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DEPARTMENT OF ENVIRONMENTAL MODELING

THE ESTIMATION OF EVAPOTRANSPIRATION USING METEOROLOGICAL DATA FROM NEMCICE STATION

DIPLOMA THESIS

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STUDENT'S DECLARATION

I, MICHAEL OPARE ASARE, hereby declare that except for reference to other people's work which have been duly cited and acknowledged, this Action Research is the results of my own effort and that it has neither in whole nor in part been presented elsewhere.

SIGNATURE…………………. DATE……………………

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SUPERVISOR'S DECLARATION

I hereby certify that preparation and presentation of this thesis was supervised in accordance with the guidelines binding the supervision of Diploma Thesis laid down by the Czech University of Life Sciences.

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ABSTRAKT

Evapotranspirace je fyzikální proces, ba až velmi obtížný, či nemožný změřit přímo. Při nemožnosti přímého změření, se výpočty založené na empirických, nebo teoretických rovnic stávají nezbytné. Tato práce hodnotí a srovnává pět empirických modelů výpočtu evapotranspirace a jejich vhodnost pro meteorologickou stanici Němčice v České republice od dubna do října. Tři modely jsou výpočtem potenciální evapotranspirace. Jeden z těchto tří modelů je teplotně založený model (TUC model) a zbylé dva jsou radiačně založené, tj. Priestley - Taylor (PT) a Penman – Monteith (PM). Zbylé dva modely jsou použity pro odhad aktuální evapotranspirace přímo použitím doplňkového přístupu, tedy modelem Brutsaert a Stricker (AA), měřící advekci a sucho. Druhým modelem je Granger a Gray (GG). Když byly modely srovnány s hodnotami výparu, model PM ukazoval přesné deterministické chování s malou náhodností. Následován byl modely TUC a PT. Součinitelé RMSE, MAE, MSE a ME byly použity pro odhad přesností modelů (odhad chyb). Výsledky ukazují, že výpočet aktuální evapotranspirace modelu GG (RMSE=2,04) byl lepší, než modelu AA (RMSE=2,75) v téměř všech měsících. V odhadu potenciální evapotranspirace měl lepší výsledky model PM (RMSE=3,87) a TUC model (RMSE= 2,10) než PT model (RMSE= 1,98) v případě deterministických pohybů a odhadů. Výše zmíněný výzkum přispívá k lepšímu pochopení výparu, procesům aktuální a potenciální evapotranspirace, predikčním schopnostem v rozdílných časových měřítcích a vodnímu cyklu v podmínkách měnícího se klimatu.

Klíčová slova: aktuální evapotranspirace, potenciální evapotranspirace, výpar z výparoměrů

ABSTRACT

Evapotranspiration is a physical process, which remains very difficult if not impossible to measure directly. In the absence of direct measurements, calculations based on empirical or theoretical equations become quite important. This study evaluates and compares five empirical evapotranspiration models and their performance in water balance studies by using meteorological data from the Nemcice station in Czech Republic from April - October. Of the five models evaluated, three models calculate potential evapotranspiration. One of the three potential evapotranspiration models belong to the temperature-based category, i.e. the TUC model, and the other two belong to the radiation-based category, i.e. the Priestley–Taylor model (PT) and the Penman- Monteith model (PM). Two of the models are used for estimating actual evapotranspiration directly using the complementary relationship approach, i.e. the advection–aridity (AA) model of Brutsaert and Stricker, and the GG model of Granger and Gray. When the models were, bench marked with Evaporation values, PM model shows accurate deterministic behavior with little randomness followed by TUC model and finally the PT model. RMSE, MAE, MSE and ME are used for model accuracy (error estimation). The results show that for the calculation of actual evapotranspiration, the GG model (RMSE= 2.04) performed better than the AA model (RMSE= 2.75) in almost all the months. In estimating the potential evapotranspiration, temperature-based methods (Penman Monteith; RMSE=3.87 and TUC models RMSE= 2.10) performed better than radiation method (Priestley-Taylor RMSE=1.98) in terms of deterministic movement and estimates. The above-mentioned research is of great importance in full understanding of Evaporation, Actual and Potential Evapotranspiration processes, of predictability on different time scales and the water cycle character under climate change condition.

Keywords: Actual Evapotranspiration, Potential Evapotranspiration, Pan Evaporation

TABLE OF CONTENTS **PAGE**

CHAPTER ONE

1. INTRODUCTION

Evapotranspiration is a collective term for all the processes by which water in the liquid or solid phase at or near the earth's land surface becomes atmospheric water vapor. The term thus includes evaporation of liquid water from rivers and lake, bare soil, and vegetative surfaces; evaporation from within the leaves of plants (transpiration); and sub-limited from ice and snow surfaces (Dingman, 2015, Shaw, 1994). Evapotranspiration is a calculated estimate of the water that evaporates from the soil and plant surfaces and water plants lose through their leaves (Shaw, 1994; Abtew and Melesse, 2012)

Evapotranspiration (ET) is one of the major components of the hydrological cycle. Around 64 % of land-based average annual precipitation returns to atmosphere due to process of evaporation (Sumner et al., 2005; Ngongondo et al., 2013; Fisher et al., 2005).

The amount of evapotranspiration fluctuates throughout the year, primarily because of temperature. Evapotranspiration is higher with warmer temperatures and lower with cooler temperatures. This is the main reason why the amount of water needed increases in the summer and decreases in the spring and fall (Hanson, 1991).

Among the many problems associated with extended periods of drought is the inability of plants to extract water at a rate fast enough to keep up with the rates of evapotranspiration that atmospheric conditions will allow. The rate of potential evapotranspiration (ET_p), the amount of water that could potentially be lost to evaporation over a vegetated surface given meteorological conditions at the time, is dependent on the intensity of solar radiation, air temperature, humidity and wind speed (Allen et al., 1998). Potential evapotranspiration combined with examining the factors contributing to actual evapotranspiration gives hydrologists an understanding of what an area's water budget will be after water is lost to this process (Thornthwaite, 1944).

Actual evapotranspiration (ET_a) describes all the processes by which liquid water at or near the land surface becomes atmospheric water vapor under natural conditions (Morton, 1983; Kite and Droogers, 2000).

Accurate estimation of both actual and potential evapotranspiration is required in hydrological studies and water resources modeling of stationary and changing climatic conditions. Most meteorological stations record rainfall, but few estimate potential and/or actual evapotranspiration despite it been important parameter in climatology. The potential evapotranspiration rate has been used almost as an estimate of the water required by crops and in determining the aridity of a climate. Actual water losses from land surfaces are strongly influenced by the supply of moisture in the soil (Denmead and Shaw, 1962).

Evapotranspiration estimates are needed in a wide range of problems in hydrology, agronomy, forestry and land management, and water resources planning, such as water balance computation, irrigation management, river flow forecasting, investigation of lake chemistry, ecosystem modeling, etc. Reliable estimates of evapotranspiration are also essential for the improvement of atmospheric circulation models (Yates, 1997).

Estimation of evapotranspiration using this data set in the study region has never been done. Results from the study will however, serve as a benchmark for future research.

1.1 Main objective

This study seeks to analyze point estimation of evapotranspiration using five well-known models. The estimation approaches are selected and applied to watersheds in Nemcice station in the Czech Republic. The selected approaches used to estimate Potential evapotranspiration are; radiation approach (Priestley-Taylor model, 1972); the Tuc method (Turc, 1961); and single source approach (Penman-Monteith model, 1964). In estimating actual evapotranspiration, the Advection- Aridity model (Brutsaert and Stricker, 1979), Granger and Gray models (Granger and Gray, 1989) are the approaches used. The goal of this study is therefore to evaluate and compare these well-known evapotranspiration estimation models in Nemcice meteorological station in the Czech Republic.

1.2 Structure

The reminder of this thesis is organized as follows: the literature review is described in the second section; the study region, the evapotranspiration models and the calculation schemes are described in the third section. The results are explicitly given in the fourth section. The discussions and conclusion are given in the fifth and sixth sections respectively.

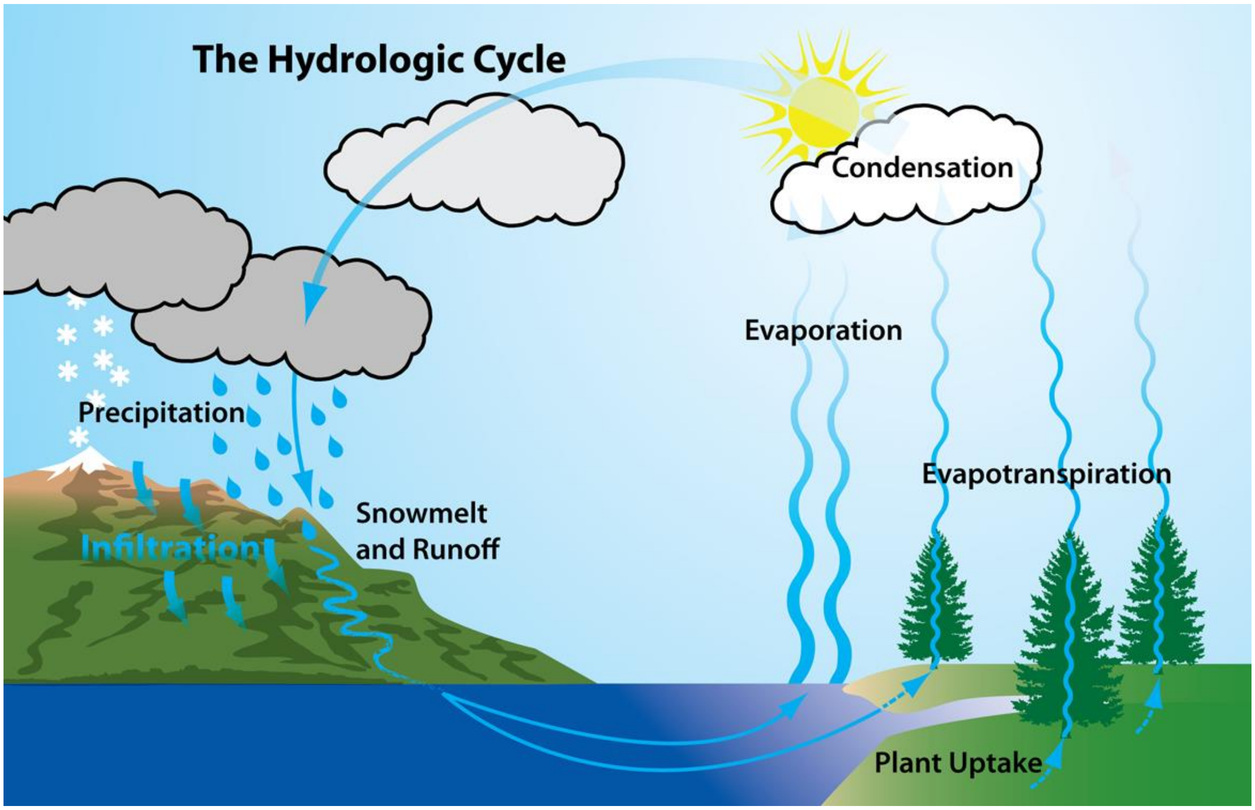
CHAPTER TWO

2. LITERATURE REVIEW

2.1 Hydrologic Cycle

Hydrology is concerned with quantifying the various components into which rainfall is partitioned and understanding the physical processes by which water is eventually returned to the atmosphere (Figure 1). The cycle through which rainfall passes before being returned to the atmosphere is termed the 'hydrological cycle'. The cycle can be, and has been, modified radically in many places by man's activities. It is subject to the vagaries of rainfall input and to climatic change. On the other hand, great strides have been made during the last 35 years in determining the nature of the physical processes and their interactions (Shuttleworth, 2012, Dingman, 2015).

