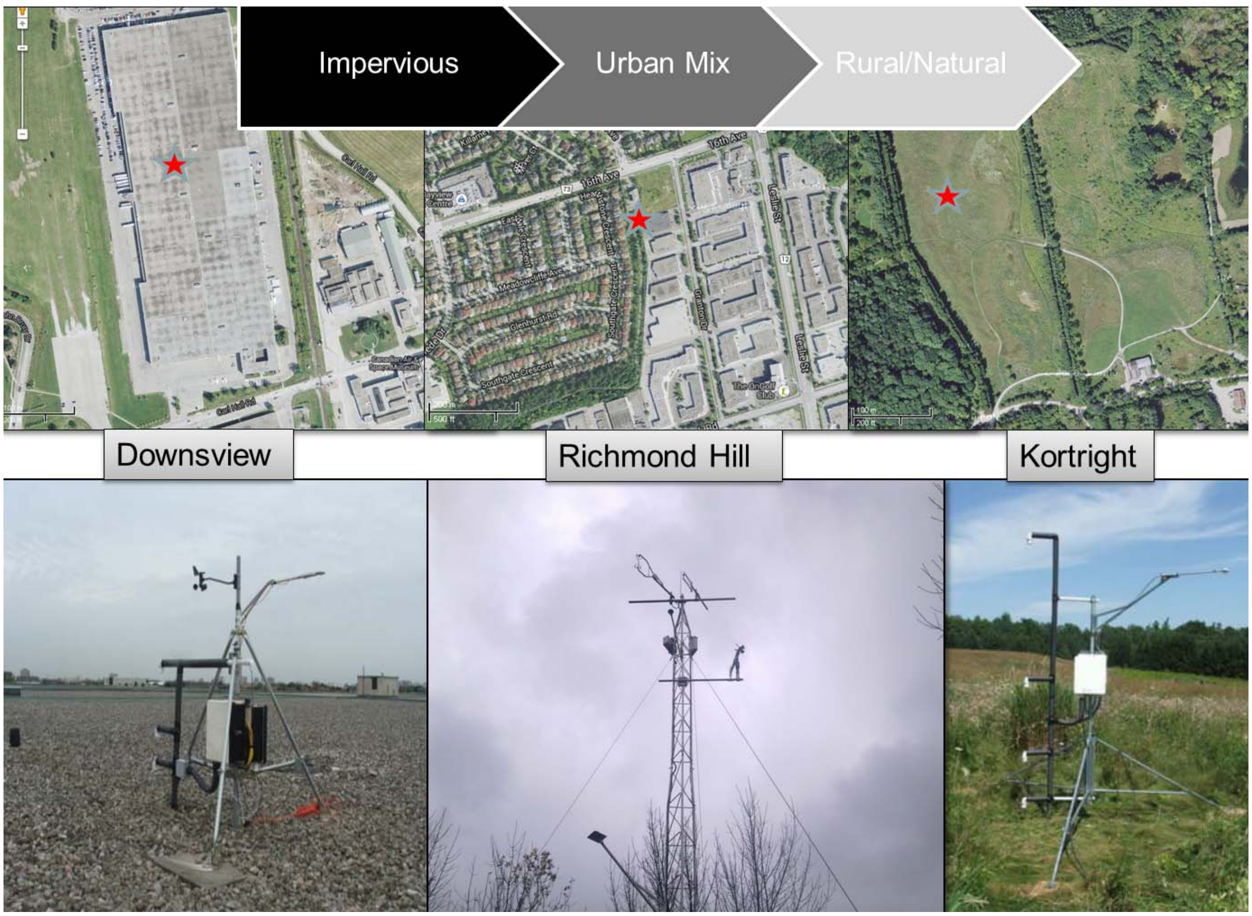
Measurement of Evapotranspiration Across Different Land Cover Types in the Greater Toronto Area



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

Sustainable Technologies Evaluation Program

December 2014

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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 $\boldsymbol{ET}$ 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.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

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

1.0 INTRODUCTION

1.1 Increasing Urbanization in the Watershed

It is projected that the population of the Greater Toronto Area (GTA) will grow by two million people in the next 20 years (TRCA, 2013). To service the growing population, infrastructure will need to be upgraded and expanded, putting strain on existing green and open spaces. In the course of urban development, natural landscapes are re-graded and engineered to convey rainwater rapidly off the surface into underground sewers resulting in flashy flows and runoff volumes up to five times greater than under natural conditions. The increase in runoff rates and volumes accelerates channel erosion, degrades aquatic habitat, impairs stream water quality and is a primary cause of urban flooding. Since the amount of water available for evaporation and transpiration (termed: evapotranspiration, ET) and infiltration decreases in proportion to the increase in runoff, attempts to restore natural functions to the landscape must carefully consider the ET component of the urban water balance. Low Impact Development (LID) initiatives aim to mitigate the effect of urban development on the water budget and water bodies. Understanding the water budget at the urban design scale will aid in the continuation and improvement of these technologies.

1.2 Intensification of the Water Cycle

As a result of observed increases in air temperatures, it is generally assumed that precipitation will increase (Huntington, 2006; IPCC, 2011). Since ET and runoff (RO) are a function of precipitation, their contribution to the water cycle will also increase. ET is a dominant factor in the hydrological cycle (Yin, 1988) and requires careful attention by water resources managers. Warming air temperatures will further increase ET rates, raising the potential for drought in upland areas. This is already experienced in urban centres through the urban heat island effect (UHI), where the dry and warm core heats the local environment due to lack of available water for evaporation, creating a positive feedback that continually exacerbates the UHI. The RO component that results from precipitation events is of high importance to water managers as rising runoff volumes increase the risk of both flooding and drought. Urban areas are particularly susceptible to flooding due to the high concentration of impervious surfaces that channel precipitated runoff into the city's underground infrastructure, degrading the natural riparian corridor and deteriorating water quality and physical habitat. Thus, during rainfall events of high intensity, duration and/or frequency, the runoff component of the water balance will be overwhelmed due to decreased groundwater recharge (G), creating flood-prone areas in urban centres. Although ET is not significant during short-lived storms, it provides an important water output between storms. The lag time between a precipitation event and stream discharge decreases with increasing urbanization, producing unprecedented peaks in measured hydrographs (Graf, 1977). In order to mitigate these impacts, stormwater should be infiltrated and treated at or close to its source.

Two recent examples of urban flooding in Toronto due to overwhelmed urban drainage systems are the 2005 and 2013 summer storms. In 2005, up to 175 mm of rainfall fell in a single 2-3 hour precipitation period, exceeding the frequency of 1 in 100 year return period rain event. Finch Avenue washed out in the vicinity of Black Creek, as its channel capacity was exceeded by the intensity of the storm (up to 6 mm/minute). Other urban areas also experienced flooding, resulting in over $500 million in damage claims. More recently, a summer storm in July, 2013 resulted in riverine and urban flooding, endangering city infrastructure by delivering 123 mm of rain in the duration of this storm event. The increasing intensification of the water cycle (i.e., flood risk) will continue to have a measureable impact on city infrastructure and maintenance costs.

In order to better manage the GTA's watershed hydrology, it is critical that estimates of water balance components be derived from measured data to the extent possible. ET is generally difficult to measure and model due to its high spatial variability and dependence on surface type; however, it has been estimated that up to 66% of the available water is consumed by the ET component, making it the dominant parameter to address over the long-term (Gerber and Howard, 1997).

2.0 THEORETICAL BACKGROUND AND PROBLEM IDENTIFICATION

Water processes and water balance studies are generally investigated at the watershed scale, which provides relatively clear input and output sources with respect to parameterization. A watershed is a naturally occurring ecological unit that collects rainwater and snowfall that accumulate within it and into a valley channel, which subsequently redirects the water into other outputs (Black, 1991). 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:

$$RO = P - ET - G - \Delta S \tag{1}$$

where RO is the runoff component into the ground system and as subsurface flow (mm), P is precipitation (mm), G is water recharging groundwater reserves (mm), ΔS is the change in water storage in the soil through infiltration and percolation (mm). Although this water balance varies widely on short time scales, it balances out on an annual basis, but this balance is difficult to achieve with urban development. The most difficult term to measure is the ET term, which for this reason is rarely measured, creating large 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 (Thornthwaite & 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). The type of model chosen for watershed modeling will ultimately impact the resultant hydrological budget. 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). $Potential\ ET$ 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. Below is an overview of the theoretical basis of watershed modeling, focusing on the quantification of the ET term, which requires knowledge of the surface energy balance.

The rate and amount of water transferred into the atmosphere is governed by the net available energy supplied by the atmosphere. The energy supplied to an ecosystem can be expressed through the energy balance equation in Watts per square metre (W/m²) is given as:

$$Q^* = Q_H + Q_E + Q_G \tag{2}$$

where Q^* is the net radiation (W/m^2), $\mathrm{Q_H}$ is the sensible heat flux that heats the air (W/m^2), $\mathrm{Q_E}$ is the latent heat flux that is used to evaporate water (W/m^2), and $\mathrm{Q_G}$ is the ground heat flux (W/m^2). The mass equivalent to $\mathrm{Q_E}$ is evapotranspiration (ET), which is the combined effect of standing water evaporation and plant respiration, whereby both processes convert liquid water to water vapour (H_2O). The two are related by $Q_E = L_V ET$ where L_V is the latent heat of vapourization and is dependent on temperature. To estimate ET, models are first used to calculate $potential\ ET$, using:

$$PET = \frac{S}{S+\gamma}(Q^* - Q_G) + \frac{\rho C_P}{r_a}\frac{VPD_z}{S+\gamma} \quad (3)$$

where S is the slope of the saturation vapour pressure versus temperature curve at mean temperature, γ is the psychrometric constant (0.066 kPa/c), r_a is the aerodynamic resistance (inversely related to windspeed) and VPD_z is the vapour pressure deficit of the air at measurement height z. This formula for the measurement of $potential\ ET$ requires radiation and soil heat flux measurements, as well as measurements of the deficit in atmospheric humidity, wind speed, surface roughness and atmospheric stability. To avoid complex measurements of parameters from the second term of Equation 3, an approximate and more simplistic formula for estimating $potential\ ET$ was proposed by Priestley and Taylor (1972) which negates the need to measure characteristics of the atmosphere and depends solely on energy supply (energy-driven model), given by:

$$PET = \alpha \frac{S}{S+\gamma}(Q^* - Q_G) \quad (4)$$

where α ($alpha$) is the Priestley-Taylor coefficient averaging 1.26, appropriate for open water bodies and other instances where moisture supply is non-limiting. This model can be expressed more simply by defining the energy supply terms in (4) as $equilibrium\ ET$ and representing them with the term QET , thus :

$$QET = \frac{S}{S+\gamma}(Q^* - Q_G) \quad (5)$$

therefore

$$PET = \alpha QET \quad (6)$$

$\mathrm{Potential\ ET}$ (W/m^2) estimated in this way has gained wide acceptance and represents the amount of water that would evaporate or transpire if it were freely available; thus, it is the maximum possible evaporation for given atmospheric conditions. It was derived 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 (Priestley & Taylor, 1972). The coefficient $alpha = 1.26$ is the best estimate derived over experimental surfaces of this type. 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. Thus, the appropriate alpha value will change with time of day, season, atmospheric conditions and surface type (Eaton *et al.*, 2001; Fisher *et al.,* 2005). Due to its variability, it is advised to directly measure ET or employ sophisticated distributed water budget models. In the absence of such options, the calibration $alpha$ values or the measured ET rates presented in this report can be utilized to estimate rates of $actual\ ET$.

