Evaluation of Evapotranspiration for Different Land Uses in the Greater Toronto Area

Kristina K. Delidjakova*, Richard L. Bello **, Glenn MacMillan*

*Toronto and Region Conservation Authority, Vaughan, ON, ** York University, Toronto, ON

INTRODUCTION

It is expected that the population within the GTA will grow by two million people in the next 20 years, which will place strain on the current infrastructure and result in decreased area of open green spaces. During urbanization, natural channels are replaced by artificial drainage solutions that reduce the natural effect of water infiltration and storage within the soil column and increase the runoff component of the water budget (Figure 1). This land cover change drastically the amount of water available for evaporation and transpiration (evapotranspiration, ET), which results in the intensification of the urban heat island effect. Stormwater runoff from urban infrastructure is a major contributor to the degradation of freshwater ecosystems, which creates a need for low impact development (LID) stormwater management strategies aimed at reproducing the pre-development hydrologic regime.

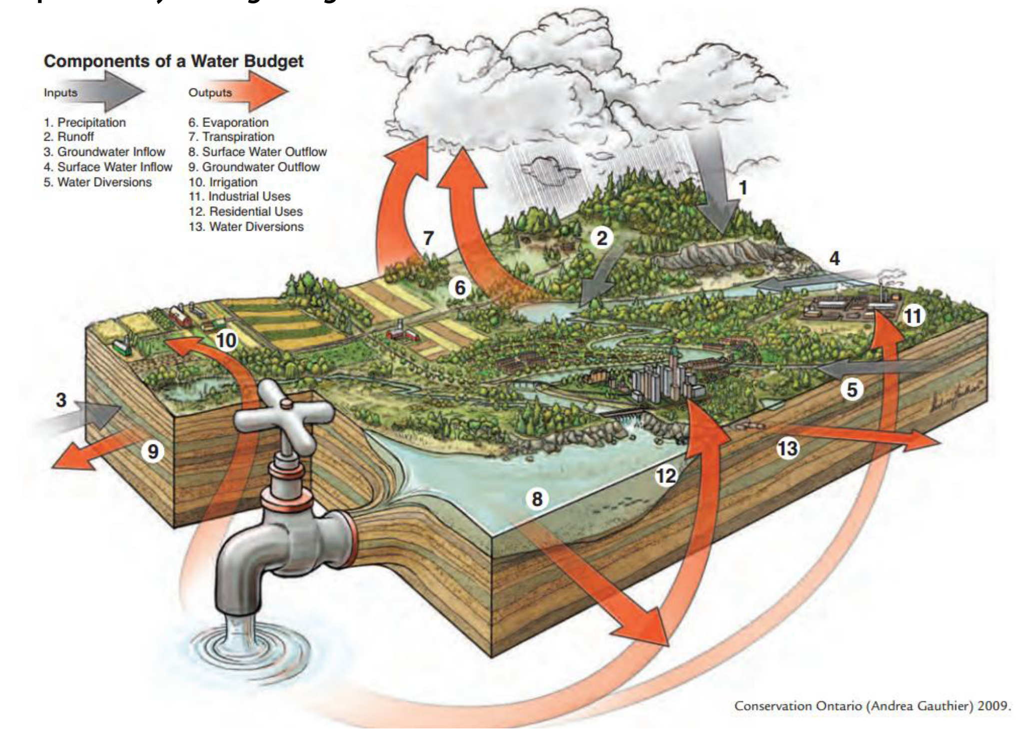

Figure 1: Components of the water budget.

OBJECTIVES

The purpose of this project is to illustrate the importance of the parameterization of the ET component of the water budget by means of the application of the Priestley-Taylor method for potential ET . The difference between potential ET and actual ET can be substantial if one relies on potential ET as an input parameter without a calibration coefficient. Data presented here illustrate the departure between the two estimates and provides alternative alpha reduction coefficient values based on different land cover types to estimate actual ET for simple modeling.