Figure 1 Hydrological Cycle



Source: Burman and Pochop, 1994.

2.2 Interception

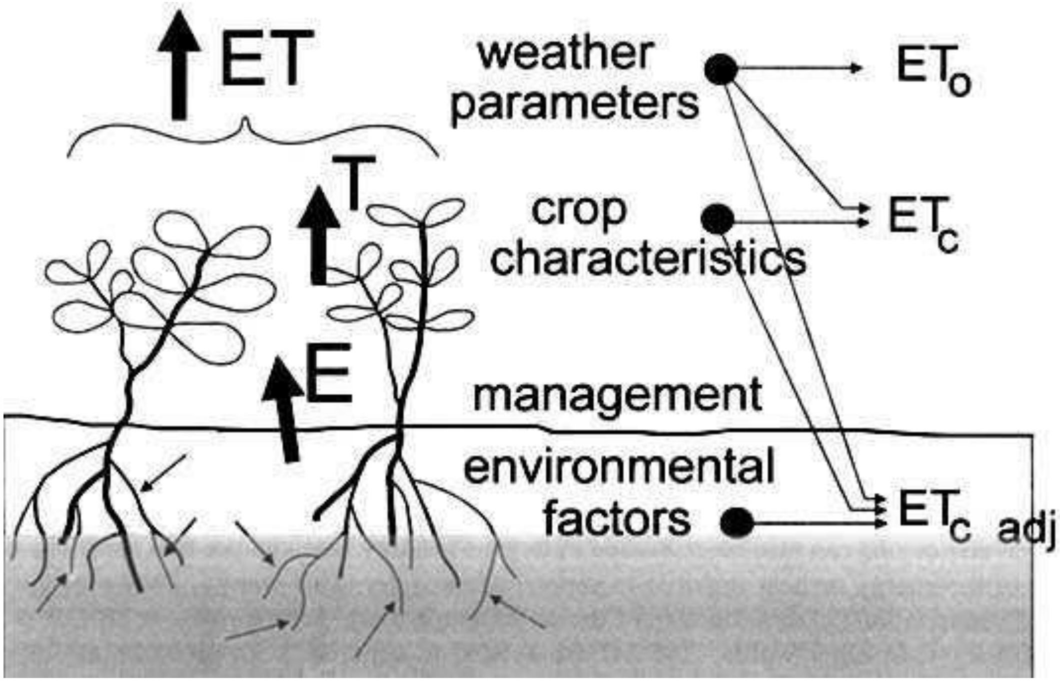
Not all precipitation reaching the land surface is available for streamflow or replenishing ground water. Rather, a portion is temporarily stored on vegetation where it is subject to evaporation. The temporal water stored on vegetation is termed as intercepted water. If we consider the total amount of precipitation (gross precipitation) delivered to a point within a land area (p), such as might be measured by a tipping bucket gage placed in a clearing or above a forest canopy, some of the water will fall between plants to land on bare ground or ground covered by lower vegetation or leaf litter, and some will run down the stems and trunks of plants to the ground surface. Precipitation stored by the canopy or leaf is subject to evaporation. We can define total interception (I_T) as the sum of the canopy interception (I_c) and litter interception(I_I) (Hornberger et al., 2014).

Intercepted moisture, stored in the canopy, is the first component of the hydrological cycle to be lost directly back to the atmosphere. In areas of high wind speed, with aerodynamically 'rough' canopies, this loss can be very rapid and in areas where the canopy is frequently wetted, the total quantity of intercepted water lost by evaporation can be a significant proportion of the total rainfall.

Interception of raindrops by canopies is also a major factor in reducing soil erosion. This has an indirect effect on the hydrological cycle, in that by conserving surface soil, infiltration is maintained. In areas of shorter vegetation interception storage is likely to be small, and the rate of loss may not exceed the potential evaporation rate. Thus, in rangelands, interception storage is unlikely to be a measurable quantity in the water balance. Many dry-season grazing areas, however, depend on perennial springs for water supply (Shaw, 1994).

2.3 Evapotranspiration; Evaporation and Transpiration

Figure 2: Evapotranspiration Process



Source: Allen et al., (1998)

Evapotranspiration varies due to wind, temperature, humidity, and water availability. Evapotranspiration is an important process in the water cycle because it is responsible for 15% of the atmosphere's water vapor (Burman and Pochop, 1994). Without that input of water vapor, clouds cannot form and precipitation would never fall.

Evapotranspiration(ET) is the combined name for the processes of evaporation(E) and transpiration(T) as shown in figure 2. When water vapor is released into the atmosphere both processes are involved, so they have been combined into one word to cover all bases. The evaporation in evapotranspiration refers to water evaporated from over land. This includes evaporation from soil, wetlands, and standing water from places like roofs and puddles. It can also refer to direct evaporation of liquid water from the leaf surface of the plant (Allen et al., 1998; Goyal and Harmsen, 2013; Shuttleworth, 2012).

Transpiration occurs when plants release water vapor from stomata in their leaves. This is caused in part by the chemical and the biological changes that occur as plants undergo photosynthesis and converts carbon dioxide into oxygen. Transpiration performs the same function as human sweating because plants do it to cool down their leaves (Shuttleworth, 2012).

Crop evapotranspiration under non-standard condition ($ET_{c\ adj}$) is the evapotranspiration from crops grown under management and environmental conditions that differ from the standard conditions. When cultivating crops in fields the real crop evapotranspiration may deviate from crop evapotranspiration (ET_c) due to non-optimal conditions such as the presence of pest and diseases, soil salinity, low soil fertility, water shortage or water logging. This may result in scanty plant growth, low plant density and may reduce the evapotranspiration rate below ET_c.

2.3.1 Potential Evapotranspiration (ET_p)

The potential evapotranspiration concept was first introduced in the late 1940s and 50s by Penman. Per Penman (1948), potential evapotranspiration rate is not related to a specific crop. The main confusion with the potential evapotranspiration definition is that there are many types of horticultural and agronomic crops that fit into the description of short green crop. So, scientists may be confused as to which crop should be selected to be used as a short green crop because the evapotranspiration rates from well-watered agricultural crops may be as much as 10 to 30% greater than that occurring from short green grass (Lawson, 1967).

2.3.2 Actual Evapotranspiration (ET_a)

The actual evapotranspiration represents the actual rate of water uptake by the plant, which is determined by the level of available water in the soil and combines simultaneously both evaporative losses from the soil surface and transpiration from the plant surface (Rijtema, 1965).

Under non-irrigated conditions it is assumed to be equal to the potential crop evapotranspiration (ET_c), in those periods of the year when precipitation exceeds potential evapotranspiration or when there is enough water stored in the soil to allow maximum evapotranspiration and thus to fulfill the crop water requirement. In drier periods of the year, when the available soil moisture is reduced below a certain level, lack of water reduces actual evapotranspiration to an extent depending on the available soil moisture. For open water or wetland, actual evapotranspiration can exceed precipitation. It is also sometimes referred to as the water balance under natural conditions (non-irrigated conditions) (Jackson, 1982).

2.3.3 Reference Evapotranspiration (ET_o)

Reference evapotranspiration is defined as the rate of evapotranspiration from a hypothetical reference crop with an assumed crop height of 0.12 m (4.72 inch), a fixed surface resistance of 70 sec m^{-1} (70 sec $3.2ft^{-1}$) and an albedo of 0.23, closely resembling the evapotranspiration from an extensive surface of green grass of uniform height, actively growing, well-watered, and completely shading the ground (Brown, 2000).

In the reference evapotranspiration definition, the grass is specifically defined as the reference crop and this crop is assumed to be free of water stress and diseases. In literature, the terms “reference evapotranspiration” and “reference crop evapotranspiration” have been used interchangeably and they both represent the same evapotranspiration rate from a short, green grass surface (Brown, 2000).

By adopting a reference crop (grass), it has become easier and more practical to select consistent crop coefficients and to make reliable actual crop evapotranspiration (ET_a) estimates in new areas. Crop coefficients are properties of plants used in predicting evapotranspiration. The most basic crop coefficient, K_c is the ratio of ET observed for the crop studied over that observed for the well calibrated reference crop under the same conditions (Stannard et al., 2013). Introduction of the reference evapotranspiration concept also helped to enhance the transferability of the crop coefficients from one location to another. In addition, with using reference evapotranspiration, it is easier to select consistent crop coefficients and to calibrate evapotranspiration equations for a given local climate (Allen et al., 1998; Snyder, 1992; Singo et al., 2016).

2.4 Factors affecting Evapotranspiration

Temperature – As temperature increases, the rate of evapotranspiration increases. Evaporation increases because there is a higher amount of energy available to convert the liquid water-to-water vapor. Transpiration increases because at warmer temperatures plants open their stomata and release more water vapor (Henry, 2007; Bell, 2011).

Air Humidity – If the air around the plant is too humid, the transpiration and evaporation rates drop. While the energy supply from the sun and surrounding air is the main driving force for the vaporization of water, the difference between the water vapor pressure at the evapotranspiring surface and the surrounding air is the determining factor for the vapor removal (Allen et al., 1996).

Wind speed – If the air is moving, the rate of evaporation will increase. The wind will also clear the air of any humidity produced by the plant's transpiration, so the plant will increase its rate of transpiration (Peterson et al., 1995).

Water availability – If the soil is dry and there is no standing water there will be no evaporation. If plants cannot get enough water, they will conserve it instead of transpiring by closing their stoma (Allen et al., 1996).

Soil type – Soil type determines how much water soil can hold and how easy it is for the water to be drawn out of it, either by a plant or by evaporation. For areas where the ground is covered by vegetation, the rate of transpiration is considerably higher than the rate of evaporation from the soil (Campbell, 1971).

Plant type – Some plants, like cacti and other succulents, naturally hold onto their water and do not transpire as much. Trees and crops are on the other end of the spectrum and can release water vapor in a year. Copious amounts of water vapor in a day. For example, an acre of corn can release 4,000 gallons of water vapor a day and a single large oak tree can transpire 40,000 gallons of water. If evapotranspiration rates are predicted, one will be able to estimate the water demands of the crop. If crops do not receive enough water, their leaves may curl and their production decline as the plants fight to conserve what water they can use. Knowledge of predicted temperature and wind conditions from weather forecasts can give you a clue to how strong the evapotranspiration rates will be (Penman, 1963).

Evaporation may also directly affect soil moisture conditions. If there is too much moisture in the soil, the farm machinery can get bogged down because it must work too hard. The weight of the machinery can also compact the wet soil, leading to lack of air for healthy root systems to develop. If the soil is too dry, however, the plants may be easily stressed due to the lack of available water and a crust may sometimes form on top of the soil. This crust may be so impermeable that when it rains on top of the crusty soil, the rain runs right off rather than soaking in (Allen et al., 1996).

