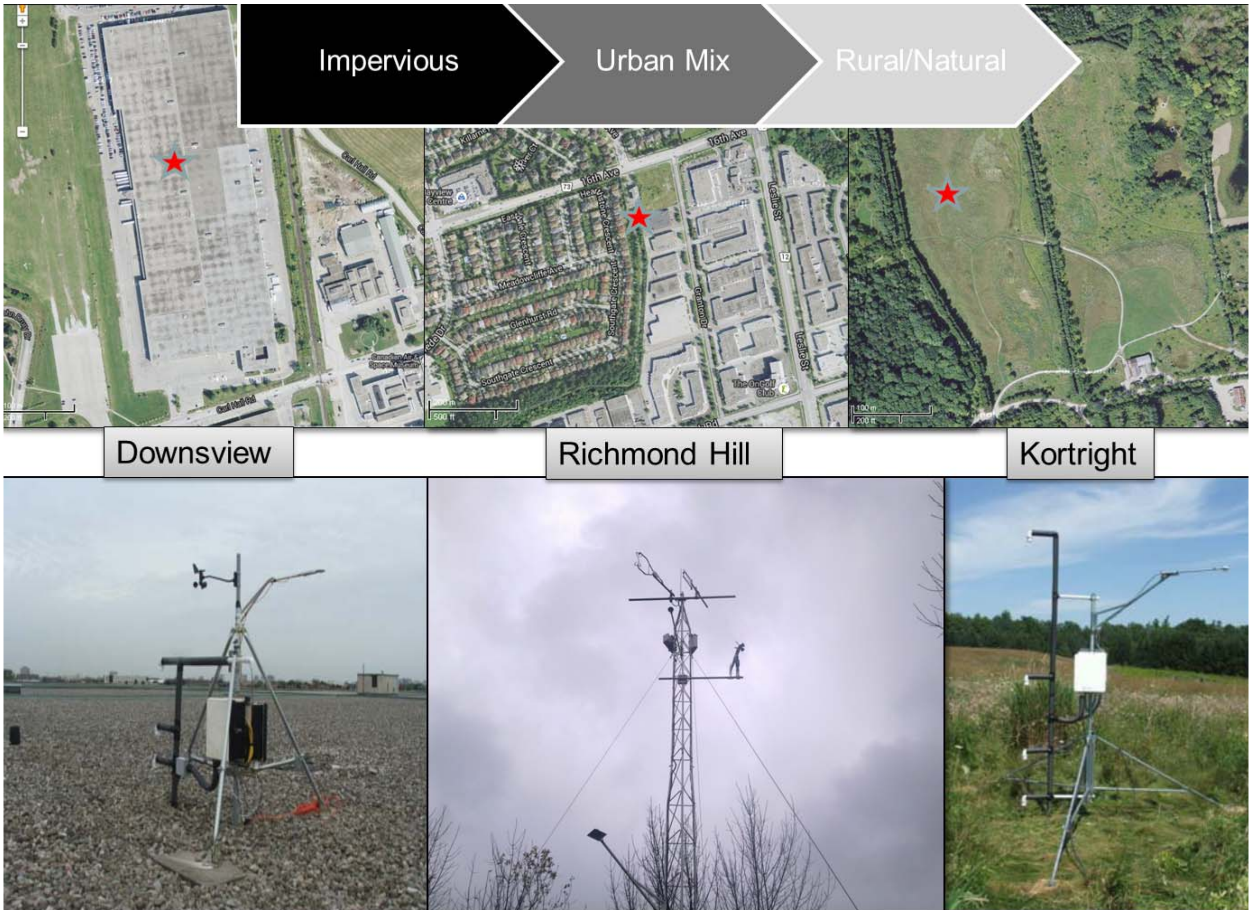
Measurement of Evapotranspiration Across Different Land Cover Types in the Greater Toronto Area



Prepared by: Toronto and Region Conservation and York University **Final Report 2014**

MEASUREMENT OF EVAPOTRANSPIRATION ACROSS DIFFERENT LAND COVER TYPES IN THE GREATER TORONTO AREA

Final Report

Prepared by:

Toronto and Region Conservation

and York University

Under the

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THE SUSTAINABLE TECHNOLOGIES EVALUATION PROGRAM

The Sustainable Technologies Evaluation Program (STEP) is a multi-agency program, led by the Toronto and Region Conservation Authority (TRCA). The program helps to provide the data and analytical tools necessary to support broader implementation of sustainable technologies and practices within a Canadian context. The main program objectives are to:

- monitor and evaluate clean water, air and energy technologies;
- assess barriers and opportunities to implementing sustainable practices;
- develop supporting tools, guidelines and policies, and
- promote broader uptake of sustainable practices through education and advocacy.

Technologies evaluated under STEP are not limited to physical products or devices; they may also include preventative measures, alternative urban site designs, and other innovative practices that help create more sustainable and liveable communities.