The reduction coefficients (actual alpha values) over different land cover types in an urban setting can eliminate the use of inferred and tabulated data, when measured data are not available. Better accuracy can be achieved where calibrated actual ET values are available in conjunction with measured ET and soil moisture conditions data; otherwise, the information provided in this study can be utilized. Therefore, the results presented in this report should be used in the absence of measured ET or sophisticated watershed water budget models. In addition, the collected hourly data can be used to calibrate existing models for the measured land use types.

It has been shown that the Priestley-Taylor model provides good estimates of ET if the value of the alpha coefficient is known. However, alpha varies over time and space on an annual, seasonal and diurnal basis. Thus, it is important to provide accurate measured alpha values for model implementation in order to obtain improved estimates of ET in an urban watershed setting. The proposed approach is recommended to eliminate the sole use of potential ET for water balance evaluation and emphasizes the importance of land cover differentiation and changing alpha value within urban watersheds.

STUDY SITES AND MEASUREMENT METHODS

Evaporation measurements were conducted at three sites within the Greater Toronto Area. The three locations are spread over two different watersheds –Rouge River (Richmond Hill) and Humber River (Kortright and Downsview) watersheds (Figure 1). Their locations were chosen to represent different land use on a local scale rather than watershed scale. Thus, the chosen study sites represent a variety of locations within the GTA, in addition to diverse land cover characteristics (Figure 2).

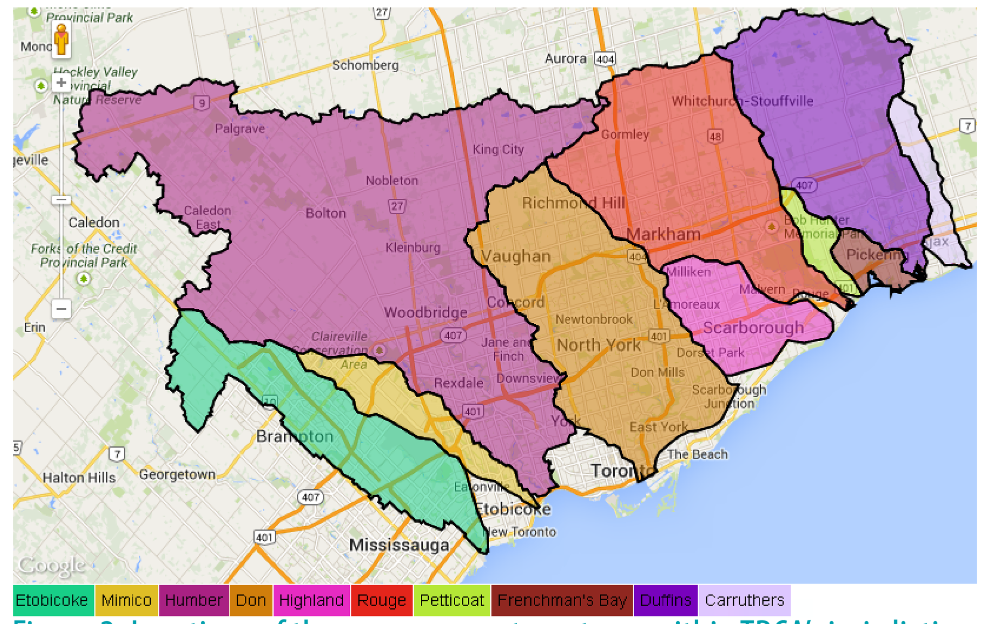

Figure 2: Locations of the measurements systems within TRCA's jurisdiction.

