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A HYDROLOGIC MODEL TO ESTIMATE DELTA WATER AVAILABILITY IN ALBERTA

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Abstract: ‘Delta Water’ is a terminology to describe the excess stormwater runoff generated from the increase in impervious surfaces associated with any land use development (e.g., urban, industrial). When allocated sustainably, stormwater use can offset potable water use and augment traditional water supplies. The Government of Alberta is exploring ways to enable access to traditionally under-utilized alternative sources in a way that is protective of public and environmental health. For stormwater allocation purposes, this includes understanding the volumes of runoff generated because of land use development. In this study, we have developed a Delta Water Assessment Tool (DWAT) to simulate long-term excess stormwater availability in Alberta. The tool includes Degree-Day snowmelt model, Morton’s evapotranspiration model, and Soil Conservation Service (SCS) Runoff Curve Number model. We applied the tool for three selected case studies in Alberta to assess its performance. The tool can successfully estimate delta water due to land use developments and the results are comparable to existing methods of estimating excess stormwater drainage. We also applied the tool at different locations across Alberta to test its applicability for varying natural regions and climatic conditions. We observed that the tool could reasonably estimate delta water availability at different locations in Alberta. Therefore, the DWAT can provide a consistent and scientifically defensible approach to support decision making under Alberta’s regulatory framework for water management.

1 INTRODUCTION

‘Delta Water’ is the excess stormwater runoff generated from the increase in impervious surfaces associated with any land use development (e.g., urban, industrial). Figure 1 shows a schematic of land use changes due to urban/industrial development where the pre-development landscape (Figure 1a) typically consists of natural land cover (e.g., agricultural land, grassland, water etc.), and the post-development landscape (Figure 1b) typically consists of a combination of natural (e.g., grassland, water) and manmade (e.g., houses, roads, industrial/commercial developments, ponds) land cover. When precipitation falls over natural land, and in particular in a semi-arid climate, only a fraction of the precipitation converts into surface and sub-surface runoff and the rest evaporates into the atmosphere. In contrast, when precipitation falls over developed land, a major portion of the precipitation converts into runoff, and only a fraction evaporates. This eventually results in higher runoff from a developed area compared to the natural landscape. The difference in runoff generated from the pre and post-developed scenario is the Delta Water (ΔW).

Stormwater management is a critical aspect of urban water management. Traditionally, stormwater management has been focused on capturing and disposing of stormwater in the most efficient way possible, the key objective being flood management and mitigating downstream impacts to a pre-development condition. More recently, stormwater is being recognized as a potentially valuable alternative water source

that, if used for beneficial purposes, has the ability to reduce diversions from natural water bodies, reduce the non-essential use of potable water, reduce loadings to rivers and streams, and provide an additional water source in water scarce areas. Alberta is developing guidance on sustainable use of stormwater and other alternative water sources including wastewater, greywater, rooftop collected rainwater, and various industrial effluents. However, a consistent and scientifically defensible approach is required to enable stormwater use while maintaining groundwater recharge and overland flow to surface water bodies.

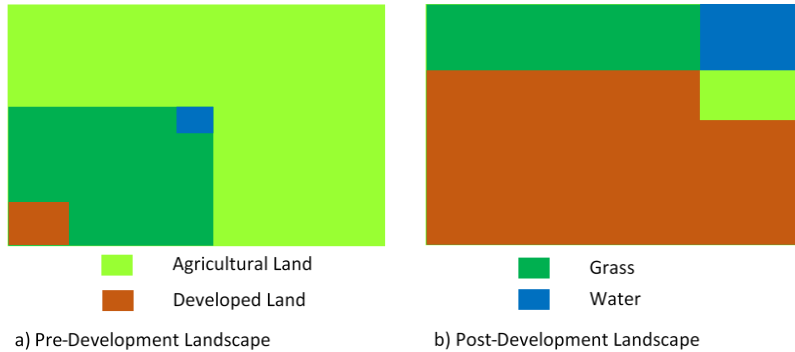


Figure 1: Schematic diagram of a typical pre and post-development scenarios

Based on the aforementioned background information, the objectives of this study are: a) develop a hydrologic model, namely, Delta Water Assessment Tool (DWAT) to estimate delta water availability in Alberta, b) test the tool for existing stormwater use projects to validate its applicability, and c) assess the applicability of the tool for varying geographic and climatic conditions. Although several commercial and academic models are available (e.g., SWMM, PCSWMM, SWAT, HECHMS etc.) which could have been used to estimate delta water, it is our understanding that a separate model with a built-in input data (e.g., climate, landuse, soil, runoff) and an automatic calibration process will allow the user to estimate delta water in a more consistent way all over Alberta. Note, the DWAT will be used as part of a larger suite of analyses to help applicants and regulators make decisions around water reuse and stormwater use projects within Alberta's regulatory framework for water management. In addition to using the DWAT to determine available stormwater, guidance is provided on meeting health outcomes through Log Reduction Targets, chemical risk assessment process, and regulatory guidance for project approval.