2.5 Atmospheric Parameters affecting evapotranspiration

2.5.1 Atmospheric Pressure (P)

The atmospheric pressure, P, is the pressure exerted by the weight of the earth's atmosphere. Evaporation at high altitudes is promoted due to low atmospheric pressure as expressed in the psychometric constant. The effect is, however, small and in the calculation procedures, the average value for a location is sufficient (Brutsaert, 1982).

2.5.2 Latent heat of vaporization (λ)

The latent heat of vaporization, λ, expresses the energy required to change a unit mass of water from liquid to water vapor in a constant pressure and constant temperature process. The value of the latent heat varies as a function of temperature. At a high temperature, less energy will be required than at lower temperatures (Garratt and Hicks, 1973). As λ varies only slightly over normal temperature ranges, a single value of 2.45 MJ kg^{-1} is taken in the simplification of the FAO Penman-Monteith equation. This is the latent heat for an air temperature of about 20°C.

2.5.3 Psychometric constant (g)

The ratio of specific heat (C_p) of moist air at constant pressure to latent heat (L_v) of vaporization of water. This constant has a value of $\gamma = C_p/L_v \cong 0.4$ (g_{water}/kg_{air}) K^{-1}. Latent heat flux, when multiplied by this constant, yields a moisture flux.

2.6 Measurement of Evapotranspiration (ET_o)

Evapotranspiration is not easy to measure. Specific devices and accurate measurements of various physical parameters or the soil water balance in lysimeters are required to determine evapotranspiration. The methods are often expensive, demanding in terms of accuracy of measurement and can only be fully exploited by well-trained research personnel. Although the methods are inappropriate for routine measurements, they remain important for the evaluation of ET estimates obtained by more indirect methods (Itier, 1996).

2.6.1 Energy balance and microclimatological methods

Any evaporation occurring during Δt must be balanced by some combination of heat inputs from radiation or sensible heat from the atmosphere or ground, and/or a loss of heat energy (i.e., a temperature reduction) in the evaporating body (Dingman, 2015). The energy arriving at the surface must equal the energy leaving the surface for the same time (Kizer et al., 1990).

The equation for an evaporating surface (energy balance) during a period Δt can be written as:

$$LE = K + Rn - G - H + A_w - \frac{\Delta Q}{\Delta t} \tag{1}$$

Where the first six terms represent average energy fluxes via the following modes: evaporation, LE; net shortwave radiation input, Rn: net output via conduction to the ground, G: net output of sensible heat exchange with the atmosphere, H: net input associated with inflows and outflows of water (water-advected energy). A_w: and ΔQ is a change in the amount of heat stored in the body per unit area between the beginning and the end of Δt(Dingman, 2015, Perrier et al., 1976).

In some situations, the atmospheric conditions above the evapotranspiring region are representative of an extensive area extending beyond the region, and there is no significant horizontal transport of energy by air movement to or from the area above the region (i.e., the water-atmosphere heat exchange is in approximate local equilibrium). When such equilibrium does not exist, horizontal air flow supply air-advected energy to the air over-lying the region to maintain the energy balance (Dingman, 2015).

Another method of estimating evapotranspiration is the mass transfer method. This approach considers the vertical movement of small parcels of air (eddies) above a large homogeneous surface. The eddies transport material (water vapor) and energy (heat, momentum) from and towards the evaporating surface. By assuming steady state conditions and that the eddy transfer coefficients for water vapor are proportional to those for heat and momentum; the evapotranspiration rate can be computed from the vertical gradients of air temperature and water vapor via the Bowen ratio (Blad and Rosenberg, 1974).

Other direct measurement methods use gradients of wind speed and water vapor. These methods and other methods such as eddy covariance require accurate measurement of vapor pressure, and air temperature or wind speed at various levels above the surface. Therefore, their application is restricted to primarily research situations (Blad and Rosenberg, 1974).

2.6.2 Soil water balance

Evapotranspiration can also be determined by measuring the various components of the soil water balance. The method consists of assessing the incoming and outgoing water flux into the crop root zone over some time. Irrigation (I) and rainfall (P) add water to the root zone. Part of I and P might be lost by surface runoff (RO) and by deep percolation (DP) that will eventually recharge the water table (Ketema and Leonard, 2012).

Water might also be transported upward by capillary rise (CR) from a shallow water table towards the root zone or even transferred horizontally by subsurface flow in (SF_{in}) or out of (SF_{out}) the root zone. In many situations, however, except under conditions with large slopes, SF_{in} and SF_{out} are minor and can be ignored. Soil evaporation and crop transpiration deplete water from the root zone. If all fluxes other than evapotranspiration (ET) can be assessed, the evapotranspiration can be deduced from the change in soil water content (D SW) over the period:

$$ET = I + P - RO - DP + CR \pm D\ SF \pm DSW \tag{2}$$

Some fluxes such as subsurface flow, deep percolation and capillary rise from a water table are difficult to assess and short time periods cannot be considered. The soil water balance method can usually only give ET estimates over long time periods of the order of week-long or ten-day periods (Ketema and Leonard, 2012).

2.6.3 Lysimeters

By isolating the crop root zone from its environment and controlling the processes that are difficult to measure, the different terms in the soil water balance equation can be determined with greater accuracy. This is done in lysimeters where the crop grows in isolated tanks filled with either disturbed or undisturbed soil (Grebet and Cuenca, 1991). In precision weighing lysimeters, where the water loss is directly measured by the change of mass, evapotranspiration can be obtained with an accuracy of a few hundredths of a millimeter, and small time periods such as an hour can be considered. In non-weighing lysimeters the evapotranspiration for a given period is determined by deducting the drainage water, collected at the bottom of the lysimeters, from the total water input (Allen et al., 1991).

A requirement of lysimeters is that the vegetation both inside and immediately outside of the lysimeter be perfectly matched (same height and leaf area index). This requirement has historically not been closely adhered to in most lysimeters studies and has resulted in severely erroneous and unrepresentative ET_c and K_c data (Allen et al., 1991).

As lysimeters are difficult and expensive to construct and as their operation and maintenance require particular care, their use is limited to specific research purposes.

2.7 Pan Evaporation

The evaporation rate from pans filled with water is easily obtained. In the absence of rain, the amount of water evaporated during a period (mm/day) corresponds with the decrease in water depth in that period (Christiansen, 1968).

Pans provide a measurement of the integrated effect of radiation, wind, temperature and humidity on the evaporation from an open water surface. Although the pan responds in a similar fashion to the same climatic factors affecting crop transpiration, several factors produce significant differences in loss of water from a water surface and from a cropped surface (Chiew and McMahon, 1992).

Reflection of solar radiation from water in the shallow pan might be different from the assumed 23% for the grass reference surface. Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime (Christiansen, 1968). There are also differences in turbulence, temperature and humidity of the air immediately above the respective surfaces. Heat transfer through the sides of the pan occurs and affects the energy balance (Thom et al., 1981).

Notwithstanding the difference between pan-evaporation and the evapotranspiration of cropped surfaces, the use of pans to predict ET_o for periods of 10 days or longer may be warranted (Thom et al., 1981). The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient:

$$ET_o = K_p\, E_{pan} \tag{3}$$

Where, ET_o = reference evapotranspiration [mm/day],
K_p = pan coefficient [-]
E_{pan} = pan evaporation [mm/day].

2.8 ET computed from meteorological Data

Owing to the difficulty of obtaining accurate field measurements, ET is commonly computed from weather data. Many empirical or semi-empirical equations have been developed for assessing crop or reference crop evapotranspiration from meteorological data (Allen et al., 1989). Some of the methods are only valid under specific climatic and agronomic conditions and cannot be applied under conditions different from those under which they were originally developed.

Numerous researchers have analyzed the performance of the various calculation methods for different locations. Because of an Expert Consultation held in May 1990, the FAO Penman-Monteith method is now recommended as the standard method for the definition and computation of the reference evapotranspiration, ET_o (Allen et al., 1994a). The ET from crop surfaces under standard conditions is determined by crop coefficients (K_c) that relate ET_c to ET_o. The ET from crop surfaces under non-standard conditions is adjusted by a water stress coefficient (K_s) and/or by modifying the crop coefficient (Allen et al., 1994).

2.9 Related Models in Estimating Evapotranspiration and their outcomes

Several attempts to calculate evapotranspiration has been done by many authors with many different models. An example is the study which evaluates seven evapotranspiration models and their performance in water balance studies by using lysimeter measurement data at the Monchengladbach hydrological and meteorological station in Germany (Xu and Chen, 2005).

Seven evapotranspiration models were evaluated, three models calculate actual evapotranspiration directly using the complementary relationship approach, i.e. the CRAE model of Morton, the advection-aridity (AA) of Brutsaert and Stricker, the GG model of Granger and Gray. The four other models calculate first the potential evapotranspiration and then actual evapotranspiration by considering soil moisture condition. Two of the four potential evapotranspiration models belong to the temperature-based category, i.e. the Thornthwaite model, the Hargreaves model and the other two belong to the radiation-based category, i.e. the Makkink model and the Priestley-Taylor model. The evapotranspiration calculated by the above seven models, together with precipitation, is used in the water balance model to calculate other water balance components (Xu and Chen, 2005).

The results show that, for the calculation of actual evapotranspiration, the GG model and the Makkink model performed better than the other models. For the calculation of groundwater recharge using the water balance approach, the GG model and the AA model performed better; for the simulation of soil moisture content using the water balance approach, four models (GG, Thornthwaite, Makkink and Priestley-Taylor out of the seven give equally good results (Xu and Cheng, 2005). It was concluded that lysimeter measured water balance components, i.e. actual evapotranspiration, groundwater recharge, soil moisture etc. can be predicted by the GG model and the Makkink model with good accuracy (Xu and Cheng, 2005).

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Experimental site

Figure 3 Map of Czech Republic showing the study area

Source: Google map

Němčice is a village in Domažlice District in the Plzeň Region of the Czech Republic. The municipality covers an area of 8.92 square kilometers (3.44 sq. mi), and has a population of 130 (as at 3 July 2006). Němčice lies approximately 11 km (7 mi) east of Domažlice, 43 km (27 mi) south-west of Plzeň, and 123 km (76 mi) south-west of Prague. Nemcice has a meteorological station owned by the Czech University of Life Sciences. This catchment area is 2 sq. km in size and can be located using 49°271’650’N 13° 267’9081’E coordinates. The elevation of this area is 590m above mean sea level. The vegetation of the catchment is primarily grass usually cut to 30cm above the soil surface. In addition, a stream lies 25m from the catchment area (study site). Trees dominate riparian vegetation and they are pruned four times in a year to allow easy and effective data collection.

3.2 Data Collection

Data collection was made at the Nemcice station in the Czech Republic within a time series of one year in every 15 minutes. For this study data obtain from April to October will be used. The meteorological data include air temperature (T ^{o}C) wind speed (m/s), and soil temperature (^{o} C) and parameters for estimation pan evaporation which includes water level, depth of rainfall and depth of pan immersed into the soil. All data are averaged into 7 month’s period. The latent heat flux can be measured directly using a variety of methods.

However, it is recognized that it is more reliable for long-term measurements to estimate from other more-easily measured fluxes that is incoming and outgoing radiation (Choudhury, 1987). However, the reflection coefficient (albedo) is used to estimate the solar net radiation as

$$R_{ns} = 1 - albedo(R_n) \tag{4}$$

Where R_n = Incoming solar radiation

Potential and actual evaporation would be calculated from this data. To estimate effectively evapotranspiration especially when the data lacks certain parameters, detailed references is made from tables and estimated values from FAO in Allen et al., (1998) and other related research works. The data is converted to CSV file for easy usage in R studio software. Microsoft excel 2016 was used to display the histogram and Correlations between the Data and the models.