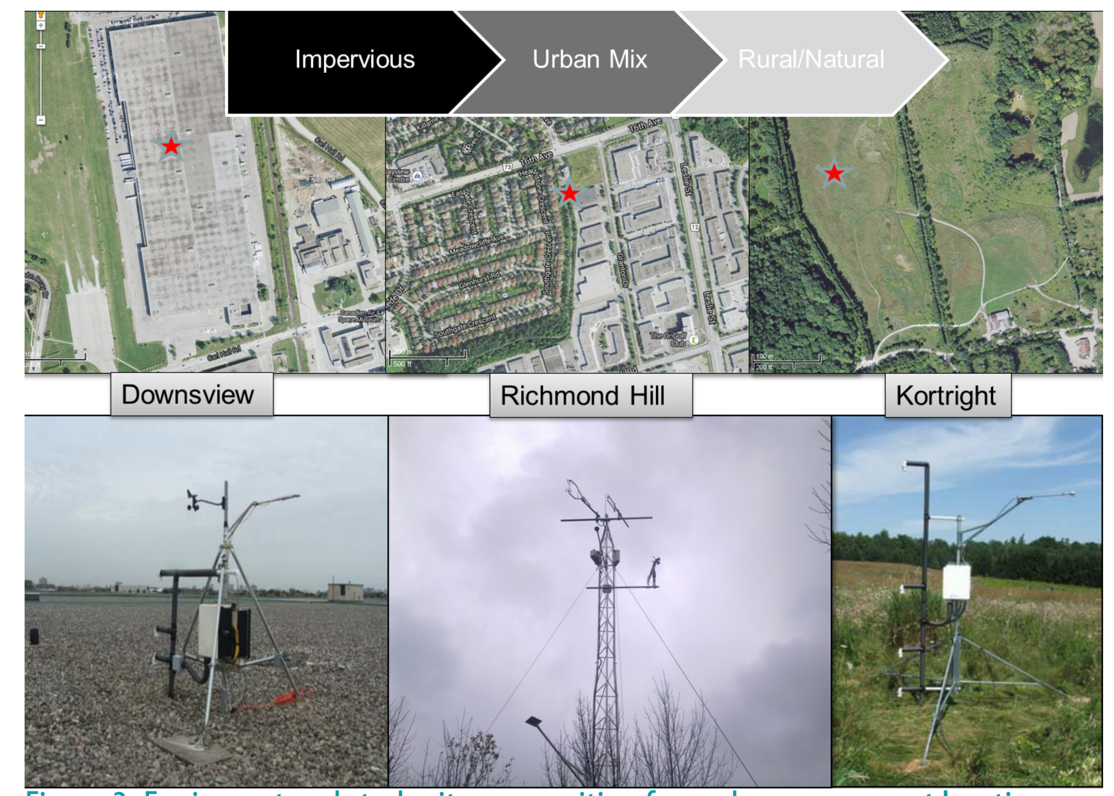

Figure 3: Equipment and study site composition for each measurement location.

The Downsview and Kortright measurement systems consisted of Bowen Ratio Energy Balance (BREB). The BREB method employs the gradient method by measuring the water vapour concentration at different heights and relating this to meteorological measurements. The gas concentrations were obtained with an infrared gas analyzer (LI-840, LI-COR Biosciences, Lincoln, NE). The concentrations are converted to the mass equivalent of evapotranspiration. Temperature profiles were measured at the same heights with shielded copper-constantan thermocouples. A net radiometer measured the incoming and outgoing solar radiation, and ground heat flux is measured with a soil heat flux plate. Sensible heat flux is determined as the residual from the other direct measurements.

The Richmond Hill measurement system employed the eddy covariance (EC) approach. The EC system consists of two fast-response instruments; three-dimensional wind components were measured by an ultrasonic anemometer and fine-wire thermocouple system (Campbell Scientific Inc., CSAT3); and water vapour fluctuations were measured by an ultraviolet kypton hygrometer (Campbell Scientific Inc., KH20), mounted at the same height. The EC technique directly measures fluxes from large fetch area over a long period of time.

What is a flux? A flux is a flow of a substance (i.e. H_2O, CO_2) per unit area per unit time.