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EXECUTIVE SUMMARY

The increasing rate of urbanization has had a profound negative effect on natural ecosystems within urban watersheds. Urbanization leads to increasing imperviousness that enhances runoff at the expense of evaporation, infiltration, and recharge, which are directly related to the health and presence of vegetation. These hydrologic changes result in extreme storm events that are characterized by peaked and short-lived hydrographs, creating large volumes of runoff during rain events. The effective implementation of stormwater management policies and procedures is closely tied to water balance model parameterization, as the under- or overestimation of certain components of the water balance will result in mismanagement of watershed resources. The evapotranspiration (ET) component of the water balance comprises up to two-thirds of precipitation, and is the most difficult to measure. Therefore, modellers often estimate ET based on generalized equations and relationships. Providing measured ET data with which to calibrate and validate water balance models will contribute significantly to improving the accuracy and reliability of these models.

Study Site and Approach

Evaporation measurements were conducted at three sites of varying impervious cover and land cover types within the Greater Toronto Area. These include a flat commercial roof at Downsview Park in Toronto, a mixed residential/industrial land use in Richmond Hill and a naturally vegetated meadow at Kortright in Vaughan. Evapotranspiration at the Downsview and Kortright sites was measured using the Bowen Ratio Energy Balance (BREB) method. The BREB method employs the gradient technique by measuring the water vapour concentration at different heights and relating this to meteorological measurements. The Richmond Hill ET measurement system employed the Eddy Covariance (EC) approach. The EC system measures water vapour transfer from the land to the atmosphere directly by correlating fast-response fluctuations in vertical wind speed with fast-response fluctuations in atmospheric water vapour density.

The hydrologic regime of watersheds is parameterized with the use of water balance models, which estimate or measure its components. Although water balance varies widely on short time scales due to temporary moisture storage, it becomes more consistent on an annual basis as the storage term becomes an increasingly smaller component of the overall balance. The most difficult term to measure is the ET term, which for this reason is rarely measured, creating uncertainty in watershed modelling. Since ET is difficult to measure, it is often inferred based on measured values of other water balance components (Viessman and Lewis, 1995; Dow and DeWalle, 2000). This is often problematic due to spatial heterogeneity and the accumulation of errors from the other terms.

There are a number of direct methods to obtain ET measurements which often require extensive data analysis and technical and frequent maintenance of expensive equipment. Such methods include the EC method, BREB method and the weighing lysimeter method. Indirect methods include modeling ET from remote sensing sources, or basing estimates on energy or temperature measurements used as inputs to watershed models. These include the water balance approach (Thornthwaite and Mather, 1955), temperature-based Hargreaves method (Hargreaves et al., 1985), energy-based method (Priestley &

Taylor, 1972) and combination (energy, temperature and resistance approaches) Penman-Monteith methods (Allen et al., 1989).

For the current analysis, the energy-based Priestley-Taylor model is used, as it is a simplified model that is often employed to estimate $potential\ ET$. $potential\ ET$ differs from $actual\ ET$ in that it represents the upper limit to evaporation under the prevailing energy and wind conditions when water supply is non-limiting. It occurs from an area that is open water or completely covered by transpiring short vegetation that has unlimited access to a soil moisture through the root system. The alpha coefficient within the model formula represents the ratio of $actual\ ET$ to $potential\ ET$, which was shown under experimental conditions on surfaces with non-limiting water supply to be 1.26. However, $actual\ ET$ deviates from $potential\ ET$, especially in situations where water supply is limiting and consequently the alpha coefficient needs to be calibrated to be representative of different surface covers in varying geographical locations, at varying antecedent moisture states. Thus, the appropriate alpha value will change with time of day, season, atmospheric conditions, and surface type. Understanding how surface cover can influence the deviation of (observed) $actual\ ET$ from (theoretical) $potential\ ET$, would provide a valuable insight into model design and decision making.

The ET monitoring datasets generated through this project can be used to calibrate regional watershed hydrologic models, or provide reduction coefficients to calculate $actual\ ET$ over the three land cover types under investigation. The collected data used for this report can be presented as hourly, daily, and monthly datasets which could be incorporated into existing models for the three seasons during 2010-2012 from April to November. Understanding the error associated with ET estimation will help improve our ability to predict the impacts of land use change, which is important in the development of effective watershed strategies as well as the design of stormwater management systems.

Study Results

The seasonal ET differs between the three sites in accordance with differences in impervious cover and vegetation. Thus, Kortright has the highest seasonal total (556 mm) and the highest evaporative efficiency (the ratio of actual ET to precipitation, ET/P), which can be explained by the dense vegetative cover and high substrate water retention properties of the ground surface at Kortright, which favours water storage and subsurface runoff over surface runoff.

The alpha value decreases with increasing urbanization. The above relationships are reflected in the calculated alpha reduction coefficients, which is highest for Kortright (0.95) and therefore closest to the theoretical value of 1.26 for saturated surfaces. Richmond Hill has the intermediate alpha value of 0.43, and Downsview has the lowest alpha value of 0.24.