2.1 Water Balance Models

It is important to note that models are representations of reality and will never achieve true results; thus, it is a question of which model is more suitable for the specific project. Different approaches for hydrologic models can be broken down as theoretical (empirically/statistically, conceptually or physically based), watershed delineation (fully distributed, semi-distributed or lumped), and temporal (continuous or single event), (David, 2014). Under the theoretical hydrologic model group, the physically-based Priestley-Taylor method is considered here. Other theoretical models estimate $potential\ ET$ using measured parameters, calculated by inferred parameters, or taken as a function of mean monthly pan evaporation measurements from nearby stations. For instance, the Penman-Monteith equation is used to calculate a reference value for crop ET as a standard for the American Society of Civil Engineers (Jensen *et al.,* 1990). However, this equation requires large amount of input data that is difficult to obtain and is therefore inferred (not calculated, but estimated from other variables). This adds complexity and uncertainty and requires elaborate instrumentation and data analysis. In addition, the CLASS model (Verseghy, 1991) is based on aerodynamic functions to estimate the latent heat flux (Q_E) and then implicitly calculates ET by implementing resistance coefficients in relation to atmospheric demand (the demand for moisture supply when the atmosphere is dry). The CLASS model is considered a research-oriented model with large amount of data requirements and complex parameterizations, and would not be feasible to use for small-scale water balance models.

Once $potential\ ET$ values have been obtained, they have to be adjusted to produce $actual\ ET$ values, and this can be done through the use of a reduction factor that the $potential\ ET$ is multiplied by to obtain a smaller, $actual\ ET$. This reduction factor is obtained from data such as soil moisture, soil temperature and greenness index (CLASS - Verseghy, 1991; HYDROLOG - Porter & McMahon, 1971, Arp and Yin, 1992; HSPF model – US Geological Survey; WATFLOOD model - Neff, 2006). Each of these reduction factors is often obtained from inferred values, which is likely to create errors that propagate into the $actual\ ET$ term. The HSPF model, for example, estimates $actual\ ET$ rates as a function of moisture storage and the $potential\ ET$; however, this becomes problematic for urbanized surfaces if the parameterization for $potential\ ET$ is intended for vegetated surfaces. Although this model provides an option for urban delineation, it aggregates any urban features into this group, despite the highly heterogeneous nature of urban terrain. In some cases, the difference between daytime and nighttime soil moisture loss is equated to the total ET rate (Trout and Ross, 2006); such approximations are problematic as they do not account for interception and impervious evaporation rates.

Some models simply rely on mean monthly values of pan evaporation from published literature as input data. Then a reduction coefficient of usually 0.7 for Class A evaporation pans is applied which is inadequate for varying land cover types. In addition, the availability of evaporation pan data is often not spatially representative of the land cover type that needs to be modeled. The original WATFLOOD model used this parameterization until roughly 1996 when the reduction coefficients based on land cover type were implemented (Neff, 1996). The transpiration of plants is constrained when the soil moisture is below field capacity (the amount of water that the soil can retain after the initial surge of water has drained). As a result, the soil moisture index relates actual measured soil moisture to a constant minimum of the wilting point and a constant maximum of field capacity to create a soil moisture index that would be multiplied by the $potential\ ET$. However, a relationship between soil moisture and ET begins to develop when ET rates surpass 4 mm/day, creating uncertainty when ET rates fall below this threshold (Neff, 1996). The percent soil moisture as a reduction coefficient is a calculated, it is not a measured parameter which introduces more room for error. For the current dataset, soil moisture from Kortright and Richmond Hill was not a good predictor of ET, implying that a model that relies on soil moisture could produce unreliable data. Thus, the coefficient factors used to reduce $potential\ ET$ to $actual\ ET$ need to be measured parameters in order to reduce the propagation of error due to large amount of inferred parameters.

Often, the ET term is neglected for short term modeling such as hourly or daily time scales due to its difficult measurement and generally small values on such short time scales (Zemadim *et al*., 2011). This results in the use of $\mathrm{potential\ ET}$ and overestimation of ET, and consequently an underestimation of the volume of infiltrated water. Since calibration data from measured ET is often unavailable at the sub-watershed scale and only modeled $\mathrm{potential\ ET}$ estimates are available, it is important to recognize the bias generated in RO and infiltration estimates and possible repercussions for management decisions. The issue can be problematic when $\mathrm{potential\ ET}$ based on $alpha = 1.26$ is used in place of the ET component of the water balance in a watershed since it would, by definition, provide an upper limit to water loss to the atmosphere (Barron *et al.,* 2013). Using approximate models like (6) is necessary in the absence of the instrumentation required for the measurement of ET; however, problems can still arise if appropriate coefficients (the alpha value in the case of the Priestley-Taylor model) for a particular watershed are unknown.

The actual alpha values presented in this report can be used when no calibration data is available to backtrack and verify the model and adjust the reduction coefficients of the preferred model to fit the dataset. They can also be used in the absence of sophisticated models and measured ET data. Significant differences in ET regimes for different land use classes are anticipated due to their high heterogeneity. This means that there is a need to improve the monitoring network to create an enhanced dataset of reduction coefficients ($alpha$ values in particular to the Priestley-Taylor model). Being able to provide a variety of alpha coefficients for different urban land cover types during different seasons will result in a simplified method without the dependence on a large number of calculated and inferred variables about surface properties. By providing $alpha$ coefficients to plug into the $potential\ ET$ formula (Equations 4,6) instead of 1.26 for surfaces typically encountered in urban watersheds, the calculated value of $actual\ ET$ will be more applicable for simplified watershed models. The results obtained from this dataset can be configured as to provide a ratio of $actual\ ET$ to $potential\ ET$; this ratio can be multiplied by $potential\ ET$ that has been obtained by any given model, to produce a value of $actual\ ET$. Additionally, mean daily ET rates (mm/day) for each month of the field season will provide validation data for existing watershed models. The availability of hourly and/or daily and monthly time steps for the observed land cover types can be used as calibration data to feed into more sophisticated models. Due to increasing impervious cover, the ET rate from the urban surfaces presented here will provide valuable information on the decreased amount of water available for the ET term of the water balance due to increasing urbanization.

3.0 STUDY OBJECTIVES

The purpose of this report 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 $\mathrm{potential\ ET}$. The difference between $\mathrm{potential\ ET}$ and $\mathrm{actual\ ET}$ can be substantial if one relies on $\mathrm{potential\ ET}$ 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 $\mathrm{actual\ ET}$ values are available in conjunction with measured ET and soil moisture conditions data; otherwise, the information provided in this report can be utilized. 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 $\mathrm{potential\ ET}$ for water balance evaluation and emphasizes the importance of land cover differentiation and changing alpha value within urban watersheds. The results presented in this report could 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 is beyond the scope of this report to include results from models other than the Priestley-Taylor energy-based model. To make use of these results for other $potential\ ET$ models, the $actual\ ET$ to $potential\ ET$ ratio can be used as a multiplier.

4.0 STUDY SITES AND METHODS

Evaporation measurements were conducted at three sites within the Greater Toronto Area and within the TRCA's jurisdiction. The three locations are spread over two different watersheds –Rouge River (Richmond Hill) and Humber River (Kortright and Downsview) watersheds– although the Downsview location is located at the boundary between the Humber and Don River 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, as explained in detail below.