2 MODEL THEORY

The hydrologic model developed for this study is the Delta Water Assessment Tool (DWAT). The DWAT uses historical climate, soil, and land use data to simulate runoff coefficients (the ratio of runoff to precipitation) for different types of land cover present in a study area. Based on the modelled runoff coefficient for different types of land cover and their proportions in pre and post-development scenarios the tool estimates the delta water due to land use developments.

If there are N types of land cover other than water, the mean annual delta water (m) is given by,

$$[1] \Delta W = \left[\sum_{i=1}^{i=N} P A C_i (F_{i_Post} - F_{i_Pre}) \right] + A(P - E)(F_{W_Post} - F_{W_Pre})$$

where, C_i is the long-term averaged runoff coefficient for a land cover; F_{i_Pre} and F_{i_Post} are the fraction of the land cover i in a pre and post-development scenario, respectively; F_{W_Pre} and F_{W_Post} are the fraction of water in a pre and post-development scenario, respectively; P and E are the long-term mean annual precipitation (m) and lake evaporation (m), respectively; and A is the project area (m^2).

In order to estimate the delta water, as given by Eq. [1], it requires estimating the long-term averaged runoff coefficient for different land covers (C_i). If p_j is the daily precipitation (mm) falling on a landscape on day j and R_{ij} is the generated runoff (mm) from land cover i on day j , the long-term averaged runoff coefficient is,

$$[2] C_i = \frac{\sum_{j=1}^{j=M} R_{ij}}{\sum_{j=1}^{j=M} p_j}$$

where, N is the total number of land cover (other than water) and M is the total number of days in a simulation period (usually a period of 30 years, or more). The generated runoff from land cover i on day j can be estimated using the Soil Conservation Service Curve Number (SCS-CN) method (USDA 1986),

$$[3] R_{ij} = \frac{(p_{ij} - I_a)^2}{(p_{ij} - I_a) + S}; I_a = 0.2 S; S = \frac{25400}{CN_i} - 254$$

where, S is the potential maximum retention after runoff begins, I_a is the initial abstraction which includes all losses before runoff begins (e.g., water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration), and CN_i is the curve number for the land cover i . Since in Alberta precipitation falls as a form of rainfall and snowfall, we incorporated the Degree-Day snowmelt model in the DWAT. The degree-day method is a temperature index approach that equates the total daily melt to a coefficient times the temperature difference between the mean daily temperature and a base temperature.

$$[4] M = C_M(T_a - T_b)$$

where, M is the snowmelt (mm/day), C_M is the degree-day coefficient (mm/degree-day C), T_a is the mean daily air temperature ($^{\circ}\text{C}$), and T_b is the base temperature (generally 0°C). The coefficient C_M varies seasonally and by location. Typical values are from 1.6 to 6.0 mm/degree-day C. In absence of site-specific information, a generally accepted value of C_M is 2.74 mm/degree-day C. The snowmelt from Eq. [4] is the total ablation of the snowpack. The runoff volume is only a portion of the snowmelt volume considering the difference between the melt volume and the runoff volume usually infiltrate into the soil and groundwater storage.

$$[5] R_{Snowmelt} = C_R M$$

where, C_R is the ratio of runoff to snowmelt (will be referred as Snowmelt Runoff Coefficient).