3.3 Methods

Flux (ground heat and net radiation) and meteorological data measured from Nemcice station in the Czech Republic from April to October were used to obtain the monthly actual evapotranspiration and to compare the monthly, daily and hourly evapotranspiration estimated from radiation approach; Priestley-Taylor model (Priestley-Taylor, 1972); mass transfer approach single source approach; adjusted Penman-Monteith model (Penman-Monteith, 1948) and temperature approach, while the complementary approaches are the AA model (Brutsaert and Stricker, 1979), G.G model (Granger and Gray, 1989).

The numerical, statistical tests, root mean square error (RMSE), mean absolute error (MAE) and others were applied. For graphical tests, time series plots were used. Each of these models and how they work is explained in detailed;

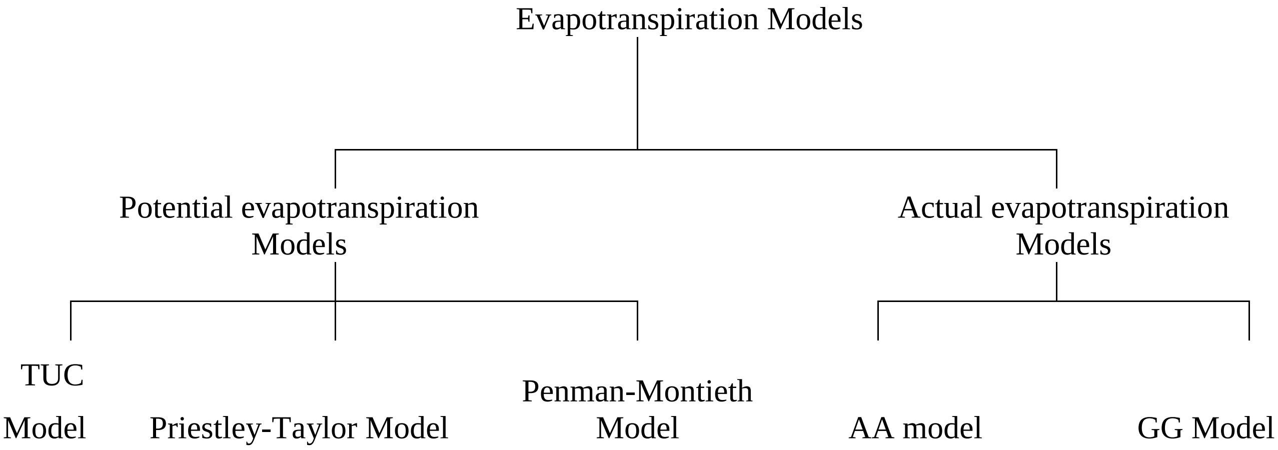


Figure 4 Schematic representation of Evapotranspiration Models

3.4 Potential Evapotranspiration models

Potential evapotranspiration (ET_p) models generally rely on micrometeorological data such as air temperature, radiation, wind speed and humidity. Of the great variety of ET_p models, three equations were chosen for evaluation in this study: The Penman–Monteith (PM) method (Penman, 1948 and Monteith, 1965), the Priestley–Taylor (PT) method (Priestley and Taylor, 1972), and the Turc (Tuc) method (Turc, 1961).

These three equations span the spectrum in data requirements from the complex PM method (requiring net radiation, soil/canopy heat flux, air temperature, humidity, and aerodynamic and surface resistance) to the less data-intensive PT method (requiring net radiation, soil heat flux, and air temperature) to the simple Tuc method (requiring air temperature and solar radiation). Generally, the more complicated and physically-based ET_p methods give the best results, but at the expense of greater data, model parameter requirements and climatic conditions of the area.

3.4.1 The Tuc model

The Turc method can be used to estimate Evapotranspiration under humid conditions because of its simplicity of the method and moderate data requirements. From Trajkovic and Vladmir, (2007), study in humid regions in 7 European countries, it was found that the reliability of Turc model depends on the wind speed. Turc method underpredicted Evapotranspiration at windy locations.

This method was developed in Western Europe for regions where the relative humidity is greater than 50%, expresses ET_p as

$$\lambda\rho_{\omega}ET_o = 0.369\frac{\mathrm{T}avg}{\mathrm{T}avg+15}(2.06R_{ns} + 50) \tag{5}$$

Where, ET_o is the potential evapotranspiration (mm day^{-1}), the latent heat λ of vaporization (here held constant at 2.451 MJ kg^{-1}), ρ_w the density of water (kg m^{-3}) R_s the daily solar radiation (W m^{-2}), and T_{avg} the mean daily air temperature °C (Turc, 1961).

3.4.2 The Priestley Taylor method

It is widely used in estimating evapotranspiration for its robust ability to capture evapotranspiration and simplicity of used (Priestly, 1972). The key point in successfully use the Priestly-Taylor model is to find a proper PT coefficient, which is variable under different environmental conditions (Zhipin and Yonghui, 2016).

This uses the concept of the theoretical lower limit of evaporation from a wet surface as the "equilibrium" evaporation to estimate ET_p where

$$\lambda\rho_{\omega}ETo = \alpha\frac{\Delta}{\Delta+\gamma}(Rn - G) \tag{6}$$

Where, Δ is the slope of the saturation vapor pressure temperature curve, γ is the psychometric constant, R_n is the net radiation (W m^{-2}), and G is the soil/canopy heat flux (W m^{-2}). Priestley and Taylor (1972) showed that for conditions of minimum advection with no edge effects, $\alpha = 1.26$. Here G is assumed to equal zero over the course of a day. The parameters Δ (in kPa °C), λ (MJ kg^{-1}) and γ (in kPa °C) were computed as

$$\Delta = \frac{4098\ e_s}{(237.3+\mathrm{T})} \tag{7}$$

$$\lambda = 2.501 - 0.002631 * \mathrm{T_{avg}} \tag{8}$$

$$\Upsilon = 0.0016286\frac{\mathrm{C}}{\lambda} \tag{9}$$

where e_s is the saturated vapor pressure (in kPa), c_p is the specific heat of moist air (1.013 kJ kg^{-1} $°C^{-1}$), P is atmospheric pressure (set equal to 101.3 kPa) and Tmin is the minimum daily temperature (in °C), respectively. Saturated vapor pressure was computed as

$$e_s = 0.6108 \exp \frac{(17.27\mathrm{T_{min}})}{(237.3+\mathrm{T_{min}})} \tag{10}$$

3.4.3 The Penman–Monteith Model

It is an extension of the Penman equation (1948) for application to vegetated surfaces through the introduction of plant specific resistance factors and is given as

$$\lambda \rho_{\omega} ETo = \frac{\Delta(\mathrm{Rn}-\mathrm{G})+\rho_{\mathrm{a}}\mathrm{C}\frac{\mathrm{PD}}{\Gamma\mathrm{a}}}{\Delta+\gamma\left(1+\frac{\Gamma\mathrm{s}}{\Gamma\mathrm{a}}\right)} \tag{11}$$

where, D is the vapor pressure deficit of the air (in kPa), ρ_a is the mean air density (kg m^{-3}), r_s the bulk surface resistance (s m^{-1}), and r_a the aerodynamic resistance (s m^{-1}). The mean air density, ρ_a, was computed using

$$\rho_a = 3.486 \frac{\mathrm{P}}{275+\mathrm{T_{avg}}} \tag{12}$$

Where, P was set equal to a constant value of 101.3 kPa and T_{avg} was the average daily temperature (in °C). The vapor pressure deficit, D, was computed as $e_s - e$, where e is the observed daily vapor pressure and e_s is saturated vapor pressure. The aerodynamic resistance was computed using Monin–Obukhov similarity

$$r_a = \frac{In\left[\frac{\mathrm{Zu-d}}{\mathrm{Zom}}\right] In\left[\frac{\mathrm{Ze-d}}{\mathrm{Zov}}\right]}{K^2 U} \tag{13}$$

Where, u is the wind speed (in m s^{-1}) and z_u is the height at which the wind speed was measured, z_e is the height of the vapor pressure/relative humidity instrument, d is the displacement height (approximated as $0.67h_c$, where h_c is the average vegetation height), z_{om} is the roughness height for momentum, z_{ov} is the roughness height for water vapor (approximated as $0.1z_{om}$) and k is von Karman’s constant (0.41). Literature values were used for z_{om}, because using a relationship between z_{om} and canopy height is not appropriate for all land cover types. Height of wind measurement (z_u), height of vapor pressure/relative humidity measurement (z_e) and average canopy height (h_c) were obtained from the personnel responsible for collecting the data. The terms z_u and z_e were assumed equal unless otherwise noted (Goyal, et al., 2013; Allen et al., 1994).

For open water sites, aerodynamic term was estimated following Shuttleworth (1993):
open water aerodynamic term(mmd^-1)

$$r_a = \frac{\gamma}{\Delta+\gamma}\frac{6.43(1+0.536U)D}{\lambda} \tag{14}$$

which incorporates the r_a formulation for open water as

$$r_a^p = \frac{4.72[In\left(\frac{Zm}{Zo}\right)]}{1+0.536u} \tag{15}$$

where z_m is a standardized measurement height of 2 m and $z_o = 0.00137$ m.

For grass/pasture sites, we computed r_s using the functions developed by Sumner and Jacobs (2005):

$$g_s = f(D)g_{max}(Rn) \tag{16}$$

$$f(D) = -0.1661n(D) + 0.235 \tag{17}$$

$$g_{max} = 5.39 * 10^{-5}R_n + 0.0033 \tag{18}$$

Where, g_s is bulk surface conductance (in m s^{-1}), D is vapor pressure deficit (in kPa) and $g_{\max}$ is the maximum bulk surface conductance. Bulk surface resistance for grass (r_s, in s m^{-1}) is the reciprocal of g_s. Average bulk surface resistance for the grass/pasture sites, calculated for each site, ranged from 284 to 319 s m^{-1}, which is consistent with published values. The published value of r_s for marsh/wetland vegetation is 55 s m^{-1} and r_s for open water is zero. For marsh and wetland sites, r_s was computed as a weighted average based on the proportion of vegetated area and open water area.

3.5 Description of Actual Evapotranspiration models based on Potential Evapotranspiration

The complementary relationship has formed the basis for the development of some evapotranspiration models (Morton, 1983, Brutsaert and Stricker, 1979 and Granger and Gray, 1989), which differ in the calculation of ET_p and ET_w. ET_a is usually calculated as a residual for the sake of completeness, the model equations are briefly summarized in what follows using the same notations as used by the original authors.

For several decades, these methods have been used to estimate evapotranspiration. These methods are attractive due to its simplicity and practicability in estimating evapotranspiration using meteorological data only. The complementary method offer a distinct advantage over the classical methods given the simplicity, ready availability of required data and the ability to estimate the total water loss as opposed to crop evapotranspiration only (Anayah and Kaluarachchi, 2014)

There are many complementary methods used in estimating the actual evapotranspiration such as the CRAE model but for this study and time constraint, the Advection-Aridity and Granger and Gray models were used.