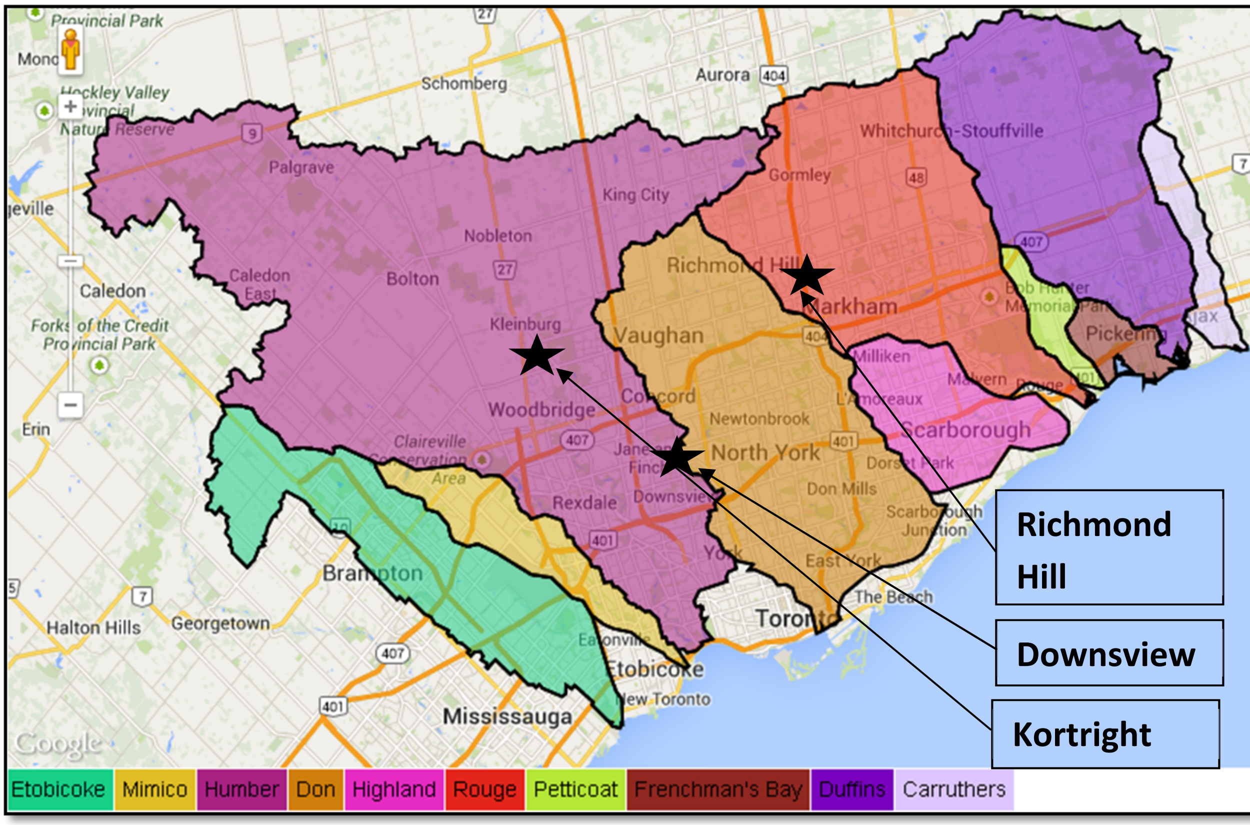

Figure 1: Map identifying the locations of the Downsview, Richmond Hill and Kortright study locations. (Source: TRCA, Google)

4.1 Downsview

This site is located at Downsview Park (43° 44.58' 00" N, 79° 28.45' 00" W), situated on top of a former aircraft hangar building. The roof area is 200 m x 700 m, which behaves as the footprint of the atmospheric measurements registered by the Bowen Ratio Energy Balance (BREB) system (Figure 2). The roof surface is covered with pebble stones that are approximately 5 cm deep, allowing for water percolation to the underlying membrane. Thus, this rooftop is not of typical composition as it allows water to be retained by the 5 cm layer of pebble stones. Since the pebbles have low capillary force due to their large size, as water reaches the roof surface, most of it is percolated down to the membrane of the roof and retained there for some period of time before being channeled into the building's drainage system. However, the increased surface area that the pebbles allow for results in higher rates of evaporation compared to a typical rooftop or a completely impervious surface. For an impervious and flat surface, any water that interacts with the surface will be limited to wetting the total flat rooftop surface before evaporating. However, the presence of pebble stones on the roof at Downsview provide increased surface area due to the presence of porosity and texture, providing a larger surface area available to be wetted by water before it runs off, and subsequently used for evaporation. Typical rooftops are comprised of a minimal layer of gravel, which is expected to retain less water. The drainage of the current rooftop was not measured due to logistical constraints.

The BREB method employs the gradient method by measuring the water vapour concentration at three different heights (0.25 m, 0.5 m, 1.0 m) 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 evaporation (no transpiration included due to lack of vegetation). Temperature profiles were measured at the same heights with shielded copper-constantan thermocouples (Omega). A net radiometer (CNR2, Kipp & Zonen, Delft, Netherlands) measured the incoming and outgoing solar radiation to produce a value for Q^*; Q_G is measured with a soil heat flux plate (HFT3-L, Campbell Scientific), attached to the roof membrane and covered with roof pebbles. Q_H is determined as the residual from the other direct measurements. Data was logged with a CR3000 data logger (Campbell Scientific, Logan, Utah). During initial measurements, measured evaporation based on Q_E was correlated with a weighting lysimeter data (±10%). Due to malfunction of the LI-840 gas analyzer during the second half of the measurement period, the lysimeter evaporation data was employed as a substitute for all measurements to maintain consistency. The lysimeter is a weighting device that mimics the ground surface of the adjacent land cover (30x30 cm in size, ±0.01 mm in resolution). A drainage expression was derived to calculate the rain water that would be removed from the lysimeter as a form of runoff. Precipitation was measured with a Davis 7852 tipping bucket rain gauge.

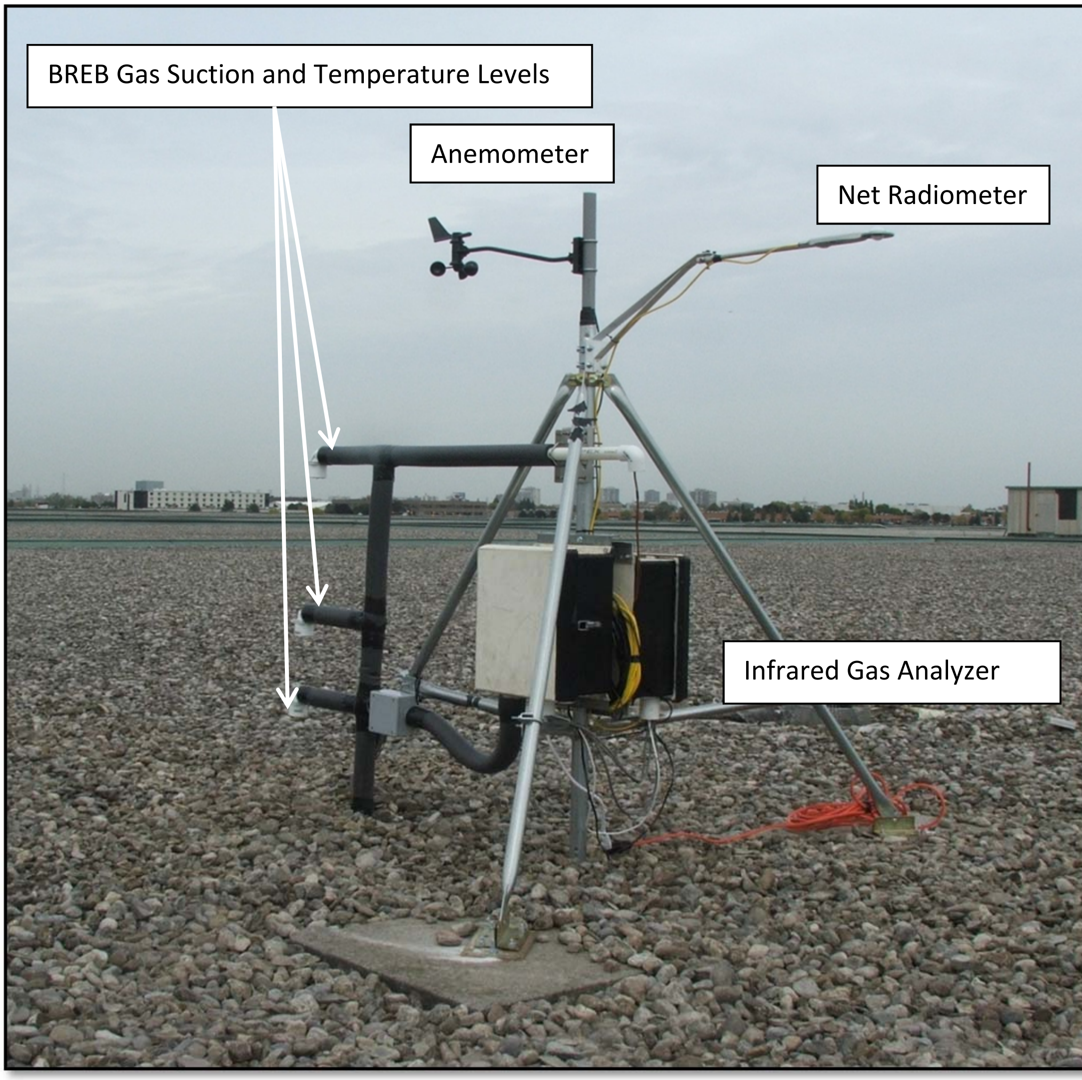

Figure 2: Bowen Ratio Energy Balance system on an extensive pebble-covered aircraft hangar roof at Downsview. Major components of the system have been identified.

4.2 Kortright

This monitoring site is located in a naturalized field within the Kortright Conservation Area (43° 50' 7" N, 79° 35' 34" W). The approximate area of the field is 44,700 m^2, vegetated mainly by timothy grass (*Phleum pretense)* and recolonized by native plants (Figure 3). The terrain is undulating and creates localized ponding under excess rain conditions. The presence of soil within this study site allows for water infiltration and storage that could subsequently be used for evaporation. The BREB system has the same configuration as for Downsview except for different measurement heights (0.25 m, 0.75 m, 1.5 m, 3.0 m). Q^* as measured with a net pyrradiometer (Middleton CN1, Middleton Solar, Victoria, Australia). Data was logged with a CR1000 data logger (Campbell Scientific, Logan, Utah). Precipitation was measured with a standard tipping bucket rain gauge.