3 MODEL DEVELOPMENT

3.1 Model Data

The model uses the gridded historical climate data (1955-2016) from the Alberta Climate Information Service (ACIS) of Alberta Agriculture and Forestry (Alberta Agriculture and Forestry 2019). The dataset contains daily time series of minimum and maximum temperature, precipitation, solar radiation, and humidity for 6900 townships (i.e. the Alberta Township System; with 6 miles x 6 miles as a basis) in Alberta. The Alberta Biodiversity Monitoring Institute (ABMI) wall-to-wall land cover data has been selected as the pre-development land use in order to estimate available water in a pre-development scenario. The ABMI wall-to-wall land cover datasets provide Alberta-wide, polygon-based representations of provincial land cover circa 2000 (Alberta Biodiversity Monitoring Institute 2012) and 2010 (Alberta Biodiversity Monitoring Institute 2013), respectively. The land cover products comprise 11 classes, including water, shrubland, grassland, agriculture, exposed land, developed land, and different forest types. The model uses Harmonized World Soil Database (HWSD) v 1.2 for soil texture information (FAO/IIASA/ISRIC/ISS-CAS/JRC 2009). The HWSD is a 30 arc-second raster database with over 15,000 different soil mapping units that combines existing regional and national updates of soil information worldwide with the information contained within the 1:5,000,000 scale FAO-UNESCO Soil Map of the World (FAO/UNESCO 1981). The model uses two observed runoff data: the University of Lethbridge lead study on mapping Alberta's surface water resources for the period 1971-2000 (Kienzle and Mueller 2013), and the annual unit runoff in Canada (Agriculture and Agri-Food Canada 2013).

3.2 Model Scale

Model spatial scale is an important consideration in model development process. As the daily climate data, land use data, soil data and runoff data are available at a township scale, we selected the spatial scale of the model as the township grid (~100 km²). Moreover, modeling the hydrology in a township grid scale will allow users to transfer hydrologic parameters (e.g., runoff coefficient information for various land cover) from township scale to project scale (1-10 km²) in order to estimate delta water due to land use developments.

3.3 Model Input Preparation

First, the hydrologic soil group (HSG) of Alberta needs to be generated. Hydrologic soil groups are the interpretive classes that have similar runoff potentials under conditions of maximum yearly wetness (Soil Science Division Staff 2017). There are four type of HSGs: A, B, C, and D. A type soils have low runoff potential and high infiltration rates when thoroughly wetted; B type soils have moderate infiltration rates; C type soils have low infiltration rates; and D type soils have high runoff potential and very low infiltration rates. In order to classify soils into hydrologic soil groups spatially distributed information on saturated hydrologic conductivity, depth to water impermeable layer, and depth to high water table are required. In this study, we incorporated a simple approach of classifying top soil layer groups based on their texture, as discussed in TR-55 report of USDA (USDA 1986). Since, the HWSD has spatially distributed information on top soil textures, as classified by USDA, we decided to use HWSD data to classify Alberta soils into four hydrologic soil groups. We found that majority of townships (58.3%) have B type soil, about 27.6% have D type, and the rest (12.9%) have either A or C type soil. About 1.2% townships do not have information on HSG from the harmonized soil data because the grid cell is composed of permanent water body.

Second, the recommended CNs based on the hydrologic soil group, land cover type and surface drainage condition need to be estimated. Table 2-2a, Table 2-2b, Table 2-2c, and Table 2-2d of TR-55 (USDA 1986) provide recommended CNs for various combinations of land cover, soil type and surface drainage conditions. Since the current study considers ABMI wall-to-wall land cover inventory data as land use input, they need to be converted into equivalent USDA land cover types. Table 1 shows the comparison and corresponding CNs for 11 types of ABMI land cover. Since for developed land, grassland, and agricultural land is sub-divided into various sub-groups, we estimated median CNs for those land cover from a wide range of sub-land use. Note, CNs indicated in the Table 1 are just the initial estimate based on land cover and soil type and will eventually be calibrated to match the observed and simulated runoff.

Table 1: Curve Numbers (CNs) adopted from TR-55 (USDA 1986)

ABMI Land cover	Equivalent USDA Land cover	CN for Soil Types (A, B, C, D) & Drainage Condition (Poor, Fair, Good)												Min	Max
		Poor				Fair				Good					
		A	B	C	D	A	B	C	D	A	B	C	D		
Water	N/A	N/A													
Snow/Ice	N/A	99													
Rock/Rubble	N/A	98													
Exposed Land	Desert shrub	63	77	85	88	55	72	81	86	49	68	79	84	49	88
Developed	Urban Areas	74	84	88	90	74	84	88	90	74	84	88	90	74	90
Shrubland	Desert shrub	63	77	85	88	55	72	81	86	49	68	79	84	49	88
Grassland	Pasture, Meadow, Bush, Woods	52.5	70	79.5	84.5	39	61.5	73.5	80	30	58	71	78	30	84.5
Agriculture	Cultivated Agricultural Land	65	75	83	86	63	73.5	82	85	61	72	81	84	61	86
Coniferous Forest	Woods	45	66	77	83	36	60	73	79	30	55	70	77	30	83
Broadleaf Forest	Woods	45	66	77	83	36	60	73	79	30	55	70	77	30	83
Mixed Forest	Woods	45	66	77	83	36	60	73	79	30	55	70	77	30	83