3.5.1 The Advection-Aridity model

In the Advection-Aridity model(AA), the ET_p is calculated by combining information from the energy budget and water vapor transfer in the Penman (1948) equation

$$ET_p = \frac{\Delta}{\Delta+\Upsilon}\frac{Rn}{\lambda} + \frac{\Upsilon}{\Delta+\Upsilon}Ea \tag{19}$$

Where, R_n is the net radiation near the surface, Δ is the slope of the saturation vapor pressure curve at the air temperature, γ is the psychometric constant, λ is the latent heat, and E_a is the drying power of the air which in general can be written as

$$E_a = f(U_z)(e_s - e_a) \tag{20}$$

Where, $f(Uz)$ is some function of the mean wind speed at a reference level z above the ground; and e_a and e_s are the vapor pressure of the air and the saturation vapor pressure at the air temperature, respectively.

In this study, Penman (1948) originally suggested an empirical linear approximation for f (U_2) which was used here

$$f(U_2) \approx f(U_2) = 0.0026(1 + 0.54U_2) \tag{21}$$

which for wind speeds at 2-m elevation in m/s and vapor pressure in Pa, yields E_a in mm/day. This formulation of $f(U_2)$ was first proposed by Brutsaert and Stricker (1979) for use in the Advection-Aridity model operating at a temporal scale of a few days. ET_p used by Brutsaert and Stricker (1979) in the original AA model:

$$ET_P^{AA} = \frac{\Delta}{\Delta+\Upsilon}\frac{Rn}{\lambda} + \frac{\gamma}{\Delta+\gamma}f(e_s - e_a) \tag{22}$$

The Advection-Aridity model calculates ET_w (Brutsaert and Stricker, 1979) using the Priestley and Taylor (1972) partial equilibrium evapotranspiration equation

$$ET_w^{AA} = \alpha \frac{\Delta}{\Delta+\Upsilon} \frac{Rn}{\lambda} \tag{23}$$

Where, α=1.26. Different values for *α* have been reported in the literature, the original value was first tested in this study the AA model:

$$ET_a^{AA} = (2\alpha - 1) \frac{\Delta}{\Delta+\gamma} \frac{Rn}{\lambda} - \frac{\gamma}{\Delta+\gamma} f(U_2)(e_s - e_a) \tag{24}$$

3.5.2 The Granger and Gray model

Granger (1989) showed that an equation like Penman could also be derived following the approach of Bouchet's (1963) complementary relationship. Granger and Gray (1989) derived a modified form of Penman's equation for estimating the actual evapotranspiration from different non/saturated land covers

$$ET_a^{GG} = \frac{\Delta G}{\Delta G+\Upsilon} \frac{Rn}{\lambda} + \frac{\Upsilon G}{\Delta \mathrm{G}+\Upsilon} E_a \tag{25}$$

Where, *G* is a dimensionless relative evapotranspiration parameter and other notations have the same meaning as in Granger and Gray (1989) showed that the relative evapotranspiration, the ratio of actual to potential evapotranspiration, $G=ET_a/ET_p$ is a unique parameter for each set of atmospheric and surface conditions. Based on daily estimated values of actual evapotranspiration from water balance, Granger and Gray (1989) showed that there exists a unique relationship between *G* and a parameter which they called the relative drying power, D_p, given as

$$D_p = \frac{Ea}{Ea+R_n} \tag{26}$$

$$G = \frac{1}{1+0.028e^{8.045D}} \tag{27}$$

Later, Granger (1998) modified to:

$$G = \frac{1}{0.793+0.20e^{4.902D}} + 0.006D \tag{28}$$

3.5.3 Pan Evaporation (E_{pan})

The estimation of evaporation using the sunken pan method from the same dataset at the meteorological station is set as the benchmark for the estimations of all the evapotranspiration models (Christiansen, 1968). The pan was dipped 30cm in the soil and because it is a controlled experiment, water was occasionally poured into the pan. The pan in this experiment is used to take information regarding water level and moisture content in the estimation of evaporation. This can be represented using the equation below;

$$\frac{\Delta(S)}{\Delta t} = I - O \tag{29}$$

Where $\frac{\Delta(S)}{\Delta t}$ = change in content level in the Pan;

I = Input which represents rainfall in this context

O = Output which represents Evaporation within this context

Figure 5: Process of Pan Evaporation using Sunken Pan Method

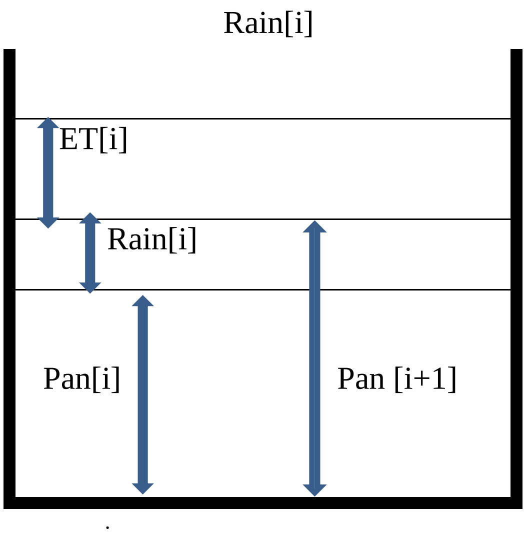


Figure 5 illustrates the process of Evaporation using the pan within a time frame [i]. Within the time frame [i], the input rain at rain[i] shows that soil level in pan is pan[i]. After input rainfall, the content within the pan is increased to pan[i+1].

The difference between pan[i+1] and pan[i] gives rise to ET[i] which represents Evaporation. From the above assumption and with a calculated pan coefficient (K) = 0.1, the best assumption was used to estimate evaporation and related directly with evapotranspiration estimates. Evaporation can be calculated as;

$$pan[i+1] = pan[i] + rain[i] - ET[i] \tag{30}$$

$$ET[i] = pan[i] + rain[i] - pan[i+1] \tag{31}$$

$$0 < ET < pan[i] + rain[i] \tag{32}$$

$pan[i+1]$ = the level of the content in pan after rain/water was added

rain [i] = the amount of rain or extra water which was put into the pan.

pan[i] = the level of the content in the pan i.e. soil level.

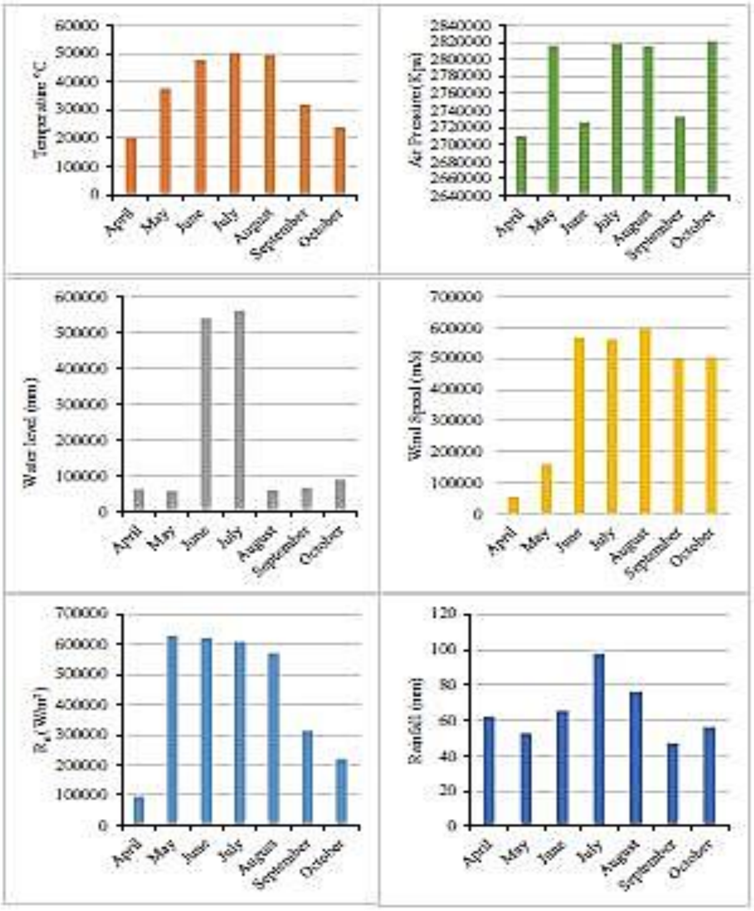
CHAPTER FOUR

4. RESULTS

4.1 Distribution of data variables

Figure 6 shows the distribution of the variables that were used in this study. Air humidity, Temperature, wind speed, water level of the evaporation pan, solar radiation and Air pressure were the variables used. The histogram below show the distribution of the variables during the study period.

Figure 6: Distribution of the variables



4.1.1 Measure of dispersion from dataset

Collection of data for this work from Nemcice station was done in 2008. For this reason, standard deviation was measured to check that the data points tend to be close to the mean (expected value) or spread out over a wider range. This was done mainly on input variables which has direct influence on Evaporation and Evapotranspiration (Table 1). Table 1 shows the standard deviation of the Data Input variables.

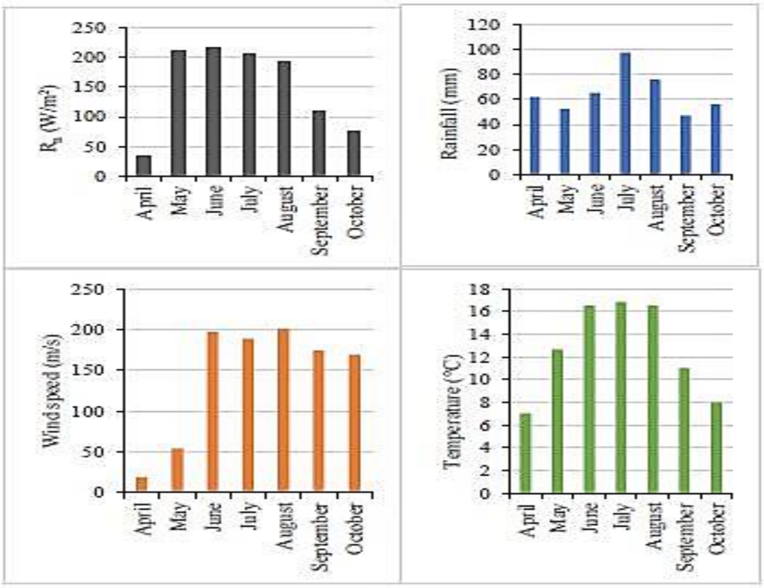
Table 1: Measure of dispersion of Data variables.

Parameters	Mean	Sd
Wind speed	143.65	121.39
Solar radiation	148.78	233.98
Temperature	25.36	18.16
Rainfall	62.05	17.11

4.2 Input variables of the dataset

Numerous studies including Brown (2000) established that four weather variables; solar radiation (amount of sunshine), wind speed, humidity and temperature impact the rate of ET. Moreover, Jensen et al., (1998) concluded that temperature is sole input of Evapotranspiration process. Below is a histogram of variables which have major influence on evapotranspiration rates from the dataset. The mean values are estimated based on the time frame to which data was worked with (April to October). Figure 7 shows mean solar radiation, mean wind speed, mean rainfall and mean Temperature in the study area**.**

Figure 7: Distribution of mean monthly values of Solar Radiation, Wind speed, Rainfall pattern and Temperature



The mean solar radiation was highest in June (215.90 W/m^2) followed by May (211.44 W/m^2) and July (204.70 W/m^2). The month of April recorded the lowest solar radiation (32.82 W/m^2). The wind speed was highest in August (201.28 m/s) followed by June (196.97 m/s). April recorded the lowest wind speed (19.14 m/s). The mean rainfall was highest in the summer month of July (97.70 mm) with September (47.05 mm) recording the lowest. Air Temperature was highest in July (16.86°C) followed by August (16.56°C) and June (16.51°C). April recorded the lowest temperature of 7.04°C.