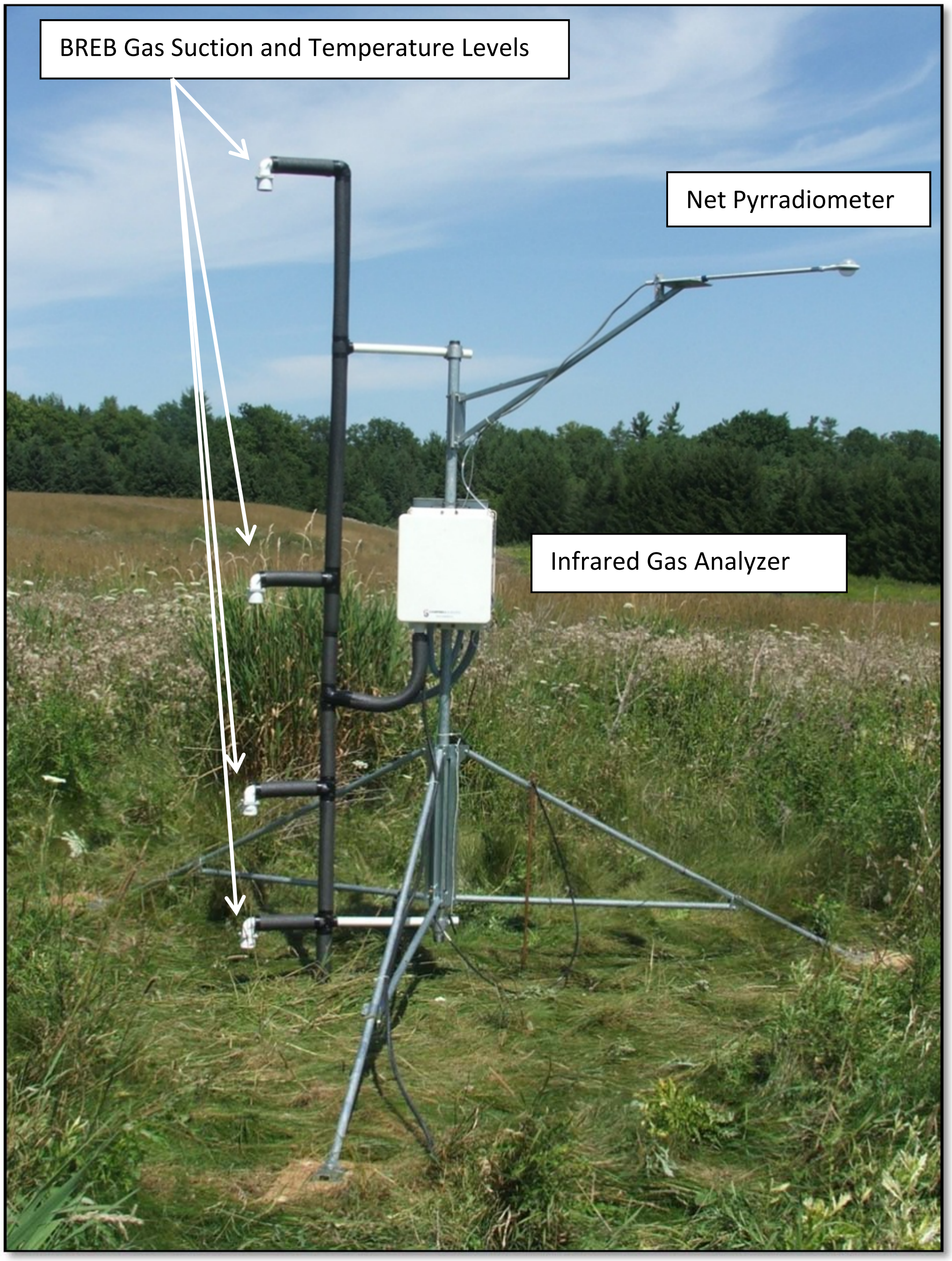

Figure 3: Bowen Ratio Energy Balance system at Kortright Conservation Area on a fallow, naturalized field. Major components of the system have been identified.

4.3 Richmond Hill

This study site is located at the margin between a residential and industrial land use areas in the town of Richmond Hill (43° 51’ 38” N, 79° 23’ 25” W). The area to the northwest (260°-350°) is mainly comprised of one or two storey residential homes with small lawns, under 300 m^2. This area extends upwind from the tower up to 2.5 km, thereby providing a sufficient footprint for reliable atmospheric measurements that are characteristic of the land use. To the southeast (140°-180°) is an extensive industrial area with manufacturing/industrial/office buildings that are up to 6.5 m tall and large in their areal extent. The parking lots are large and numerous, with small front lawns. This land use type extends to 2.5 km upwind of the measurement tower, providing sufficient footprint for meteorological measurement.

The eddy covariance (EC) approach was used to measure turbulent fluxes for latent (Q_E) and sensible heat (Q_H) at a height of 9.34 m (Figure 4). The EC system consist 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. To characterize the meteorological conditions, measurements were obtained by a net-pyrradiometer (Kipp&Zonen model, NR-LITE), temperature and relative humidity sensor (Campbell Scientific Inc., HMP45C), wind speed and direction anemometer (RM YOUNG, 05103-1-L), soil heat flux and moisture sensors (Campbell Scientific Inc., HFT3 and TCAV-L, respectively). All data were logged to a micrologger (Campbell Scientific Inc., CRX3000) programmed by Campbell Scientific Inc. to output 30-minute averages of the 10Hz flux measurements onto an SD card. Precipitation data was obtained from the neighbouring Buttonville Airport and supplied by Environment Canada.

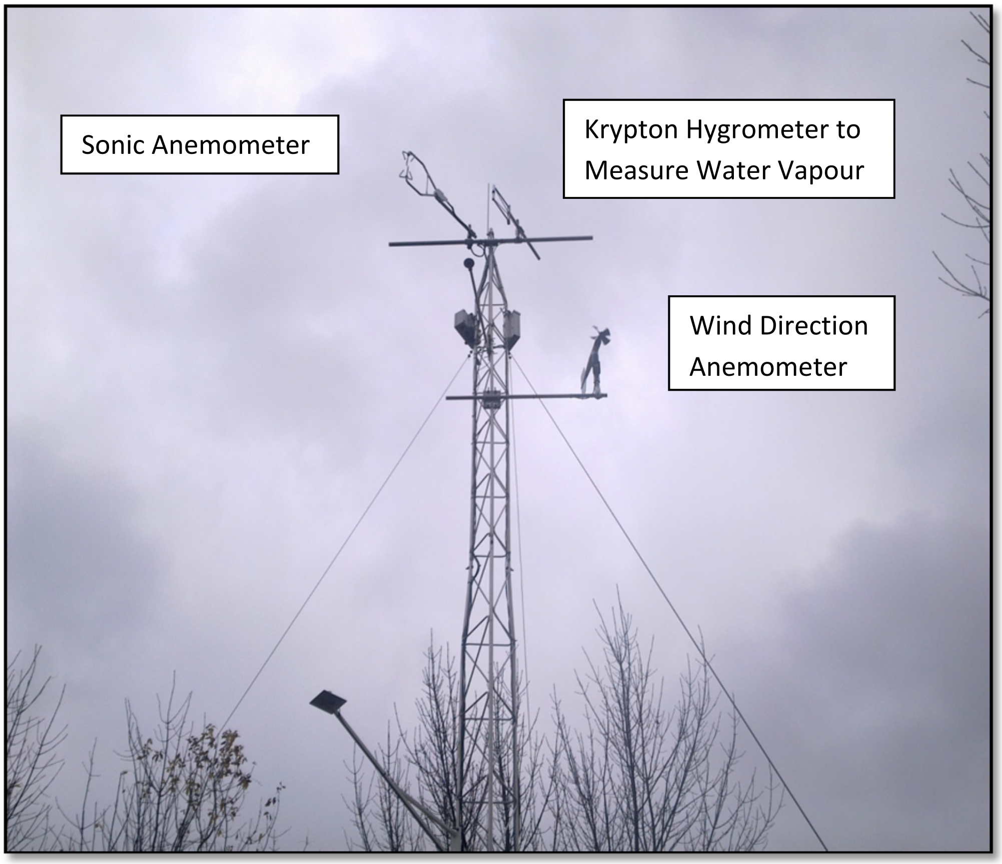

Figure 4: Eddy Covariance system in Richmond Hill within a residential/industrial area. Major components of the system has been identified.

5.0 STUDY FINDINGS

5.1 Temperature and Energy Balance

Table 1 presents average monthly values for the measurement periods of 2010-2012 for the Downsview, Richmond Hill and Kortright Locations. The seasonal averages and totals are representative of the months from April to November. The rest of the monthly data are presented for overall depiction of the sites' micro-climate on an annual basis. Measurements are not highly reliable during the winter months and have been omitted from subsequent analysis. Temperatures are generally higher for the Downsview location in comparison to Kortright due to the moderating effect of the presence of vegetation at Kortright. This is reflected in the Bowen Ratio values (represented by Q_H/Q_E , whereby values over one represent energy portioning favouring the warming of the atmosphere, and values less than one favour evaporation with associated cooling of the environment). The Downsview location which represents the most urbanized (no presence of transpiring and water-retaining vegetation and soil substrate) has the highest Bowen Ratio values (seasonal average of 3.79), thereby heating the overlaying air. The Kortright location has the lowest Bowen Ratio values (seasonal average of 0.41), revealing the strength of the evaporative regime at this fallow naturalized field. Richmond Hill stands as the intermediate location with a Bowen Ratio value of 0.96 due to its inclusion of residential and industrial buildings, both of which contain variously sized lawns and vegetation that contribute to evaporation. Through these results, it is evident that there exists a gradient of surface types from highly urban to highly rural, represented as Downsview→Richmond Hill→Kortright, respectively.

5.2 Evaporative Efficiency

The mass seasonal (April to November) evapotranspiration (mm) differs between the three sites in accordance with the suggested surface type gradient, whereby Kortright has the highest seasonal total (556 mm), which is significantly higher than for Downsview (210 mm) and Richmond Hill (280 mm). The evaporative efficiency ($\mathrm{ET/P}$) (Table 1) 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. The stored water is subsequently available to evaporate between rainfall events and to provide a continuous supply of water to the transpiring vegetation during dry periods in the form of subsurface water storage. This results in a generally cooler environment that offsets the UHI forming in adjacent built areas.

Table 1: Summary average monthly parameters for Downsview, Richmond Hill and Kortright study sites. Season includes April to November months only. Blank cells indicate lack of available data. The Bowen Ratio value is derived by Q_H/Q_E. If it is higher than 1, more energy goes into warming the air; if it is lower than 1, more energy goes into evaporation and cooling the environment. ‡ All energy units are in $MJ/m^2/d$.