Third, two types of evaporative loss are required in this study: shallow lake evaporation (SLE) and actual evapotranspiration (AET). SLE is the evaporation from a water surface where the seasonal sub-surface heat storage is insignificant (e.g., stormwater pond), AET is the amount of water lost to evapotranspiration from a soil-plant continuum of a larger area. Alberta Environment and Parks (AEP) has historically computed evapotranspiration estimates using the Morton's Complementary Relationship Areal Evapotranspiration (CRAE) Model (Morton 1983). In this study, we applied the CRAE model to estimate monthly SLE and AET at a township scale.

4 MODEL PROCESSES

4.1 Initial Estimation of Runoff Coefficient

Figure 2 shows a simplified flowchart of the model processes. For each land cover present in a township, the model will utilize the township scale daily precipitation and daily mean air temperature. Depending on the base temperature set by the user, usually 0 °C, the daily precipitation converted into rainfall or snow water equivalent (SWE). The SWE accumulation occurs if the air temperature continued to be less than the base temperature. The snowmelt model only triggered when the air temperature becomes more than the base temperature. The rainfall converted into surface runoff based on the soil type, surface drainage condition, and CNs for the corresponding land cover. The process continues for 62 years (1955-2016) to calculate the long-term mean annual runoff from each land cover. The ratio of the long-term mean annual runoff to long-term mean annual precipitation will provide runoff coefficient for the corresponding land cover. The process will continue to estimate runoff coefficient for all of the land cover present in the township.

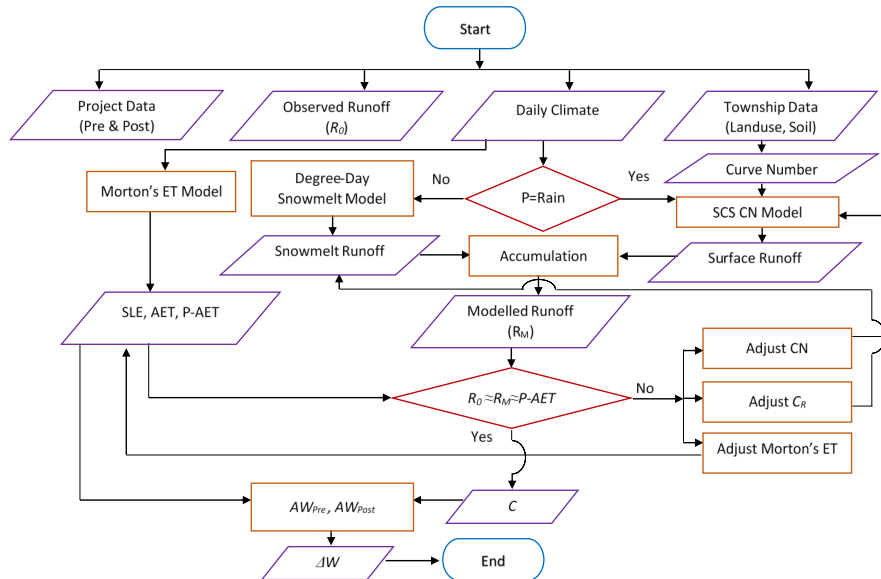


Figure 2: Flowchart of the hydrologic model to estimate delta water (R_0 =Observed Runoff, R_M =Modelled Runoff, SLE =Shallow Lake Evaporation, AET =Actual Evapotranspiration, P =Precipitation, CN =Curve Number, C_R =Snowmelt Runoff Coefficient, AW_{Pre} =Pre-Development Available Water, AW_{Post} =Post-Development Available Water, C =Runoff Coefficient, ΔW =Delta Water).

4.2 Model Calibration

In this study, the goal of model calibration is to maintain the pre-development water balance in a township by matching the long-term net precipitation (precipitation-actual evapotranspiration, or $P-AET$) with the long-term average observed runoff (R_0) and long-term modelled runoff (R_M). At the first step of the calibration, the model crosschecks the mean annual $P-AET$ with the mean observed runoff (R_0). If the different between $P-AET$ and R_0 is not within a certain limit (usually 1% of R_0 or 0.5 mm, whichever is smaller), we adjust the modelled AET by a multiplying factor. The next step is to adjust the snowmelt runoff coefficient (C_R). We estimated the initial value of C_R for each land cover by calculating the ratio of mean