THEORETICAL BACKGROUND AND DATA ANALYSIS

The hydrologic regime of watersheds is parameterized with the use of water balance models, which estimate or measure its components. The water balance equation is expressed as:

$$RO = P - ET - G - \Delta S$$

Although this water balance varies widely on short time scales, it balances out on an annual basis. The most difficult term to measure is the ET term, which for this reason is rarely measured, creating uncertainty in watershed models.

An inferred approach to estimate ET is to measure the rest of the water balance components (Viessman and Lewis, 1995; Dow and DeWalle, 2000), although this tends to be problematic due to difficulty of spatial representation 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 an Eddy Covariance (EC) method, Bowen Ratio Energy Balance (BREB) method and the weighing lysimeter method. Indirect methods include modeling ET from remote sensing sources, or based on energy or temperature driven parameterizations for watershed models. These include the water balance approach, 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 implemented to calculate potential ET, (PET). PET is not the same as actual ET, but rather represents the upper limit to evaporation under the prevailing energy and wind conditions if water supply is non-limiting.

$$PET = \alpha \frac{s}{s+\gamma}(Q^* - Q_G) \qquad QET = \frac{s}{s+\gamma}(Q^* - Q_G) \qquad PET = \alpha QET$$

With available measurements, the first step is to calculate equilibrium ET (QET). The difference between QET and PET becomes the presence of the alpha value, which is estimated to be 1.26 under non-limiting moisture conditions. This means that in order to obtain PET, QET needs to be adjusted by a factor of 1.26. However, if we want to obtain actual ET, the QET needs to be adjusted by a factor less than 1.26, since actual ET is always less than PET. In this project, alternate alpha values are presented which, when multiplied by QET, result directly in actual ET (Table 1).

PET (W/m^2) estimated in this way has gained wide acceptance. 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 coefficient αlpha=1.26 is the best estimate derived over experimental surfaces of this type. However, actual ET deviates from PET, especially in situations where water supply is limiting and consequently the αlpha coefficient needs to be calibrated to be representative of different surface covers in varying geographical locations. Thus, the appropriate αlpha value will change with time of day, season, atmospheric conditions and surface type.

RESULTS AND DISCUSSION

The seasonal ET differs between the three sites in accordance with the suggested surface type gradient, whereby Kortright has the highest seasonal total (555.70 mm, Table 1). The evaporative efficiency (ET/P) therefore tends to be highest for Kortright, which can be explained by the high substrate water retention properties of the ground surface at Kortright, which favours water storage and subsurface runoff over surface runoff.

Table 1: Summary avereage monthly parameters.

Downsview	T (°C)	ET (mm)	P (mm)	ET/P	ET (mm/d)	Bowen Ratio	Alpha
April	8.98	26.2	57.57	0.53	0.87	3.37	0.28
May	16.89	37.83	76.97	0.57	1.22	3.86	0.29
June	20.83	30.65	118.33	0.29	1.02	6.39	0.14
July	25.41	18.82	86.79	0.32	0.61	10.78	0.07
August	22.83	26.16	83.67	0.34	0.84	5.68	0.15
September	17.34	25.57	117.04	0.22	0.85	3.04	0.24
October	10.59	24.04	95.55	0.25	0.78	1.46	0.35
November	4.91	20.59	56.19	0.64	0.69	0.8	0.42
Season	**15.97**	**209.86**	**692.1**	**0.3**	**0.86**	**3.79**	**0.24**

R. Hill	T (°C)	ET (mm)	P (mm)	ET/P	ET (mm/d)	Bowen Ratio	Alpha
April	8.89	28.4	54.7	0.63	0.95	2.26	0.39
May	17.48	33.36	74.47	0.63	1.08	1.31	0.35
June	22.18	56.85	141.27	0.48	1.9	0.67	0.46
July	25.83	54.82	88.57	0.76	1.77	0.74	0.41
August	24.59	53.39	85.03	0.63	1.72	0.5	0.5
September	19.11	36.31	118.13	0.34	1.21	0.71	0.5
October	12.13	22.49	94.1	0.25	0.73	0.87	0.52
November	5.99	13.94	60.4	0.39	0.46	1.01	0.48
Season	**17.38**	**280.38**	**719.8**	**0.39**	**1.15**	**0.96**	**0.43**