Downsview	Temp (°C)	E (mm)	P (mm)	ET/P	E (mm/d)	Q* ‡	Q_G ‡	Q_H ‡	AET (Q_E) ‡	Bowen Ratio	Alpha	QET ‡	PET ‡	AET/PET
January	-4.58	21.10	30.90	0.84	0.68									
February	-2.83	21.22	23.41	0.91	0.76									
March	3.87	27.25	53.75	0.60	0.88									
April	8.98	26.20	57.57	0.53	0.87	8.50	-0.35	6.87	2.14	3.37	0.28	5.45	6.87	0.31
May	16.89	37.83	76.97	0.57	1.22	11.14	-0.04	8.43	2.82	3.86	0.29	7.96	10.03	0.29
June	20.83	30.65	118.33	0.29	1.02	12.31	0.15	10.39	1.72	6.39	0.14	9.12	11.49	0.15
July	25.41	18.82	86.79	0.32	0.61	12.18	0.11	11.01	1.03	10.78	0.07	9.58	12.07	0.09
August	22.83	26.16	83.67	0.34	0.84	9.95	-0.01	8.00	1.71	5.68	0.15	7.70	9.71	0.18
September	17.34	25.57	117.04	0.22	0.85	6.68	-0.17	5.00	1.83	3.04	0.24	4.93	6.21	0.29
October	10.59	24.04	95.55	0.25	0.78	3.35	-0.40	2.10	1.63	1.46	0.35	2.40	3.03	0.54
November	4.91	20.59	56.19	0.64	0.69	1.33	-0.55	0.84	1.10	0.80	0.42	1.06	1.34	0.82
December	-0.53	24.65	31.19	0.81	0.80									
Season	15.97	209.86	692.10	0.30	0.86	8.18	-0.16	6.58	1.75	3.79	0.24	6.03	7.59	0.33

Richmond Hill	Temp (°C)	E (mm)	P (mm)	ET/P	E (mm/d)	Q* ‡	Q_G ‡	Q_H ‡	AET (Q_E) ‡	Bowen Ratio	Alpha	QET ‡	PET ‡	AET/PET
January	-4.55	13.30	45.03	0.31	0.43	-0.22	-0.46	1.14	1.08	1.07	0.97	0.14	0.17	12.82
February	-2.85	18.56	35.87	0.58	0.66	0.89	-0.35	1.81	1.56	1.27	0.89	0.58	0.73	2.74
March	4.17	19.78	63.70	0.50	0.64	4.68	0.03	2.23	1.71	1.33	0.38	2.40	3.03	0.57
April	8.89	28.40	54.70	0.63	0.95	6.68	0.25	5.40	2.40	2.26	0.39	3.71	4.68	0.52
May	17.48	33.36	74.47	0.63	1.08	9.70	0.89	3.74	2.87	1.31	0.35	6.28	7.91	0.37
June	22.18	56.85	141.27	0.48	1.90	12.30	0.68	3.17	4.79	0.67	0.46	8.65	10.90	0.44
July	25.83	54.82	88.57	0.76	1.77	12.58	0.64	3.34	4.66	0.74	0.41	9.46	11.92	0.39
August	24.59	53.39	85.03	0.63	1.72	8.90	0.26	2.18	4.37	0.50	0.50	6.71	8.46	0.52
September	19.11	36.31	118.13	0.34	1.21	5.21	-0.13	1.94	2.97	0.71	0.50	3.89	4.90	0.61
October	12.13	22.49	94.10	0.25	0.73	1.92	-0.49	1.56	1.79	0.87	0.52	1.59	2.01	0.91
November	5.99	13.94	60.40	0.39	0.46	0.58	-0.60	1.19	1.16	1.01	0.48	0.65	0.81	1.43
December	-0.12	11.44	51.63	0.24	0.37	-0.42	-0.63	1.03	0.94	1.07	0.75	0.12	0.15	7.41
Season	17.38	280.38	719.80	0.39	1.15	7.13	0.13	2.73	2.93	0.96	0.43	5.08	6.40	0.62

Kortright	Temp (°C)	E (mm)	P (mm)	ET/P	E (mm/d)	Q* ‡	Q_G ‡	Q_H ‡	AET (Q_E) ‡	Bowen Ratio	Alpha	QET ‡	PET ‡	AET/PET
January	-5.12	19.00	43.37	0.46	0.61	0.24	0.25	-0.03	0.20	1.79				
February	-3.49	26.98	29.60	0.95	0.96	2.07	-0.49	0.95	1.61	1.33				
March	3.03	30.84	54.53	0.91	0.99	5.63	0.79	2.28	2.47	1.45	0.89	2.54	3.21	0.79
April	7.58	36.78	54.80	0.77	1.23	9.20	2.22	3.93	3.05	1.64	0.69	4.26	5.37	0.59
May	14.99	76.56	72.27	1.34	2.47	12.11	3.40	2.67	6.04	0.74	0.93	6.12	7.71	0.79
June	18.69	97.70	140.87	0.80	3.26	13.78	3.21	2.57	8.00	0.65	1.03	7.79	9.82	0.82
July	22.45	118.24	88.80	1.75	3.81	15.21	3.11	2.71	9.40	0.57	0.96	9.42	11.87	0.79
August	20.05	98.90	87.60	1.11	3.19	12.52	1.92	2.09	7.91	0.52	1.00	7.19	9.06	0.86
September	15.18	63.40	105.73	0.62	2.11	8.19	0.66	1.44	5.50	0.60	1.06	4.85	6.11	0.89
October	8.78	40.86	97.60	0.45	1.32	4.33	-0.42	1.36	3.79	0.73	1.11	3.17	3.99	0.95
November	3.33	23.26	50.67	1.89	0.78	2.01	-0.92	0.78	1.98	1.00	1.08	1.42	1.79	1.11
December	-0.48	16.64	42.57	0.46	0.54									
Season	13.88	555.70	698.33	0.79	2.27	9.67	1.65	2.53	6.08	0.41	0.95	6.07	7.65	0.81

5.3 Evapotranspiration and $alpha$

The above relationships are reflected in the calculated $alpha$ reduction coefficients, which also follow the proposed urban-rural gradient (Table 1). It 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. Therefore, the alpha value decreases with increasing urbanization which is explained by a larger departure between $\mathrm{actual\,ET}$ and $\mathrm{potential\,ET}$. From Figure 5 it is evident that 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 $\mathrm{actual\,ET}$ rates at the same rate as the increase in modeled $\mathrm{potential\,ET}$. Alpha values tend to be lower during the warmer months due to high energy supply that increases the $\mathrm{potential\,ET}$ (Equation 4). At this time of the year, Q^* is large, and although this increased available energy results in higher rates of $\mathrm{actual\,ET}$, it has a larger influence on the $\mathrm{potential\,ET}$ model. At this time, the air is dry and the atmospheric demand increases, the alpha values drop and the model becomes less satisfactory (de Bruin & Keijman, 1979; Parlange and Katul, 1992). Although the atmospheric demand is high, it does not imply that there is high ET, since surface moisture may or may not be available, regardless of atmospheric demand. For the surfaces measured, the Priestley-Taylor method does not produce nearly 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 $potential\ ET$, reduction coefficients need to be implemented.

5.4 Inter-annual Variation in Evapotranspiration and $alpha$

There exists inter-annual variation of alpha and ET for each site, in accordance with meteorological conditions, such as precipitation, temperature, and energy supply (Figure 5). For instance, the 2011 Kortright season has generally higher alpha values, which can be attributed to a wetter season (755 mm) in comparison to 2010 (696 mm) and 2012 (644 mm). The increased moisture availability created wetter soil conditions, driving the ET process, and conveying the ecosystem to evaporate closer to the potential rate. In addition, the difference in ET values between each site is large, as Downsview has nearly constantly low ET rates throughout the season. This is a direct result of a lack of vegetation and soil substrate that provide water storage for subsequent dry events. The evaporation that does occur is a function of the increased surface area due to the presence of pebble stones. Thus, when it rains, some water is retained around the surface of the pebble stones before it reaches the drainage system of the building. Despite the increase in available energy to evaporate water during the warm months, Downsview values tend to decrease during the high-energy summer months. The Richmond Hill location follows an intermediate pattern of ET in correlation with an increase in available energy during the summer months. Lastly, Kortright undergoes the highest rate of change in evaporation throughout the measurement period, coinciding with the natural rhythm of the annual water cycle.

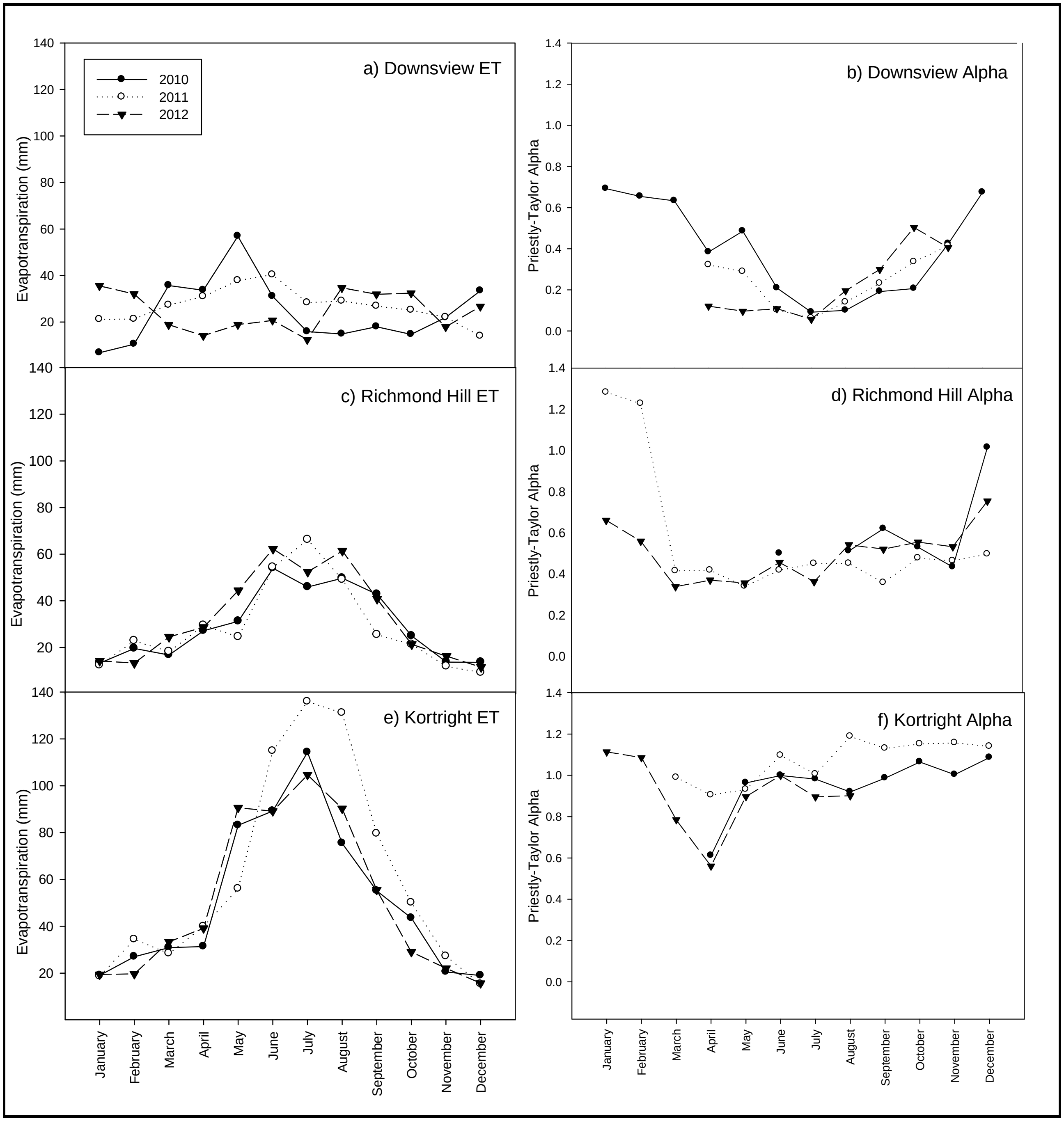

Figure 5: Evapotranspiration (ET) and measured $alpha$ variability on a monthly basis for different land cover types, 2010-2012. a) Downsview ET; b) Downsview $alpha$; c) Richmond Hill ET; d) Richmond Hill $alpha$; e) Kortright ET; f) Kortright $alpha$.