open water season (April-October) runoff to the mean open water season (April-October) precipitation, assuming that runoff from a melting snow in winter months is comparable to the runoff from equivalent precipitation in open water season. However, frozen soils often work as a barrier for infiltration, which may result in more modelled runoff in winter due to a melting snow compared to the runoff generated from equivalent amount of rainfall in open water season. The model runs for the calibration period using the initial value of C_R and then estimates the mean winter runoff percentage (November-March runoff as a fraction of the mean annual runoff). If the mean winter runoff is less than 10% (an arbitrary threshold based on experience and data analysis on small watersheds) then the C_R is adjusted to ensure at least 10% winter runoff proportion for the township. Finally, the model adjusts the curve number for different land covers. In general, higher CNs result in higher runoffs from a land cover for the same location and climatic condition, and vice versa. Runoff CNs are initially estimated from Table 1 for each land cover present in a township are based on a combination of land cover type, hydrologic soil type, and surface drainage condition. There is no CN required for land class 'water' as the available water from the corresponding area will be calculated as net precipitation (i.e., precipitation - shallow lake evaporation). For the land classes 'snow/ice' and 'rock/rubble' CNs are set to 99, and 98, respectively. Therefore, the model will calibrate the CNs for the other eight land classes: exposed land, developed land, shrubland, grassland, agricultural land, coniferous forest, broadleaf forest, and mixed forest. The theoretical minimum and maximum CN values for these land classes are 0, and 100, respectively. However, analysing the TR-55 recommended CN values we set the minimum (30) and maximum (98) CNs limits, as well as lower and upper bounds of CNs for auto-calibration purposes (see the two right most columns in Table 1).

4.3 Model Validation

The model calibration process adjusts ten calibration parameters (Morton's Adjustment Factor, Snowmelt Runoff Coefficient, and Runoff Curve Numbers for eight land classes) by preserving the overall water balance of a township at a time period for which observed runoff data is available. Since the model estimates delta water availability based on 62 years (1955-2016) of climate data, it is also important to validate the water balance of the township for the period 1955-2016 using the calibrated parameters. This is achieved by crosschecking the 1955-2016 net precipitation (precipitation-actual evapotranspiration, or P-AET) with the 1955-2016 modelled runoff (RM) for the township. If validation is not satisfactory, the user can change the runoff data source to achieve a comparatively better match between the 1955-2016 P-AET and 1955-2016 RM. Note, in the calibration and validation stage the model only compares the modelled and observed parameter in a long-term (68 years) annual average basis. Therefore, we only used percent bias to evaluate the model results in calibration and validation.

4.4 Calibrated Runoff Coefficient

Once model calibration and validation is completed, the model calculates the long-term (1955-2016) mean annual runoff from each land cover. The ratio of the long-term mean annual runoff to long-term mean annual precipitation provides the runoff coefficient for the corresponding land cover. The process continues to estimate runoff coefficient for all of the land cover present in the township.

4.5 Estimating Delta Water for a Project

Once the calibrated and validated runoff coefficient for each land class in a township is available, the model can use project scale and township scale data to estimate delta water (ΔW). Required project scale data are project area, fraction of different land classes in pre-development scenario, and fraction of different land classes in post-development scenario. Essential township scale data are the mean annual precipitation and mean annual lake evaporation. The model assumes that the runoff coefficient of natural land cover does not change from pre to post-development scenario; only their fraction changes. However, the runoff coefficient of developed land in a pre-development and post-development scenario could be different. When a natural land is converted into urban/industrial development, a majority fraction of the project area in a post-development scenario becomes developed land. The model has the functionality to estimate the CN for the developed land, and hence the runoff coefficient in the post-development scenario.

5 MODEL APPLICATION

5.1 Selected Case Studies

We applied the model for three selected case studies in Alberta to assess its performance. Figure 3 shows a map of these three case study locations. Table 2 shows information on township location and project information of these case studies. The pre-development land use is based on the ABMI Year 2000 land cover data, and the post-development land use is estimated from the project development maps. To assess the model performance in a consistent manner, the hydrologic model parameter for all of the case studies remain same (e.g., $T_b=0$ °C, $C_M = 2.74$ mm/degree-day C). We calibrated the model against both available runoff layers: University of Lethbridge (UL) runoff layer (1970-2000) and Agriculture and Agri-Food Canada (AAFC) median runoff layer (1950-2006). Then we validated the model for the period 1955-2016. Table 2 also shows the simulated long-term (1955-2016) mean annual delta water (ΔW) for the case studies. We compared the simulated delta water with the approved *Water Act* authorizations based on the interim accepted practice for the use of storm drainage (Alberta Environment and Parks 2011). According to the interim accepted practice, the allowable storm drainage from a catchment area will be equal or less than the difference between the mean annual pre-development and projected post-development volumes of water lost to evapotranspiration. Since prior to the development of these projects downstream users were not relying upon this volume of water, its use will presumably not result in any impact to existing users or licences. For these case studies, project proponents submitted the estimates of projected post-development evapotranspiration. However, estimates of pre-development evapotranspiration are from the actual evapotranspiration contour map for Alberta generated by AEP.