Kortright	T (°C)	ET (mm)	P (mm)	ET/P	ET (mm/d)	Bowen Ratio	Alpha
April	7.58	36.78	54.8	0.77	1.23	1.64	0.69
May	14.99	76.56	72.27	1.34	2.47	0.74	0.93
June	18.69	97.7	140.87	0.8	3.26	0.65	1.03
July	22.45	118.24	88.8	1.75	3.81	0.57	0.96
August	20.05	98.9	87.6	1.11	3.19	0.52	1
September	15.18	63.4	105.73	0.62	2.11	0.6	1.06
October	8.78	40.86	97.6	0.45	1.32	0.73	1.11
November	3.33	23.26	50.67	1.89	0.78	1	1.08
Season	**13.88**	**555.7**	**698.33**	**0.79**	**2.27**	**0.41**	**0.95**

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 (Figure 4). 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 PET . Alpha values tend to be lower during warmer months due to high energy supply that increases the PET. For the surfaces measured, the Priestley-Taylor method does not produce satisfactory results, due to the fact that the theoretical requirements of unlimited water supply are not met. In order to utilize results from the Priestley-Taylor method for PET, reduction coefficients need to be implemented.

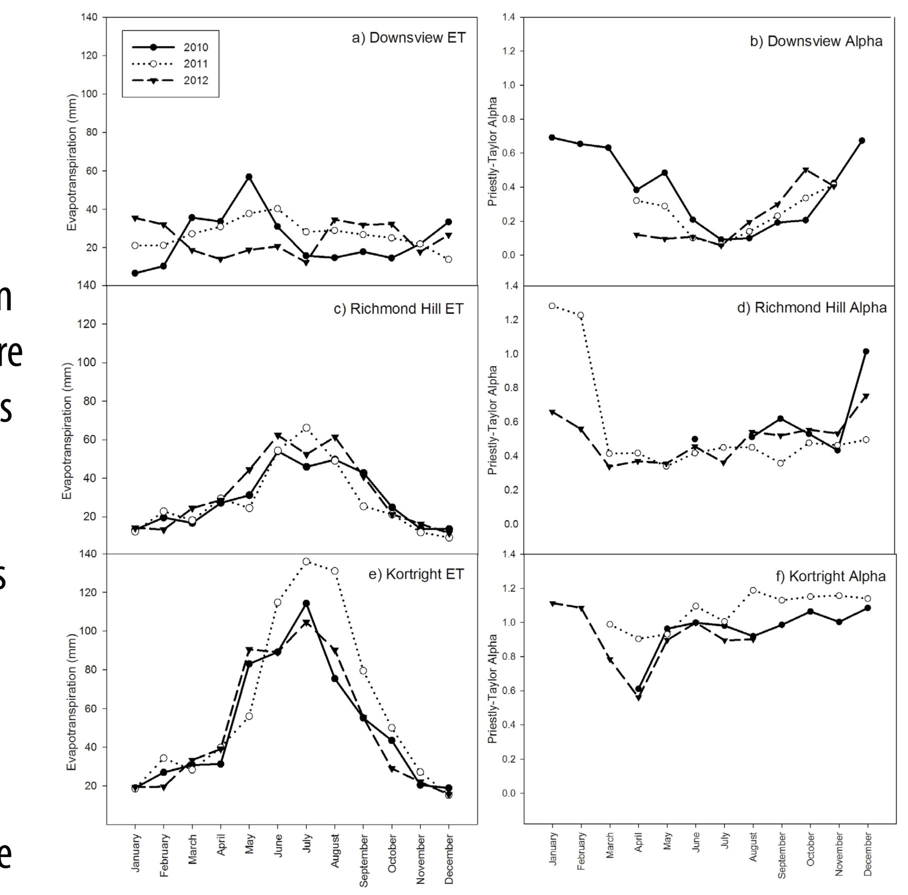

Figure 4: ET and alpha variability on a monthly and annual basis.