The interplay between $\mathrm{actual\,ET}$ and $\mathrm{equilibrium\,ET}$, which in turn produces an actual alpha value compared to the theoretical alpha value of 1.26 for $\mathrm{potential\,ET}$ (Figure 6). As shown for the three surface types measured, alpha is always lower than the theoretical value (shown as $\mathrm{potential\,ET}$ line with slope of 1.26). The surface-type gradient is visible in these figures, as the Kortright alpha values are the closest to the theoretical model, albeit not equal. This indicates that for natural surfaces, there will be the least deviation from $\mathrm{potential\,ET}$ to $\mathrm{actual\,ET}$. The measured alpha values for Richmond Hill and Downsview continue to decrease, whereby the Downsview alpha values are so low a pattern is difficult to determine. Thus, for all sites, if one uses the $\mathrm{potential\,ET}$ to construct a water budget, ET may be overestimated (Knowles, 1996; Snelgrove, 2002). This illustrates the need to understand how alpha values vary over different surface types that are generally water limited. On average for each site, 30% (70%), 39% (61%) and 79% (21%) of precipitation went into evaporation (infiltration and/or runoff) for Downsview, Richmond Hill, Kortright, respectively (Table 1). Using the theoretical value of alpha to model a water budget, there will be an overestimation of ET and an underestimation of RO and infiltration, creating an imbalance between the real water budget and the modeled water budget.

5.5 Actual ET to Potential ET Ratio and Applicability to Other Models

The $alpha$ value is specific to the Priestley-Taylor model, which limits the applicability of the current results to the application for other models. For this reason, a ratio of $actual\ ET$ to $potential\ ET$ (AET/PET) serves the purpose of extending the current results obtained by the Priestley-Taylor model to any other model which produces a value for $potential\ ET$. The ratio value can be multiplied by a $potential\ ET$ value to produce an estimate of $actual\ ET$. The results presented in Table 1 follow the same urban to rural gradient as previously discussed parameters. The ratio is lowest for Downsview, with a seasonal average of 0.33 (i.e. $actual\ ET$ is only 33% of $potential\ ET$); the Richmond Hill seasonal average is 0.62; and the Kortright seasonal average is 0.81. As anticipated, the Kortright naturalized field evaporates the closest to the potential rate, which is a reflection of the soil column’s water-holding capacity and presence of transpiring vegetation.

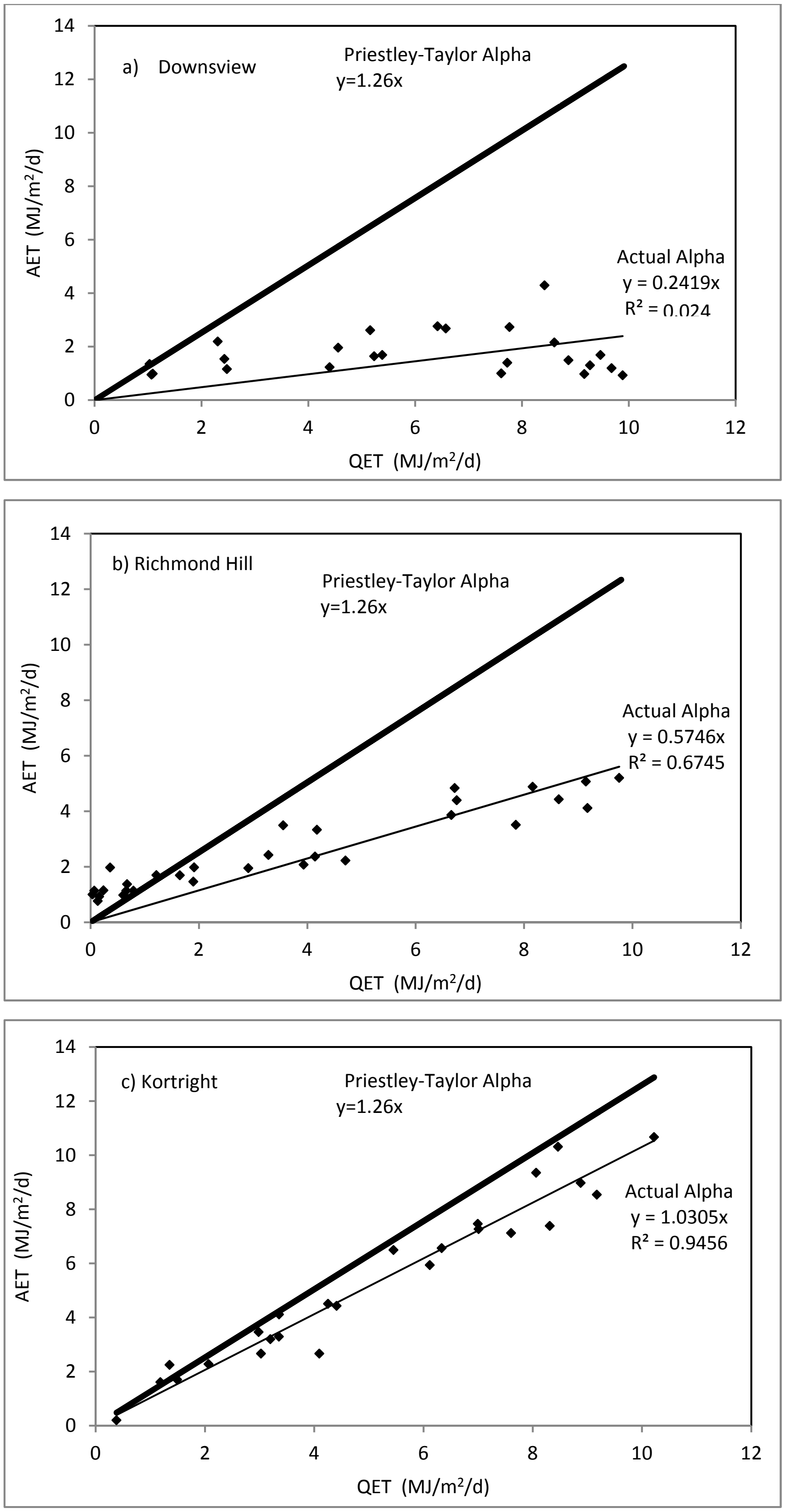

Figure 6: Variability in actual $alpha$ values calculated using $actual\ ET$ and $equilibrium\ ET$ in energy units, in relation to $potential\ ET$ with $alpha$ =1.26. a) Downsview; b) Richmond Hill; c) Kortright**.** Slope of the line in the linear equations is the $alpha$ value.

5.6 Case Study – Development of a Simplified Evapotranspiration Model with Potential and Actual Evapotranspiration

Presented is a ***simplified monthly water budget evapotranspiration model*** for the three major watersheds with consideration for land cover type. Table 2 contains information on the percent land cover type for these watersheds, under the simple categories of urban, natural, rural and open water. This classification was selected as it coincides with the land cover found at the three measurement sites. The measured and/or alpha values to feed into the ET model are shown in Table 3 on a monthly time scale. Presented are also typically used theoretical values (alpha=1.26) used for water balance modeling. The alpha for saturated surfaces is equal to the theoretical value of 1.26; the natural surface is equated to the values obtained at Kortright; urban surface is equated to values obtained at Richmond Hill; the rural surface is inferred as an average between the natural and urban values (*included for the purpose of completeness rather than as suggested values for modeling*); the semi-impervious cover is equated to values collected at Downsview; and the completely impervious is taken as an alpha value representative of a 10% ET regime. *This is an inferred value based on Downsview data during periods before rain events, and is included for the purpose of completion.* The purpose is to illustrate the departure of ET when calculated using different alpha reduction coefficients.

Table 2: Land cover type percent cover for the Humber River (TRCA, 2008), Don River (TRCA, 2009) and Rouge River (TRCA, 2007) watersheds.

	Percent Land Cover Type		
Land Cover Type	Humber River	Don River	Rouge River
Urban	40.2	79.4	35
Natural	32.2	15.7	24
Rural	26.2	4.6	40
Open Water	0.6	0.3	1

Table 3: Theoretical, measured and interpolated $alpha$ values for different land cover types on a monthly time scale to be used in a simple ET model.

	Alpha Values for Various Surface Types					
	Saturated *(Theoretical)*	Natural *(Kortright)*	Rural *(Average of Natural and Urban)*	Urban *(Richmond Hill)*	Semi-impervious *(Downsview)*	Completely impervious *(E/P≈0.1)*
April	1.26	0.69	0.82	0.38	0.28	0.05
May	1.26	0.93	0.80	0.34	0.29	0.05
June	1.26	1.03	0.84	0.42	0.14	0.05
July	1.26	0.96	0.80	0.34	0.07	0.05
August	1.26	1.00	0.86	0.47	0.15	0.05
September	1.26	1.06	0.86	0.46	0.24	0.05
October	1.26	1.11	0.88	0.49	0.35	0.05
November	1.26	1.08	0.85	0.45	0.42	0.05

The values from Table 3 are graphed in Figure 7 for better representation. The gradual decrease in the alpha value is observed from completely saturated surfaces to completely impervious surfaces. There is an evident monthly variability, where a similar alpha value may apply for two different surface types (i.e. semi- and completely impervious in July). This clearly shows the variability of the evaporative efficiency of different surface types which are frequently encountered in urbanized watersheds. Once the alpha values are weighted with respect to the percent cover data for each urban watershed, ET can be modeled. This is shown in Figure 8 for the three watersheds on a monthly basis during the season. For comparison, one series represents the ET that would be obtained if one uses an alpha value of 1.26. The model 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. These results would have significant consequences for construction and engineering decisions related to water routing, storage and runoff solutions. If ET is overestimated by a large factor, runoff and/or infiltration will be underestimated by the same factor, resulting in erroneous water budget conditions under large rain events.