Table 2: Simulated delta water (ΔW) for selected case studies in Alberta

Project Name, Location & Area	Land use ¹		Mean Annual Water Balance ² (mm)				ΔW (mm)	
	Pre	Post	Calibration (UL ³ :1970-2000) (AAFC ³ : 1950-2006)		Validation (1955-2016)		UL	AAFC
			UL	AAFC	UL	AAFC		
Calgary 1 (T025R29M4) A= 0.323 Km ²	Dv=5.88% Ag=94.12%	W=2.9% Gr=3.4% Dv=93.7% (PR=33.9%, Com=40.7 %, Res=25.4%)	P-AET=28.0 R ₀ =27.4 R _M = 27.1	P-AET=61.2 R ₀ =60.4 R _M =60.5	P-AET= 20.5 R _M = 26.9	P-AET=63.5 R _M =60.9	107	139
Calgary 2 (T024R02M5) A= 0.241 Km ²	Ag=100%	W=3% Gr=17% Dv=80% (Ind=27.8%, Res=72.2%)	P-AET=44.9 R ₀ =44.2 R _M = 44.1	P-AET=65.6 R ₀ =64.9 R _M =64.9	P-AET=38.6 R _M = 43.83	P-AET=76.2 R _M =66.89	51	66
Calgary 3 (T026R01M5) A= 1.377 Km ²	W=1.4% Ag=98.6%	W=3.9% Gr=8.6% Dv=87.5% (PR=36.9%, Com= 10.3%, Res=52.8%)	UL P-AET=32.1 R ₀ =31.4 R _M = 31.5	P-AET=22.8 R ₀ =22.2 R _M =22.1	UL P-AET=18.1 R _M = 31.04	P-AET=23.1 R _M =22.2	62	73

¹Dv=Developed Land, Ag=Agricultural Land, Gr=Grassland, W=Water, PR=Paved Road, Com=Commercial Area, Ind=Industrial Development, Res=1/8 Acre House

²R₀=Observed Runoff, R_M=Modelled Runoff, P=Precipitation, AET=Actual Evapotranspiration

³UL=University of Lethbridge Runoff Layer, AAFC= Agriculture and Agri-Food Canada Runoff Layer

The first case study (Calgary 1) is located at the northeast corner of Calgary within the Township T025R29M4. The dominant pre-development land uses of this township are agricultural land (57%), developed land (29%), and grassland (13%); and the hydrologic soil type is B. The pre-development land use of the project area (32.3 hectare, or 0.323 km²) are 94.12% agricultural land and only 5.88% developed land. The projected post-development land use is 93.7% developed land, 3.4% green grass, and 2.9% water. The developed land consists of 33.9% paved road, 40.7% commercial and business developments

and 25.4% residential area. The mean annual precipitation (1955-2016) of the township is 410 mm. The mean annual observed runoff at the township scale is 27.36 mm and 60.42 mm according to UL runoff layer (1970-2000) and AAFC runoff layer (1950-2006), respectively. Model calibration with the UL runoff (27.36 mm) results long-term (1955-2016) mean annual actual evapotranspiration and lake evaporation of 390 mm and 681 mm, respectively. The net precipitation (equivalent to long-term runoff) and modelled runoff are 20.46 mm and 26.9 mm, respectively. If we calibrate the model with AAFC runoff (60.42 mm), the long-term (1955-2016) mean annual actual evapotranspiration and lake evaporation become 347 mm and 606 mm, respectively; while the net precipitation and modelled runoff become 63.5 mm and 60.9 mm, respectively. Calibrating the model with AAFC runoff provides better performance of the model in validation (4% underestimation, compared to 31.5% overestimation calibrating against UL runoff). We compared the results with the approved *Water Act* authorization based on the interim accepted practice. The pre-development mean annual evapotranspiration estimated for the project area is 123,579 m³ and the projected post-development evapotranspiration is 88,700 m³. Therefore, the maximum allowable stormwater diversion is 34,879 m³ (equivalent to 108 mm of water distributed over the project area). This amount of delta water (108 mm) is very close to the long-term mean delta water, as simulated by DWAT, for the project when calibrated against the UL runoff layer (107 mm), and falls within the range of annual modelled delta water (88 mm to 208 mm) when calibrated against AAFC runoff layer.