The use of potential ET in watershed models significantly overestimates ET (Figure 5). For a simple model, the series with alpha of 1.26 is clearly overestimating the ET, as it 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.

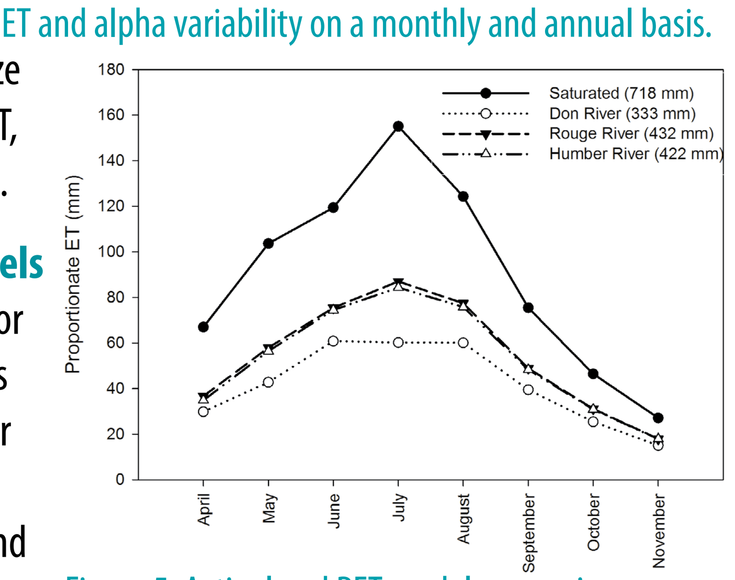

Figure 5: Actiual and PET model comparison.

SUMMARY AND RECOMMENDATIONS

Measured ET is related to PET 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.

• It is recommended to use the measured (and/or inferred from measurements) alpha values 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 PET measurements. The values presented here reflect a gradient of land covers typical of urban watersheds.

• The long-term monitoring of evapotranspiration is recommended for improved estimation of actual ET, equilibrium ET, PET and alpha. This is to provide an increased set of data to develop more sophisticated relationships between the ET parameters of interest and routine atmospheric parameters.

REFERENCES

Dow CL, DeWalle DR (2000) Trends in evaporation and Bowen raion on urbanizaing watersheds in eastern United States. Water Resources Research, 36, 1835-1843. **Priestley CHB, Taylor RJ (1972)** On the assessment of the surface heat flux and evaporation using large scale parameters. Monthly Weather Review, 100, 81-92. **Viessman W, Lewis G (1995)** Introduction to Hydrology. Harper Collins College Publishers, New York.

ACKNOWLEDGEMENTS

Funding support from the following organizations is gratefully acknowledged: York University Faculty of Arts and Liberal Studies, Mitacs Accelerate Program, Region of Peel. Derek Smith was responsible for the Eddy Covariance tower installation and ongoing maintenance. System design and field monitoring support was in part provided by Derek Smith, Daphne So and Joshua Arnett and Shishir Handa.

CONTACT INFORMATION

Glenn MacMillan, C.E.T.
Senior Manager, Water & Energy, TRCA
9520 Pine Valley Drive, Vaughan, Ontario, L4L 1A6
Tel: 289-268-3901, E-mail: GMacMillan@trca.on.ca

Kristina Delidjakova, M.Sc.
Technical Analyst, STEP, TRCA
9520 Pine Valley Drive, Vaughan, OntariO, L4L 1A6
Tel: 289-268-3906, E-mail: KDelidjakova@trca.on.ca

www.sustainabletechnologies.ca