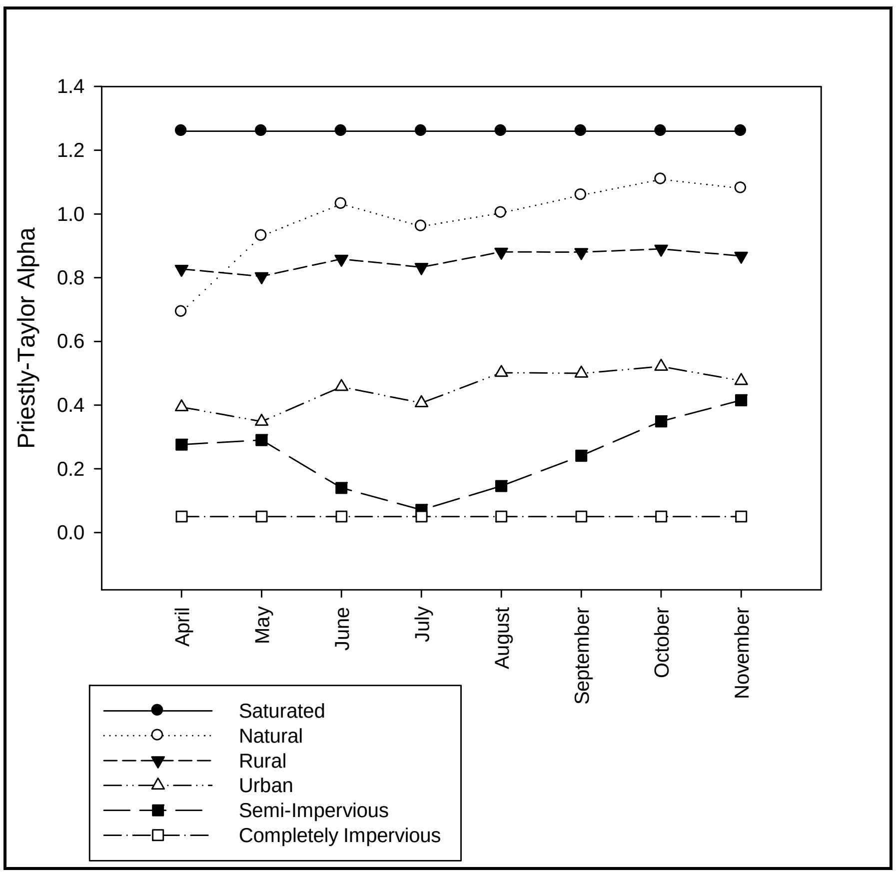

Figure 7: Theoretical, measured and interpolated $alpha$ values for different land cover types on a monthly time scale. The higher the $alpha$ value is, the more ET is expected to occur.

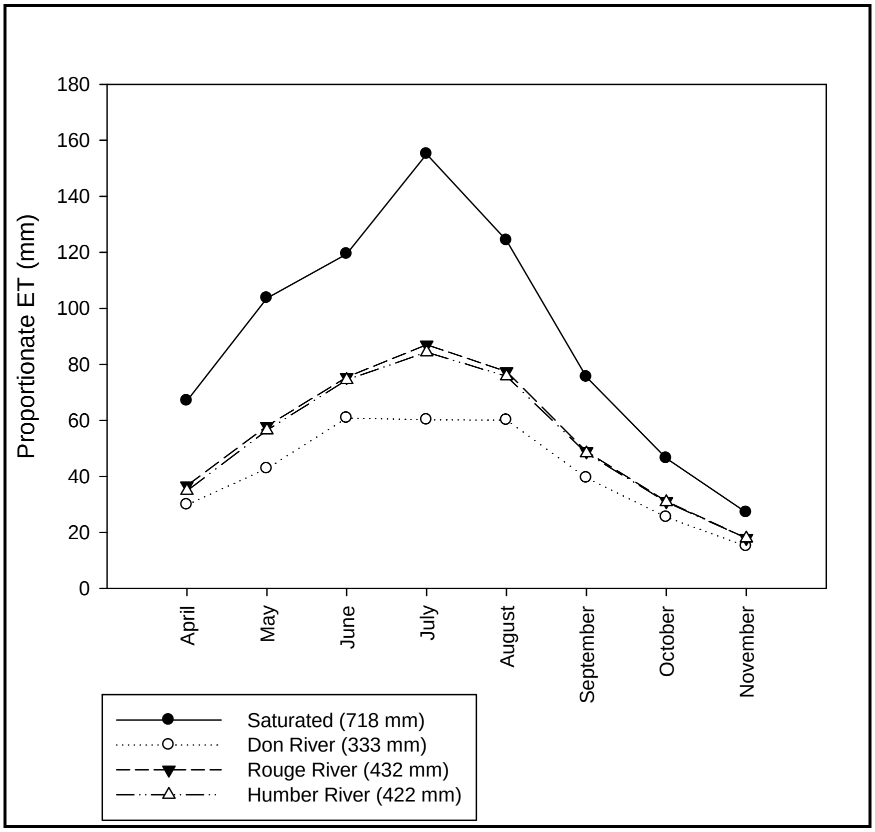

Figure 8: Modeled ET over the Don River, Rouge River and Humber River watersheds adjusted for different $alpha$ value based on land cover. Saturated curve is represented with the Priestley-Taylor theoretical $alpha = 1.26$. Bracketed values in the legend represent seasonal (April to November) total ET.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The purpose of this report was to illustrate the importance of the inclusion and parameterization of evapotranspiration (ET) in water budget analysis. Data provided in this report could serve the purpose of model validation data and/or provide $actual\, ET$ estimates for the observed land use types that are typically found within urban watersheds. The study took place over three distinctly different land cover types to assess their different partitioning of water into the ET component of the water budget. It was found that modeled ET based on the Priestley-Taylor theoretical alpha value of 1.26 resulted in the overestimation of ET, as expected considering its theoretical assumptions. Calculated alpha values were consistently lower than 1.26 as a result of lack of available water. The Kortright site experienced alpha values closest to that for freely evaporating surface due to its water retention properties within a vegetated soil column, thus sustaining ET between rain events. The Downsview location experienced the lowest alpha values, as its rooftop location rapidly drains water away from the surface, which is covered with a thin layer of pebble stones. The increased surface area that the pebble stones provide in comparison to a completely impervious surface allow for higher evaporation than other constructed and impervious structures. The Richmond Hill location resulted in intermediate alpha values due to the high variability in the land cover that was being measured. A simplified model was constructed to evaluate the difference between ET, modeled with the theoretical alpha value, and ET modeled with alpha values that are representative of the various land cover types encountered within large urban watersheds. It was found that ET was highly overestimated if the model used only the theoretical alpha value of 1.26. The findings show the use of $potential\, ET$ in simplified water budget models should be avoided, as it would result in significant overestimation of the ET rate. The same gradient pattern across the three sites was observed for AET/PET ratios, whereby Kortright AET was closest to its PET value. Data presented in such manner can be fed into any other model that provides an estimate of PET. This is an important parameter to present, as it removes the constraint of the Priestley-Taylor model as per the calculated alpha value.

Urbanization is a major driver of land use change in each major watershed of the Greater Toronto Area, along with rural and natural areas. For this reason, understanding how each of these land use types contributes to the water balance will improve parameter selection for watershed modeling and water management. With proper knowledge of where the water goes, improved management practices can take place to maintain hydrological and ecological functions of watersheds. Urbanization has had a negative impact on watershed functioning with respect to streambank erosion, increased peak flow flood risk, reduction in groundwater and subsurface flow due to water channeling into infrastructure and other negative consequences to the ecosystems within watersheds. To mitigate the growing urban infrastructure that removes and channels rainwater away from the decreasing amount of permeable and evaporating surfaces, low impact development (LID) measures should be adopted more widely.

6.2 Recommendations

The recommendations outlined below are provided for consideration during water balance modeling and measurement options.

1. It is recommended to use the measured (and/or inferred from measurements) $alpha$ values presented in Table 1 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 indicator of the percent deviation between the two terms. This ratio can be multiplied (similar to a reduction factor) to $potential\ ET$ obtained from other $potential\ ET$ formulas, in order to obtain $actual\ ET$.

3. The long-term monitoring of evapotranspiration is recommended for improved estimation of $actual\ ET$, $equilibrium\ ET$, $potential\ ET$ 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. This will also reveal in more detail the monthly and inter-annual variability of ET, which can be implemented into models for improved accuracy.

4. In order to expand on the land use types to derive $alpha$ values, there are plans to move the Richmond Hill Eddy Covariance station on a rooftop within a highly industrialized area near major highways. This will provide an additional set of ET values that will be representative or large areas of the GTA. Additionally, the Downsview rooftop BREB has been moved to a Kortright wetland location next to the Archetype House and future BRE Innovation Park to assess the pre- and post-development water balance of the proposed sustainable development. This dataset will provide $alpha$ values closer to the theoretical value of 1.26, and/or between 1.26 and $alpha$ obtained for the Kortright field. This can be added to the table of suggested $alpha$ values to be used for water balance models.

5. An additional ET measurement dataset was implemented in Spring, 2014 by integrating pan evaporation at the Kortright measurement site. This provides a comparative dataset to the adjacent BREB system to assess the performance and reliability of the pan reduction coefficient, typically given a value of 0.7.

6. In order to gain a better understanding of urban and suburban watershed water balance through modeling of energy balance data, it is important to improve the spatial resolution of meteorological stations (Piringer *et al.*, 2002) and calibration stations that measure ET (BREB, EC or pan). There exists a need for micrometeorological measurements at 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.

GLOSSARY

Actual Evapotranspiration – The observed, measured, or calculated amount of water that exits the system and enters the atmosphere through the combined process of evaporation and transpiration.