The value of alpha is not constant, but varies throughout the year. The alpha at Kortright changes the least throughout the year due to the mitigating effects of the vegetation and soil substrate, both of which are able to increase the $actual\ ET$ rates at the same rate as the increase in modeled $potential\ ET$. Alpha values tend to be lower during warmer months due to high energy supply that increases the $potential\ ET$. For the surfaces measured, the Priestley-Taylor method does not produce satisfactory results, because the theoretical requirements of unlimited water supply are not met. In order to utilize results from the Priestley-Taylor method for $potential\ ET$, reduction coefficients need to be implemented.

The actual to $\boldsymbol{potential\ ET}$ ratio decreases with increasing urbanization. The Downsview $actual\ ET$ was 33% of the $potential\ ET$, which was the lowest of the three sites. For Richmond Hill, the percent difference was 62% and for Kortright it was 81%. This coincides with the observed gradient from urban to rural for other parameters. The obtained ratio can be utilized for other models, as long as they produce a $potential\ ET$ value. As such, the ratio can be multiplied by the $potential\ ET$ to produce an estimate of $actual\ ET$.

Differences between $\boldsymbol{potential\ ET}$ and actual $\boldsymbol{ET}$ are significant at the watershed scale. For a simple monthly model, $potential\ ET$ estimates result in an ET value that is 54% larger than the total ET for the Don River watershed; 40% larger than the Rouge River watershed; and 42% larger than the Humber River watershed.

Recommendations

Measured ET is related to $potential\ ET$ through an energy-based model (Priestley & Taylor, 1976) by comparing the experimentally-derived alpha coefficient of 1.26 to the measured alpha coefficient for the three study sites. Average monthly alpha values were less than 1.26 for all three sites during the measurement period from April to November, 2010-2012. This means that if water budget models use alpha of 1.26, ET will be **overestimated**, runoff and infiltration will be **underestimated** and the potential for flood risk and need for stormwater management will be **underestimated**. The recommendations outlined below are provided for consideration during water balance modeling and measurement options.

1. It is recommended that the measured (and/or inferred from measurements) $alpha$ values presented in Table 3 be used when modeling the water balance that do not make use of calibration data, instead of relying on the theoretical $alpha$ of 1.26. The measured monthly ET rates can also be used in the absence of $potential\ ET$ measurements. The values presented here reflect a gradient of land covers typical of urban watersheds.

2. For instances when the Priestley-Taylor model has not been used to calculate $potential\ ET$, the ratio of $actual\ ET$ to $potential\ ET$ can be used, which is an indication of the deviation between the two terms. This ratio can be multiplied (similar to a reduction factor) by $potential\ ET$ in order to obtain $actual\ ET$. This also applies to $potential\ ET$ as calculated from models other than the Priestley-Taylor model.

3. Long-term monitoring of evapotranspiration is recommended for improved estimation of $actual\ ET$, $equilibrium\ ET$, $potential\ ET$ and alpha. This will provide a larger data set upon which more sophisticated relationships between the ET parameters of interest and routine atmospheric parameters can be developed. This will also reveal in more detail the monthly and inter-annual variability of ET, which can be incorporated into models for improved accuracy.

4. ET should be measured on a larger range of land use types to provide a more complete gradient of alpha values. Pan estimates of evaporation should also be measured concurrently in order to assess the relationship between $actual\ ET$ and pan evaporation with the aim to propose pan evaporation coefficients.

5. In order to gain a better understanding of the urban and suburban watershed water balance through energy balance modeling, it is important to improve the spatial resolution of meteorological stations that measure ET. Micrometeorological measurements are needed within each surface group type in order to model the data properly using suggested $alpha$ values, and possibly contribute to the list for other surface types.

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SYMBOL	DESCRIPTION	UNITS
Q^*	Net Radiation	W/m^2
Q_H	Sensible Heat Flux	W/m^2
Q_E	Latent Heat Flux	W/m^2
Q_G	Ground Heat Flux	W/m^2
RO	Runoff	mm
P	Precipitation	mm
ET	Evapotranspiration	mm
G	Groundwater Recharge	mm
ΔS	Change in Storage through Infiltration	mm
PET	Potential Evapotranspiration	W/m^2 (or mm if divided by L_V)
QET	Equilibrium Evapotranspiration	W/m^2 (or mm if divided by L_V)
AET	Actual Evapotranspiration	W/m^2 (or mm if divided by L_V)
L_V	Latent Heat of Vapourization	kJ/g
s	Slope of Saturation Vapour Pressure Curve	Unitless
γ	Psychrometric Constant	~0.033kPa/°C
α	Alpha	Theoretical=1.26
ρ	Air Density	Kg/m^3
C_P	Specific Heat of Air	J/g/K
VPD_z	Vapour Pressure Deficit at Height z	kPa
r_a	Aerodynamic Resistance	s/m