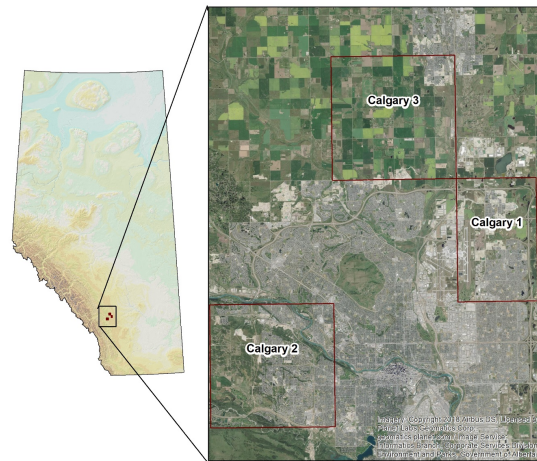


Figure 3: Location of Delta Water Assessment Tool (DWAT) case studies in Calgary, Alberta

The second case study (Calgary 2) is located at the western part of Calgary within the Township T024R02M5. The pre-development land use of the project area (24.1 hectare, or 0.241 km²) is 100% agricultural land. The projected post-development land use is 80% developed land, 17% green grass, and 3% water. The developed land consists of 27.8% industrial development and 72.2% residential area. The delta water due to the projected land use development is estimated as 12,183 m³, which is equivalent to 51 mm (ranges from 21 mm to 113 mm annually within 1955-2016) if the model is calibrated against the UL runoff layer. However, if we calibrate the model against AAFC runoff the simulated delta water become 15,837 m³, which is equivalent to 66 mm (annual range from 31 mm to 140 mm). We compared the results with the approved *Water Act* authorization based on the interim accepted practice (74.5 mm) which falls within the range of modelled delta water (21 mm to 113 mm; average 51 mm) and (31 mm to 140 mm; average 66 mm) when calibrated against UL and AAFC runoff layer, respectively.

The third case study (Calgary 3) is located at the northern part of Calgary within the Township T026R01M5. The pre-development land use of the project area (137.71 hectare, or 1.3771 km²) is 98.6% agricultural land and 1.4% water. The projected post-development land use is 87.5% developed land, 8.6% green grass, and 3.9% water. The developed land consists of 36.9% paved road, 10.3% commercial and business area, and 52.8% residential area. The delta water due to the projected land use development is 84,871 m³, which is equivalent to 62 mm (ranges from 37 mm to 88 mm annually within 1955-2016) if the model is calibrated against the UL runoff layer. However, if we calibrate the model against AAFC runoff the simulated delta water becomes 100,687 m³, which is equivalent to 73 mm (annual range from 45 mm to 103 mm).

We compared the results with the approved *Water Act* authorization based on the interim accepted practice (174 mm), which is quite high compared to the modelled delta water (62 mm and 73 mm). We analysed further to investigate this disagreement between the two methods. The estimated pre-development evapotranspiration for Calgary 3 (564,611 m³) provides an equivalent evaporative loss of 410 mm from the project area, which is comparable to the modelled AET. The post-development evapotranspiration (325,137 m³) provides an equivalent evaporative loss of 236 mm from the project area, which seems low compared to the other case studies (274 mm for Calgary 1 and 336 mm for Calgary 2). In general, higher proportion of developed land in a project area provides a lower post-development to pre-development evapotranspiration ratio. This is because converting natural land into developed land generally decreases actual evapotranspiration. Therefore, increasing proportion of natural land converted into developed land creates greater proportional decrease in actual evapotranspiration from the area. The fractions of developed land for Calgary 1 (93.7%) and Calgary 2 (80%) align with this concept as the projected post-development to pre-development evapotranspiration ratio for Calgary 1 and Calgary 2 are 0.72 and 0.82, respectively. However, the projected post-development to pre-development evapotranspiration ratio for Calgary 3 is only 0.60 even though Calgary 3 has 87.5% developed area. Therefore, it is fair to say that the projected post-development evapotranspiration for Calgary 3 was underestimated, which presumably resulted in the disagreement between the estimated delta water from these two methods.