Aerodynamic Resistance – The ease with which heat and water vapour are transported from the evaporating surface to the atmosphere.

Alpha– The alpha value of 1.26 is the average coefficient found by Priestly & Taylor (1976) that is multiplied by the equilibrium evapotranspiration in order to obtain potential evapotranspiration. This value was obtained with the use of experimental data, whereby $actual\ ET$ was measured, $potential\ ET$ was calculated, and the coefficient to relate the two was estimated as an average of 1.26 for saturated surfaces with unlimited supply. In cases when potential evapotranspiration is not achieved by the system, the alpha coefficient will be less than 1.26.

Atmospheric Boundary Layer – The lowest layer of the atmosphere that is directly influenced by the surface characteristics, typically the lowest 1 km.

Atmospheric Demand – The atmosphere's need for moisture as a function of its vapour pressure deficit and wind speed. The higher the vapour pressure deficit and wind speed, the more moisture the atmosphere will be able to extract from the system through evapotranspiration if moisture is available.

Atmospheric Stability and Instability – The state of the atmosphere that governs the depth of the atmospheric boundary layer and is dependent on wind speed and air parcel temperature. A stable atmosphere usually occurs at night when wind speeds are higher and the air is suppressed, decreasing the depth of the atmospheric boundary layer. An unstable atmosphere usually occurs during the day when wind speeds are lower and the atmospheric boundary layer expands. The lower the height of the atmospheric boundary layer, the more concentrated pollutants will become.

Bowen Ratio Energy Balance Method – A micrometeorological technique to measure the vertical movement of water vapour and/or carbon dioxide. It measures the gas concentration at multiple vertical levels to establish a gradient (the difference between two measurement points), which will determine the net vertical movement. The method includes measurement of net radiation and ground heat flux to measure the complete energy balance.

Capillary Force – Opposite to the downward push of gravity, capillary force helps water molecules attach to small soil particles and remain in place or rise upwards. The capillary force is greater in soils with small pores than ones with large pores.

Eddy Covariance Method – A micrometeorological method to measure the vertical movement of water vapour and/or carbon dioxide. It samples the density of each gas at a single measurement height at high frequency (usually 10 times per second, 10 Hz). This measurement is correlated to an adjacent high frequency measurement of the vertical movement of wind (eddies), hence eddy covariance or eddy correlation method. Thus, it calculates the number of gas molecules transferred vertically within a volume or air.

Equilibrium Evapotranspiration – The amount of water that exits the system and enters the atmosphere under conditions when the atmosphere and the evaporating surface have reached equilibrium. This is due to the assumption that a dry air mass that moves over a moist surface will increase in its moisture until equilibrium is achieved.

Evaporation – The amount of water that is converted from a liquid state to a gaseous state to leave a wet surface and enter the atmosphere. This occurs when the atmosphere is drier than the surface, and the water is continually evaporating with the purpose of reaching a state of equilibrium between the two systems.

Evaporative Efficiency – The amount of evaporation that occurs compared to the total amount of precipitation. A high evaporative efficiency refers to high amount of evaporation for a given amount of precipitation.

Evapotranspiration- The combined effect of wet surface evaporation and plant transpiration during the process of water removal from the system in the form of water vapour.

Field Capacity – The maximum volume of water that can be held within a given soil column after the force of gravity has drained the excess volume of water.

Footprint – The upwind area which influences the horizontally moving air mass that is eventually measured at a meteorological station. The extent of the footprint is dependent on measurement height, surface roughness of the upwind area, and atmospheric stability and instability.

Ground Heat Flux – As part of the surface energy balance, this is the amount of energy that is transferred from the surface to the subsurface through the process of conduction. This occurs when a temperature differential with depth exists, whereby the energy will move from areas of high temperature to areas of low temperature.

Hydrograph – A graph the shows the rate of water flow (discharge) over a period of time at a single location in a stream, river or any outlet through which water flows. It is usually graphed to show the rate of discharge for a specific precipitation event. It is characterized by a rising limb at the beginning of the storm, a peak discharge towards the end of the storm when accumulated water continues to flow, and falling limb when the system is able to infiltrate/redistribute the water at a faster rate than the arrival of water.

Infiltration – The rate at which water enter the soil column and is removed from the ground surface. Different soils have different infiltration rates. Soils with large pores (low capillary force) have high infiltration rates but low water retention. Soils with small pores (high capillary force) have low infiltration but once water enters these soils, it is retained better.

Latent Heat Flux – As part of the surface energy balance, this is the amount of energy that is used to convert liquid water to water vapour through the process of evapotranspiration. Evapotranspiration is the mass equivalent (see latent heat of vapourization) to the energy term of latent heat flux. This occurs when a moisture difference between the surface and the atmosphere exists, and energy is directed towards replenishing the atmosphere with moisture as opposed to with heat (sensible heat flux). Unlike sensible heat flux, no temperature change of the water is observed in the latent heat flux, only a change in state is observed (hence *latent*).

Latent Heat of Vapourization – The amount of energy required to convert a unit mass of a liquid to unit mass of water vapour without a change in temperature. To convert from the energy unit of latent heat flux to the mass unit of evapotranspiration, the latent heat flux is divided by the latent heat of vapourization.

Low Impact Development – A stormwater management strategy that aims to mitigate the negative impacts of urbanization on the natural hydrological regime. It focuses on lot-level mitigation to increase the amount of stormwater runoff infiltration at the source before it reaches the municipal storm sewer system. It encourages infiltration, evapotranspiration, filtration, harvesting and detention of stormwater runoff.

Net Available Energy – The net amount of energy available for a system to utilize. It is a function of long-wave (indirect sun energy) and short-wave (direct sun energy) energy that is either incoming or outgoing. The net energy that results is the amount of energy available for a system to partition between ground heat flux, latent heat flux and sensible heat flux.

Peak Streamflow – The highest discharge rate (volume of water per unit time) that is observed for a given precipitation event. Peak streamflow usually increases with an increase in urbanization and impervious areas that rapidly channel stormwater to streams, without the mitigating effect of infiltration. It is reduced with increasing permeability as stormwater is able to infiltrate the soil and is slowly released over longer period of time.

Permeability – The ease with which water can enter and flow within a volume of material. Soils are permeable surfaces that accept water by infiltrating it, while urban structures are impermeable as they do not accept water for infiltration, and instead channel that water directly to storm sewers or to streams, rivers and lakes.

Potential Evapotranspiration – The capacity of the atmosphere to remove water from the ground surface in the form of evaporation and/or transpiration (i.e. atmospheric demand), assuming an unlimited water supply to maintain actively transpiring vegetation.

Reduction Coefficient – A single number index used to scale down a variable. For example, the potential evapotranspiration is multiplied by a reduction coefficient in order to obtain a lesser value for the actual evapotranspiration. The reduction coefficient can represent a combination of influencing variables such as soil moisture, soil temperature, greenness index, or each influencing variable can have its own reduction coefficient. These influencing variables behave to limit the potential rate of evapotranspiration. The reduction coefficients presented here are termed actual alpha values, as opposed to the theoretical alpha value of 1.26.

Riparian Corridor – The land adjacent to a river channel that that is unique in its physical habitat and is sustained by the presence of the river channel and vice versa. This transition zone is usually within the water body floodplain and is an important indicator of the health of the ecosystem.

Runoff – When an impermeable land surface is present or when the soil has reached its infiltration capacity or has become fully saturated, the excess stormwater that begins to flow over land is termed runoff. The excess water flows over land into low-lying areas, streams, rivers, lakes or into the stormwater sewer system.

Saturation Vapour Pressure – The vapour pressure observed when equilibrium is reached between a wet surface and the overlying air. At this point, the number of water vapour molecules that enter and exit the system is equal.

Sensible Heat Flux - As part of the surface energy balance, this is the amount of energy that is transferred between the earth's surface and the atmosphere. This occurs when a temperature difference in the air column exists, whereby the energy will move from area of high temperature to areas of low temperature. Unlike the latent heat flux, a temperature change is observed in the presence of sensible heat flux.

Subsurface Flow – A runoff producing mechanism defined by the gradual flow of water beneath the surface that sustains low flow conditions in water bodies. This flow delivers water during and between precipitation events and contributes to the hydrograph of a water body.

Surface Energy Balance – The components of the energy balance define the energy properties of a surface and how it interacts with the atmosphere through the interplay between net available energy, ground heat flux, latent heat flux and sensible heat flux. Their different interactions will deem the system as dry, moist, cold or warm and will determine how much these properties interact with the soil.

Transpiration – The process of water movement through a plant's biomass out of its stomatal pores and into the overlaying air. The process is equivalent to evaporation, except the liquid water originates within the vegetation.

Urban Heat Island - An urban area that is characteristically warmer than the surrounding rural and less-developed area. The higher air temperature is a direct result of human activities such as building infrastructure, industry and traffic. The urban structures create, retain and continually release heat. The lack of permeable vegetated surfaces restricts the land and vegetation available for evapotranspiration and its associated cooling effect.

Vapour Pressure – A measure of the amount of moisture in the air. High vapour pressure refers to a large number of water vapour molecules bumping against east other in a given volume, i.e. high water content.

Vapour Pressure Deficit – The amount water vapour needed to achieve a state of equilibrium between the surface and the overlying air. It is the difference between the observed vapour pressure and the saturation vapour pressure.

Water Budget – It is used to describe the inputs, outputs and changes in storage of water from a system, usually calculated at the scale of a single hydrological unit such as a watershed. The main components of a water budget are precipitation, evapotranspiration, surface runoff, groundwater recharge and change in storage.

Water Table – The depth below which the soil is saturated with water that fills all voids. It varies with season and is typically closest to the ground surface during the spring snowmelt period.

Watershed – A hydrological unit defined by its inputs and outputs of water as having separate drainage areas from adjacent watersheds. The fallen precipitation will collect in each watershed designated drainage area as separated by ridges of higher elevation.

Weighting Lysimeter Method – A method used to measure the actual evapotranspiration by mimicking the composition of the surface being monitored. The container that holds the representative soil and vegetation rests on a sensitive scale that measures the mass of water lost (drainage from the container is taken into account).

Wilting Point – The soil moisture content at which the plant wilts. At this point, it becomes too difficult for the plant roots to counteract capillary forces, resulting in the use of their biomass water for transpiration and eventual desiccation.

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