4.3 Estimation of Potential Evapotranspiration during the warm season (April-October)

The three evapotranspiration models are applied to the data at the Nemcice Station to calculate potential evapotranspiration. The calculations are made on monthly, daily and hourly basis during the warm season of April-October. These are the months which experience high solar radiation.

The calculated potential evapotranspiration was tested against Pan Evaporation estimates (Christiansen, 1968) and are presented in Table 2 ,3, 4. To see the comparison of the models with Pan Evaporation for monthly, daily and hourly basis are presented in Figures 8,9,10,11, 12, 13,14.

Table 2 shows monthly potential evapotranspiration values and pan evaporation. Pan Evaporation values recorded for monthly, daily and hourly are the same for Potential and Actual evapotranspiration. July recorded the highest in terms of Pan Evaporation (114.51mm/month), followed by June (116.60mm/month) and September (70.09mm/month). The month of October was the lowest (18.07mm/month) and May (56.70mm/month). The TUC model estimated 79.14mm/month for July which was the highest followed by June (78.51mm/month). The month of April was the lowest of all (13.36mm/month). Comparatively PT gave the lowest estimates in May (7.17mm/month), June (1.39mm/month), July (0.55mm/month) and August (16.22mm/month). The potential evapotranspiration estimate for July (81.55mm/month) was the highest for PM with the month of October (0.87mm/month) as the lowest.

Table 2: Monthly ET_P values and Pan Evaporation

Models	MONTHLY POTENTIAL EVAPOTRANSPIRATION ESTIMATES (mm/month)							
	April	May	June	July	August	September	October	**Total**
Pan Evaporation	65.02	56.70	111.60	114.51	62.57	70.09	18.07	**72.26**
TUC	13.36	69.90	78.51	79.14	73.56	36.35	22.05	**59.92**
PT	10.56	7.17	1.39	0.61	0.55	16.22	32.14	**9.81**
PM	3.58	14.02	49.20	81.55	30.20	14.50	0.87	**27.70**

Table 3 shows daily Potential evapotranspiration and the Pan Evaporation for TUC, PT and PM models.

Table 3: Daily ET_p and Pan Evaporation values

Models	DAILY POTENTIAL EVAPOTRANSPIRATION ESTIMATES (mm/d)							
	April	May	June	July	August	September	October	**Total**
Pan Evaporation	0.43	1.83	3.72	3.70	2.02	0.46	0.58	**2.35**
TUC	0.45	2.25	2.62	2.55	2.37	1.21	0.17	**11.62**
PT	0.35	0.23	0.05	0.02	0.12	0.54	1.68	**0.43**
PM	0.12	0.45	1.64	2.63	1.30	0.50	0.03	**0.95**

The month of June (1.83mm/day) provided the highest daily Pan Evaporation value with April (0.43mm/day) being the lowest. Amongst the models, PM gave the highest daily evapotranspiration value which was in July (2.63mm/day) followed by TUC in June

(2.62 mm/day).

Table 4 shows hourly Potential Evapotranspiration as against the Pan Evaporation for TUC, PT and PM models. The hourly ET_p estimate for TUC in June and July was 0.11mm/h. This was same for PM in July. The hourly ET_p was highest in October for Priestley-Taylor. The Pan Evaporation was highest in June and July (0.15mm/h).

Table 4: Hourly ET_p and Pan Evaporation values.

Models	HOURLY POTENTIAL EVAPOTRANSPIRATION ESTIMATES (mm/h)							
	April	May	June	July	August	September	October	**Total**
Pan Evaporation	0.02	0.08	0.15	0.15	0.08	0.02	0.12	**0.09**
TUC	0.02	0.10	0.11	0.11	0.10	0.10	0.03	**0.08**
PT	0.01	0.01	0.01	0.01	0.01	0.02	0.07	**0.02**
PM	0.01	0.02	0.10	0.11	0.10	0.02	0.01	**0.05**

Table 5 shows the accuracy of the Priestly-Taylor model using RMSE, MAE, MSE and ME. The months of June and July recorded the highest error estimations using all the statistical tools while the remaining months recorded least errors (April, May, August, September and October). The MSE recorded the highest average error for the Priestly-Taylor model and the ME recorded the least average error.

Table 5: Statistical Indices for Priestly-Taylor model

Models	Month	RMSE	MAE	MSE	ME
PT	April	0.53	0.39	0.28	0.11
	May	0.35	0.26	0.12	0.14
	June	4.36	3.80	19.04	3.80
	July	4.30	3.80	19.00	3.80
	August	0.46	0.41	0.21	0.39
	September	0.82	0.49	0.67	-0.07
	October	3.06	1.49	9.35	-0.92
	Average Total	**1.98**	**1.52**	**6.95**	**1.04**

Table 6 shows the accuracy of the TUC model using RMSE, MAE, MSE and ME. The ME is the least average error for the TUC model while RMSE recorded the least average error. April recorded the least error values and July recorded the highest error estimates.

Table 6: Statistical indices for TUC model

Models	Month	RMSE	MAE	MSE	ME
TUC	April	0.55	0.29	0.29	0.06
	May	2.11	1.84	4.45	-1.84
	June	2.67	2.14	7.18	1.25
	July	3.18	2.64	10.16	1.23
	August	2.13	1.96	4.33	-1.94
	September	1.42	0.85	1.31	-0.74
	October	2.68	2.15	7.18	1.25
	Average Total	**2.10**	**1.69**	**4.98**	**-0.10**

Table 7 shows the accuracy of the PM model using RMSE, MAE, MSE and ME. The months of April and October error estimates recorded the least values as compared with June and July which recorded the highest estimated values.

Table 7: Statistical indices for PM model

Models	Month	RMSE	MAE	MSE	ME
PM	April	0.54	0.42	0.29	0.06
	May	4.35	2.42	18.90	-2.09
	June	9.74	6.02	94.77	-2.76
	July	5.27	4.45	27.74	1.15
	August	2.04	1.15	4.16	-0.88
	September	4.60	2.22	21.19	-1.57
	October	0.61	0.58	0.37	0.54
	Average Total	**3.87**	**2.46**	**23.91**	**-0.79**

From Tables 5,6,7, PT gives the smallest RMSE (1.98), followed by Tuc (2.10) with PM given the highest error (3.87).

Figures 8,9,10,11,12,13,14 show Pan Evaporation (ET), TUC model, PT model and PM model estimates from April to October.

Figure 8: ET_p estimates for ET, TUC, PT, PM for April

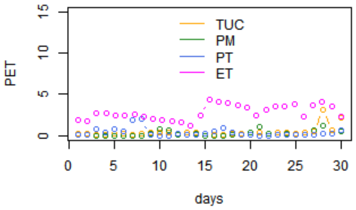


Figure 9: ET_p estimates for ET, TUC, PT, PM for May

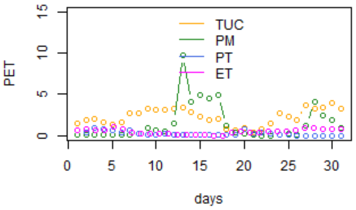


Figure 10: ET_p estimates for ET, TUC, PT, PM for June

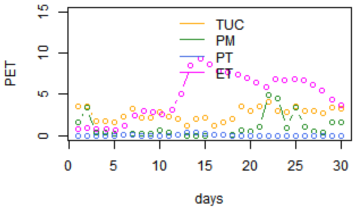


Figure 11: ET_p estimates for ET, TUC, PT, PM for July

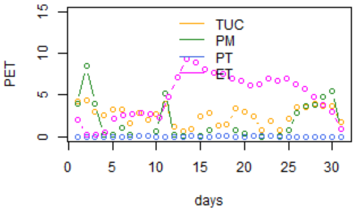


Figure 12: ET_p estimates for ET, TUC, PT, PM for August

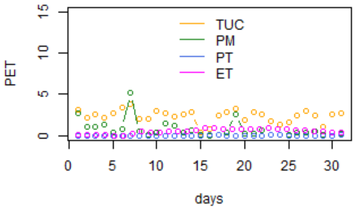


Figure 13: ET_p estimates for ET, TUC, PT, PM for Sept

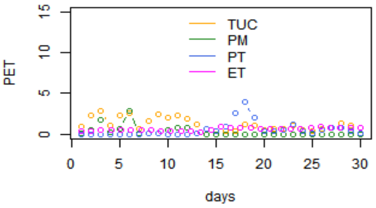
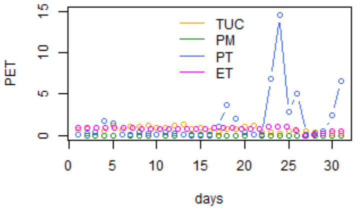


Figure 14: ET_p estimates for ET, TUC, PT, PM for October



4.4 Relationship between Potential Evapotranspiration models and data variables

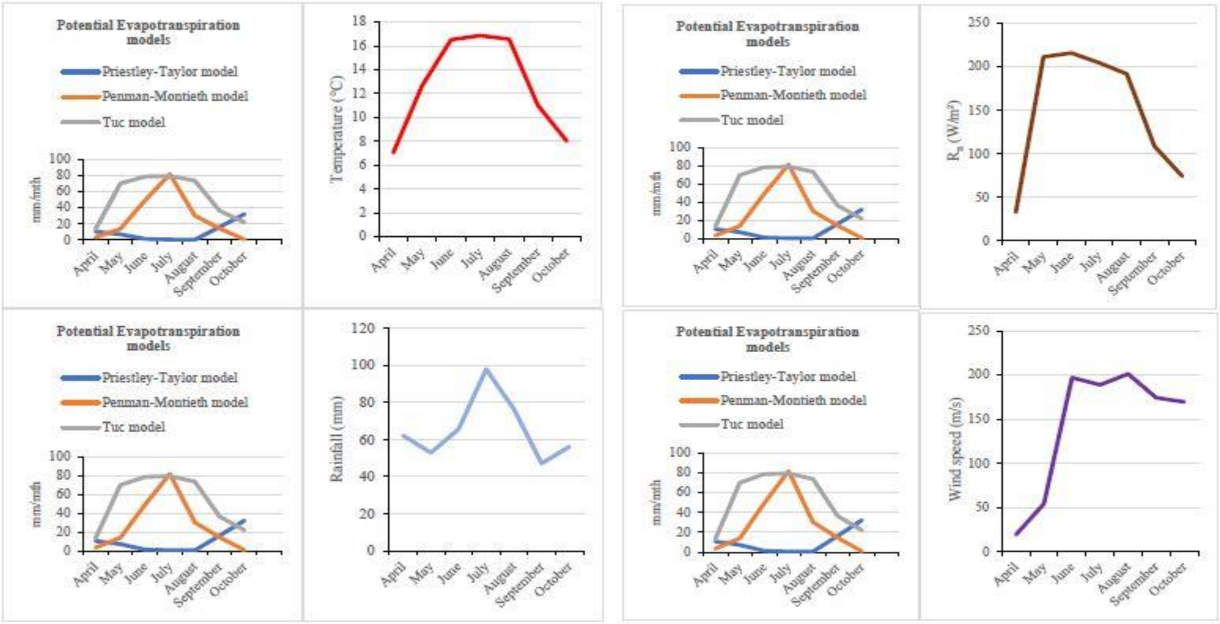
Table 8 gives the correlation coefficient (R) of TUC Model, Priestley-Taylor Model and Penman-Monteith Model with the Data Input variables**.**

Table 8: Correlation Coefficient (R) of Data variables and ET_P Models

Models	Mean Solar Radiation (W/m^2)	Mean Wind Speed (m/s)	Mean Rainfall (mm)	Mean Temperature (°C)
TUC	0.99	0.49	0.54	0.96
PT	-0.71	-0.09	-0.59	-0.79
PM	0.69	0.53	0.84	0.83

Figure 15 shows the relationship between monthly mean values from data variables and monthly estimates using Potential Evapotranspiration models in this study.