5.2 Provincial Testing

In addition to the three case studies, we applied the model in fourteen different locations in Alberta to assess its performance for varying climate and land use conditions. For each location, a study area of 5 km² was chosen. We selected the ABMI Year 2000 land cover data as the pre-development land use data source. The proportion of different land cover in the pre-development scenario are selected as the dominant natural land cover within the township (e.g., 100% agricultural land), or a combination of multiple land covers (e.g., 50% agricultural land and 50% grassland). The proportion of different land use in post-development are selected arbitrarily as 80% developed land, 17% grass, and 3% water. For all locations, the proportions of developed land were further subdivided into 35% paved road, 10% commercial and business development, and 55% residential area. To assess the model performance in a consistent manner, the hydrologic model parameters for all of the studies remain same (e.g., $T_b=0$ °C, $C_M = 2.74$ mm/degree-day C). We calibrated the model against both available runoff layers: University of Lethbridge (UL) runoff layer (1970-2000) and Agriculture and Agri-Food Canada (AAFC) median runoff layer (1950-2006). Then we validated the model for the period 1955-2016. Based on the performance of the model in validation stage, we estimated the potential mean annual delta water in these study areas and presented them on the map (Figure 4) as graduated symbols. Larger symbol sizes demonstrate higher potential of delta water based on consistent pre- and post-development scenarios. As shown in Figure 4, the estimated delta water varies widely with natural regions, geographic locations, and climatic conditions. Study locations with higher mean annual precipitation and higher observed runoff result in higher delta water availability (e.g., Fox Creek-158 mm, Priddis-137 mm, Slave Lake-120 mm, etc.). In contrast, study locations with lower mean annual precipitation and lower observed runoff result in lower potential of delta water (e.g., Red Deer-69 mm, Lethbridge-55 mm, etc.). Study locations in boreal forest and foothills areas provide higher estimated delta water (e.g., Cold Lake-119 mm, Fort McMurray -79 mm) compared to the study locations in central parkland and grassland (e.g., Edmonton-61 mm, Medicine Hat-34 mm, etc.)

6 SUMMARY AND CONCLUSIONS

In this study, we have developed a Delta Water Assessment Tool (DWAT) to simulate long-term excess stormwater (delta water) availability in Alberta. The tool includes Degree-Day snowmelt model; Morton's evapotranspiration model; and SCS Runoff Curve Number model. First, the tool uses historical climate, soil, and land use data to daily simulate surface runoff in a pre-development scenario. The simulated daily runoff is then converted into a long-term mean annual runoff and eventually calibrated against historical mean annual runoff at a township scale. Based on the modelled mean annual runoff generated from each land cover, and mean annual precipitation falling on those land covers, the model estimates long-term mean runoff coefficients. Then, based on these modelled runoff coefficients for different types of land cover and their proportions in pre-development and post-development scenarios, the tool estimates the delta water

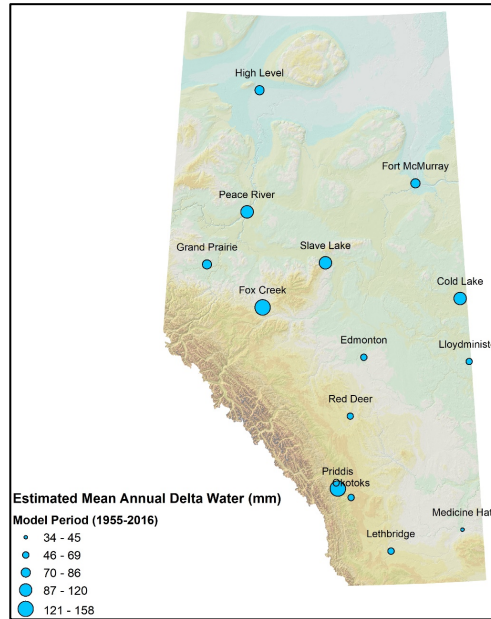


Figure 4: Delta Water Assessment Tool (DWAT) provincial testing locations

availability due to land use development. We applied the tool for three selected case studies in Alberta to assess its performance. The tool can successfully estimate excess stormwater (delta water) due to land use developments and the results are comparable to the existing method of estimating stormwater drainage (Alberta Environment and Parks 2011). We also applied the tool at different locations in Alberta to test its applicability for varying natural regions and climatic conditions. We observed that the tool could reasonably estimate delta water availability at different locations in Alberta. Therefore, the DWAT can provide a consistent and scientifically defensible approach to support decision making under Alberta's regulatory framework for water management.

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