Scenarios	Water use (ML)	Freshwater withdrawal (ML)	Net water (ML)	Internal water reuses/harvesting	Return to env. (Treated)
1	4974.5	4974.5	-3630.1	-	WW
2	4485.7 (-9.8%)	4485.7 (-9.8%)	-3537.0 (2.6%)	-	WW
3	3018.8 (-39.3%)	3018.8 (-39.9%)	-2203.1 (39.3%)	-	WW
4	3018.8 (-39.3%)	1721.8 (-65.4%)	-1426.5 (60.7%)	GW, RW	WW
5	3018.8 (-39.3%)	1426.5 (-71.3%)	-1426.5 (60.7%)	GW, RW, WW	-
6A	3018.8 (-39.3%)	985.9 (-80.2%)	-985.9 (72.8%)	GW, RW, WW, SW	-
6B	2569.3 (-48.3)	536.4 (-89.2%)	-536.4 (85.2%)	GW, RW, WW, SW	-

Note:
i. GW: Greywater recycling; RW: Rain water harvesting: WW: Wastewater (black water); SW: Stormwater harvesting; env: environment
ii. Parenthesis indicates a percentage change in the value from Scenario 1
iii. Negative sign indicates a reduction

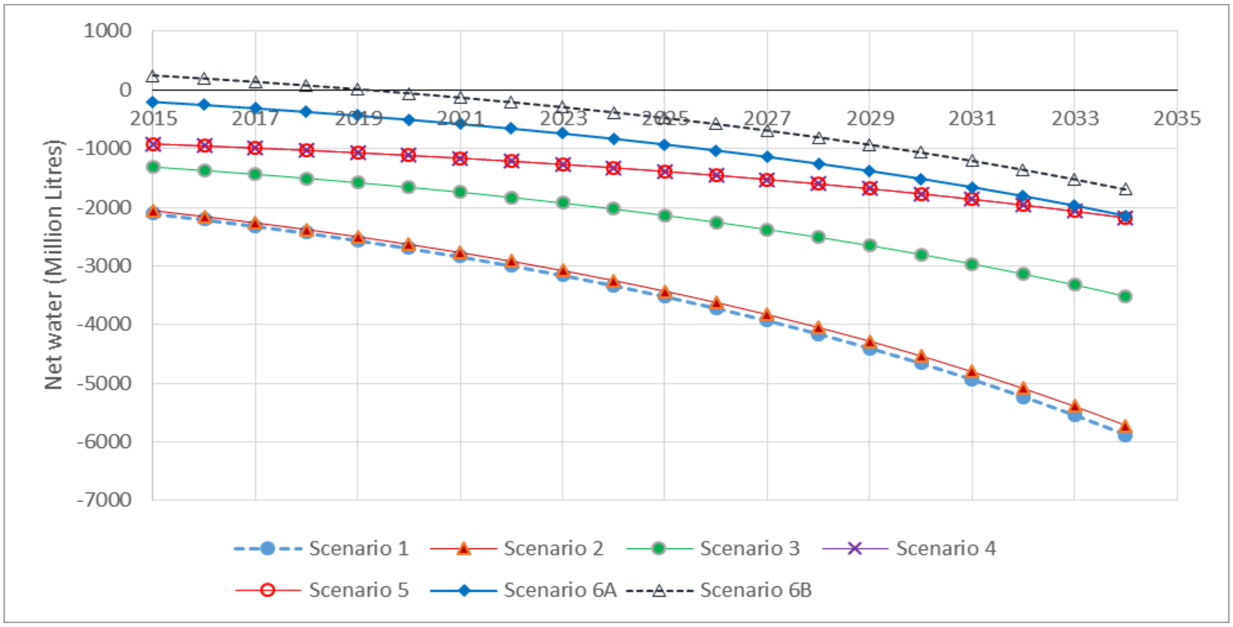

Figure 5: Scenario analysis for achieving net-zero water in Peachland

A typical urban community has no agriculture. The NZW and even net-plus water can only be achieved in Scenario 6B, a typical urban Peachland community (without considering agriculture) for the initial five years from 2015 to 2019 (Figure 5). The annual net-plus water will be approximately 246 ML, 193 ML, 137 ML, 77 ML, and 12 ML from 2015 to 2019 respectively, showing a decreasing trend due to increasing water demand. In a net-plus and NZW condition, the water withdrawal by a community is less or equal to its discharge to the same watershed. In Scenario 6B, the NZW can be achieved by taking the following measures:

- Reduction of per capita water demand by using efficient water fixtures and appliances
- Irrigation demand reduction through xeriscaping, water efficient crops, and efficient irrigation
- Residential water conservation by behavioural change
- Water supply by rooftop rainwater harvesting for portable purposes (≈149L/cap/day)
- Greywater recycling in houses and use of the recycled water for non-potable purpose and some portion for potable use if freshwater is not supplied (≈126L/cap/day)
- Wastewater (black water) recycling and use of the recycled water for non-potable purposes (≈64L/cap/day)
- Stormwater harvesting, treatment, and use for non-potable purposes (≈95L/cap/day)

4 CONCLUSIONS

The system dynamics model for the urban water system of Peachland was developed and validated using the historical data of the monthly water consumption of the Peachland community. The developed model was applied to analyze the net-zero water potentiality of the community by considering six different scenarios from 2015 to 2034. In the base case scenario, two thirds of the supplied water will be consumed by irrigation and will not be directly available to the community for reuse. Moreover, the community lies in a semi-arid region having less precipitation. For these reasons, multiple measures are required to achieve net-zero water in the community. In particular, Peachland can only achieve net-zero or even net-plus water for the initial five years when Peachland is considered as a typical urban community without agriculture (Scenario 6B). In the five-year period, the net-zero water can be achieved by using efficient water fixtures, efficient water appliances, efficient irrigation, behavioural water conservation, reclaimed water use, rooftop rainwater harvesting, and stormwater harvesting (Scenario

6B). However, due to the projected increase in water demand, the NZW water condition cannot be achieved after 2019.

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