Figure 15: Relationship between Potential Evapotranspiration models and Data Variables



The Penman-Monteith has the strongest relationship with rainfall (R=0.84) and Temperature (R=0.83). The Penman -Monteith model (PM) also has a strong relationship with solar radiation (R= 0.69) and wind speed (R= 0.53). An increase or decrease in the amount of rainfall resulted in an increase or decrease in PM estimates whereas an increase in wind speed resulted in an increase in Penman-Monteith model estimates as seen in figure 15.

The TUC model has the strongest relationship with solar radiation (R= 0.99) and Temperature (R= 0.96) hence an increase or decrease in solar radiation and temperature resulted in an increase or decrease in TUC estimates. This means that the Turc model is solely dependent on the amount of solar radiation. From Table 8, rainfall has a strong relationship with TUC estimates (0.54). The relationship between wind speed and TUC is moderate (R= 0.49). This means that speed of the wind has marginal influence on TUC estimates. There was a negative correlation between Priestly-Taylor model and all the Data Input Parameters (R= -0.71; R= -0.59; R= -0.79) excluding Wind Speed. This means that an increase in any of the parameters resulted in a decrease in PT Model estimate. Table 8 shows that wind speed has no relationship with Priestley-Taylor Model (-0.09).

4.5 Correlation for Potential Evapotranspiration models

Table 9 Shows the correlation among the Potential Evapotranspiration models

Table 9: Correlation of Potential Evapotranspiration Models

	TUC	PT	PM
TUC	1	-0.77	0.76
PT	-0.77	1	-0.69
PM	0.76	-0.69	1

From the above table, Penman-Monteith has a very strong relationship with the TUC model (R=0.76). The Priestly-Taylor model negatively correlated with the Penman-Monteith and the TUC model.

4.6 Estimation of Actual Evapotranspiration during the warm season (April-October)

Two (2) actual evapotranspiration models were tested against Pan Evaporation estimates and are presented in Tables 10, 11, 12. It is seen that on monthly basis Granger and Gray (GG) model gives the smaller error compared with Advection-Aridity model (Table 13). Figures 16,17,18,19,20,21,22 illustrate further the actual evapotranspiration models (GG model and AA model) with the Pan Evaporation.

Table 10 shows the monthly actual evapotranspiration compared with Pan Evaporation. The AA model estimated 126.70 for August was the highest followed by June (120.84).

The month of April was the lowest of all (78.25mm/month). The GG model estimated ET$_a$ highest in June (130.87mm/month) followed by August (119.32mm/month) and July (119.00mm/month) with April being the lowest (1.92mm/month).

Table 10: Monthly Actual ET and Pan Evaporation values

Models	**MONTHLY ACTUAL EVAPOTRANSPIRATION ESTIMATES (mm/month)**							
	April	May	June	July	August	September	October	**Total**
Pan Evaporation	65.02	56.70	111.60	114.51	62.57	70.09	18.07	**71.2**
AA	78.25	90.99	120.84	118.80	126.70	113.90	114.50	**109.0**
GG	1.92	38.15	130.87	119.00	119.32	57.19	40.83	**72.5**

Table 11 shows the daily actual evapotranspiration and Pan Evaporation.

Table 11: Daily Actual ET and Pan Evaporation estimates

Models	**DAILY ACTUAL EVAPOTRANSPIRATION ESTIMATES (mm/d)**							
	April	May	June	July	August	September	October	**Total**
Pan Evaporation	2.17	1.83	3.72	3.69	2.02	2.34	0.58	**2.34**
AA	2.61	2.94	4.03	3.83	4.10	3.80	3.70	**3.57**
GG	0.06	1.23	4.36	3.84	3.85	1.91	1.32	**2.37**

The AA model estimated the highest daily ET$_a$ in August (4.10mm/day) followed by June (4.03mm/day) and the lowest in April (2.61mm/day). The Granger and Gray model estimated 4.36 for June which was the highest followed by August (3.85mm/day) with April (0.06mm/day) being the lowest.

Table 12 shows the hourly actual evapotranspiration compared with Pan Evaporation. The hourly actual evapotranspiration for Advection and Aridity model and Granger and Gray was similar in the months of June (0.17mm/h, 0.18mm/h) July (0.18mm/h, 0.16mm/h) and August (0.17mm/h,0.16mm/h).

Table 12: Hourly Actual ET and Pan Evaporation estimates

Models	**HOURLY ACTUAL EVAPOTRANSPIRATION ESTIMATES (mm/h)**							
	April	May	June	July	August	September	October	**Total**
Pan Evaporation	0.09	0.08	0.15	0.15	0.08	0.10	0.02	**0.10**
AA	0.11	0.12	0.17	0.16	0.17	0.16	0.15	**0.15**
GG	0.00	0.05	0.18	0.16	0.16	0.10	0.05	**0.10**

Table 13 shows the error estimations of GG model during the warmer months of April to October. April recorded the least monthly error values followed by October. In totality, ME recorded the least average error estimates and MSE was the highest error estimate.

Table 13: Statistical indices for GG model

Model	Month	RMSE	MAE	MSE	ME
GG	April	0.43	0.40	0.18	-0.39
	May	1.52	0.89	2.29	-0.71
	June	2.44	2.03	5.98	-0.50
	July	3.26	2.73	10.60	-0.07
	August	3.76	3.47	14.19	-3.46
	September	1.88	1.51	3.54	-1.48
	October	0.98	0.78	0.98	-0.73
	Average Total	**2.03**	**1.68**	**5.39**	**-1.04**

Table 14 shows the accuracy of the AA model using RMSE, MAE, MSE and ME.

The error estimate in the month of April is smallest in all the months with August recording the highest error values.

Table 14: Statistical indices for AA model

Model	Month	RMSE	MAE	MSE	ME
AA	April	2.16	2.16	4.67	-2.16
	May	2.54	2.51	6.46	-2.51
	June	2.09	1.85	4.37	-0.16
	July	2.28	2.03	5.19	-0.10
	August	3.70	3.68	13.72	-3.68
	September	3.32	3.29	11.03	-3.29
	October	3.13	3.11	9.81	-3.11
	Average total	**2.75**	**2.66**	**7.89**	**-2.14**

Tables 13 and 14 demonstrated that the average total RMSE was lower for GG model than the AA model.

Figure 16: ET_a estimates for ET, AA, GG for April

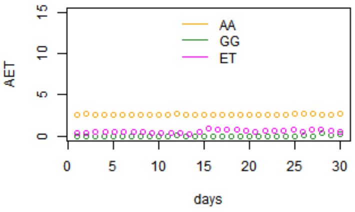


Figure 17: ET_a estimates for ET, AA, GG for May

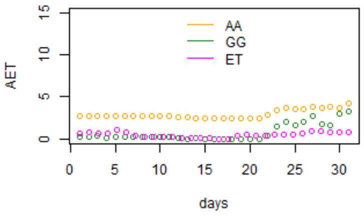


Figure 18: ET_a estimate for ET, GG, AA for June

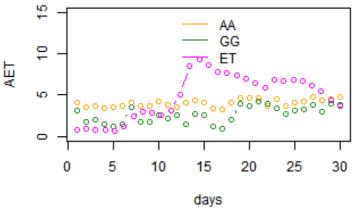


Figure 19: ET_a estimate for ET, GG, AA for July

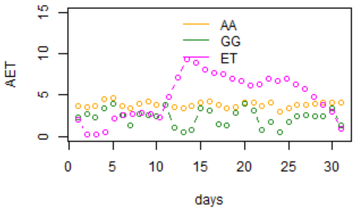


Figure 20: ET_a estimates for ET, GG, AA for August

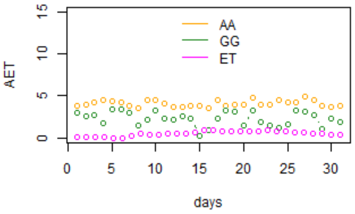


Figure 21: ET_a estimates for ET, GG, AA for Sept

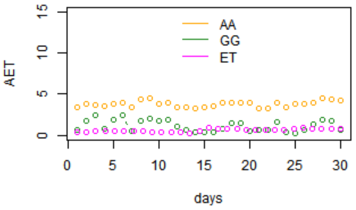
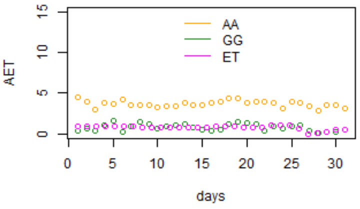


Figure 22: ET_a estimates for ET, GG, AA for October



4.7 Relationship between Actual Evapotranspiration models and data input variables

Table 15 gives the correlation coefficient of Granger and Gray Model and Advection-Aridity Model with the Data Input Variables.

Table 15: Correlation Coefficient (R) of Data Variables and Actual Evapotranspiration Models

Models	Mean Solar Radiation (W/m$^{2)}$	Mean Wind Speed (m/s)	Mean Rainfall (mm)	Mean Temperature (°C)
GG	0.77	0.82	0.63	0.93
AA	0.50	0.99	0.38	0.67

Figure 23: Relationship between Actual Evapotranspiration models and data input variable

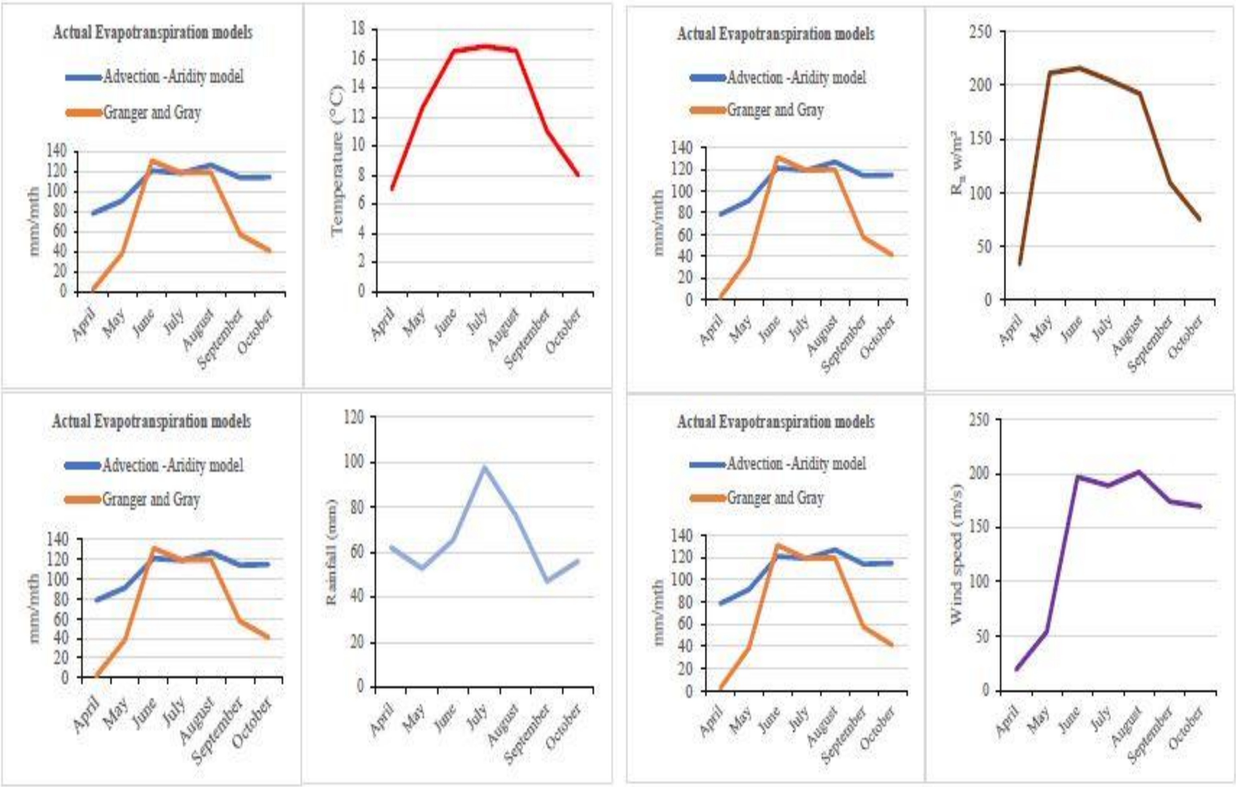


Figure 23 shows the association between the monthly mean values of data Input Parameters and monthly estimates of Actual Evapotranspiration models used in the study. The Granger and Gray model shows direct dependency with wind speed (R= 0.82). Wind speed increased in May and remained relatively stable throughout the rest of the months, the Granger and Gray model did same. The relationship between solar Radiation and Granger and Gray model was very strong.

The results established that there is a strong relationship between Granger and Gray Model and Rainfall (R= 0.63). As rainfall increases Granger and Gray model estimates increases. This is evident in September where rainfall decrease resulted in the decrease of Granger and Gray estimates. Among all the variables, temperature has the strongest relationship with the Granger and Gray Model (R= 0.93). Hence increase or decrease in temperature results in increase or decrease in Granger and Gray model estimates.

The speed of the wind had the strongest relationship with Advection-Aridity model (R= 0.99). This means that the Advection-Aridity model is highly dependent on wind speed. There was a moderate correlation between rainfall and Advection-Aridity model (R= 0.38), meaning that the amount of rainfall has marginal influence on Advection-Aridity model estimates. Solar Radiation has a strong correlation with the Advection-Aridity model (R= 0.50). Air Temperature (R= 0.67) has a strong relationship with the Advection-Aridity model. Hence an increase or decrease in temperature influence Advection-Aridity model estimates.

4.8 Correlation for Actual Evapotranspiration variables

Table 16 shows the correlation between Advection-Aridity model and Granger and Gray model.

Table 16: Correlation between Granger and Gray and Advection-Aridity models

	AA	GG
AA	1	0.85
GG	0.85	1

Table 16 above established that there exists a strong relationship between the AA and GG models in estimating Actual Evapotranspiration.

4.9 Correlation of Potential and Actual Evapotranspiration models

Table 17: Correlation (R) of Evapotranspiration models

Models	AA	GG
TUC	0.53	0.83
PT	-0.14	-0.61
PM	0.52	0.81

The table above shows the correlation between Potential and Actual Evapotranspiration models. It was established that the Priestley Taylor model is negatively correlated with all the other models. There is a strong correlation among the Penman- Monteith, Granger and Gray, Advection-Aridity and the TUC models. The strongest relationship exists between Granger and Gray and Advection-Aridity (R=0.85), TUC, Granger and Gray (R=0.83), Penman-Monteith and Granger and Gray (R=0.81) models.

CHAPTER FIVE

5. DISCUSSION

5.1 Estimation of Pan Evaporation

The controlled experiment was done because of the fluctuations in the weather at certain times during the study period.

The monthly Evaporation values for April and May which are (65.02mm/month) and (56.70mm/month) respectively have different effect due to the amount of water which was put manually into the pan. The decrease in Evaporation rate shows that if water is available at the reference surface, soil factors do not affect Evaporation, however, Evaporation may decrease overtime as soil water decrease.

The months of June and July experience high solar Radiation and high amount of rainfall leading to the increase in evapotranspiration. This resulted in drastic increase in evaporation values (116.60mm/month and 114.51mm/month respectively). This is also seen in both daily and hourly basis Tables 3,4,11,12. As radiation goes down Evaporation values decrease continuously in the months compared with values obtained in June and July.

In month September, Evaporation increased a little from the estimate of August. From the values of Evaporation in table 2, October (18.07mm/month) observed a sharp decrease. This can be attributed to the continuous decrease in solar Radiation and an increase in the amount of rainfall as compared to the month of September. The randomness in Pan evaporation in April, May, September and October is because of the fluctuations in the weather and the difference in amount of input of water at different times (controlled experiment) and this effect is clearly seen on daily basis from figures 8,9,13,14. Moreover, in a study carried out by Peterson et al., (1995) reported in Abtew et al., (2007) disclosed that Pan Evaporation data (1945 to 1990) from eastern and western United States, Europe, Middle Asian and Siberian Regions of the former Soviet Union, recorded a significant decline of Pan Evaporation. The decrease in Pan Evaporation was attributed to a decrease in diurnal temperature range and an increase in low cloud cover.

5.2 Estimation of Potential Evapotranspiration in time scales

Per Grace and Quick (1988), evaporation from an Evaporation Pan is always greater than Potential Evapotranspiration. The reasons for these differences are best explained by reference to the conditions imposed by the definition of potential evapotranspiration and analysis of realities of these conditions. Hence values for Evaporation when bench marked with Evapotranspiration values show that ET_p values are less as compared to the Evaporation values from Tables 2,3,4.

The TUC model recorded high values of ET_p of all the months with June, July and August as highest. This is directly attributed to the peak of summer temperature because of energy from the sun (solar Radiation). The TUC Model is highly dependent on solar radiation and temperature with the strongest correlation coefficient of (R= 0.99; R= 0.96). The TUC model estimates ET_p based on Temperature and Radiation. This conforms with Fisher and Pringle, (2013) who stated that TUC model estimates Evapotranspiration based on Temperature and Solar Radiation.

Comparatively, Priestly-Taylor model performance with evaporation estimates and TUC model, observed some irregularities from the month of June. Potential Evapotranspiration values started decreasing in June (1.39mm/month) and July (0.61mm/month) which are expected to give the highest estimates (Tables 2,3,4) and an increase in September (16.23mm/month) and October (32.14mm/month) which are supposed to decrease because of cold temperature and limited solar energy. The irregularities could be attributed to some missing or exclusion of parameters in estimating evapotranspiration.

The Priestley-Taylor approach neglects the influence of vapor deficit on evapotranspiration, relying on the assumption that Evapotranspiration depends on solar radiation and temperature. The data requirement does not include some hardly available meteorological variable such as relative humidity. Hence this evapotranspiration can be computed in places where Penman-Monteith calculations cannot be performed due to data lacking (Jamieson, 1982; Pereire and Nova, 1992).

However, the Penman Monteith model shows deterministic movement right from the month of April, as ET_p started increasing and decrease in September to October with disparities in May and June. The Aerodynamic term used by Penman-Monteith has a significant role in the deterministic values of the ET_p estimates as compared to TUC and PT models. Its considers the wind speed term, roughness height which affect the humidity of the air and increases the ET_p values. As wind speed reduces ET_p values decrease.

Penman-Monteith model is probably the most widely known estimator. Penman-Monteith equation has a sound physical basis. In contrast to the pan observations and the empirical models, the PM model is based on a simplified radiation budget (Grace and Quick, 1988)

For the accuracy of the methods used in estimating evapotranspiration in this study, coefficient of determination (R^2) will not be used. This conforms to Nikam et al., (2004) who concluded that on seasonal and monthly scale the coefficient of determination do not give actual representation of accuracy of method with respect to closeness of ET with Pan Evaporation. Hence performance evaluation of each of the method for this study was done using error.

Based on error in estimating potential evapotranspiration the Priestley-Taylor model recorded the lowest RMSE values (1.98) as shown in Table 5. The PT model gave the smallest error in estimating evapotranspiration in the months of May, April, August and September followed by Tuc in the month of April (0.55) with the average total error of 2.10 and Penman Monteith with an average total error of 3.88.

Per Batchelor (1984); Cuenca and Nicholson (1982) Penman Monteith may require local calibration of wind function to achieve satisfactory results. It must however be noted that there was overestimation and underestimation of evapotranspiration when compared to evaporation estimates in some of the models during the summer months of June, July and August (where evapotranspiration is expected to go up) which led to high errors. This may be attributed to the control experiment where the Pan is filled with water to check for evaporation.

The Pan method is susceptible to microclimate conditions under which the pans are operating and the rigor of station maintenance hence special precautions and management if not applied may lead to high errors in Evaporation estimation (Christiasen, 1968). Christiasen (1968) further reported that the Pan produces significant differences in loss of water from a water surface and from cropped surface and as such solar radiation from water in the shallow pan might be different from the assumed 23% for the grass reference surface. The Pan method would give acceptable estimates depending on the location of the pan.

Moreover, the overestimation and underestimation of Evapotranspiration values can be improved by a local calibration of the input variables (data values) in each model (Xu and Singh, 2005). Recalibration of the parameter values is not done in this study because the main purpose is to examine the applicability and accuracy of the models in the study region with their original parameter values.

5.3 Estimation of Actual Evapotranspiration in time scales

The Advection-Aridity model and Granger and Gray model were used in estimating Actual Evapotranspiration. The Granger and Gray model performed better than the Advection-Aridity model. As radiation increased from June to August, ET_a increased. The Granger and Gray model performed so well as bench marked with the Evaporation values showing the deterministic pattern as seen from figures 16,17,18,19. The Granger and Gray model has very strong relationship with all the data input variables.

Advection-Aridity model in September (113.90mm/month) and October (114.50mm/month) recorded high values. The differences in estimates between the high solar radiation months of June (120.84mm/month), July (118.80mm/month) and August (126.70mm/month) and low solar radiation months of September, October are small. This may be attributed to the slight difference in wind speed from June to October as shown in figure 23.

The Advection-Aridity model is very sensitive to wind speed (R= 0.99), especially from wind speeds above 4 m/s. In fact, wind speed exhibits the strongest relationship with Advection-Aridity model (fig 23; table 15) than any climatic variable. The first step in improving the Advection-Aridity model must necessarily be to reparametrize the wind function f (U_2) (Hobbins et al., 1999). However, no reparameterization was done in this study.

In a similar work conducted by Lui et al., (2010) in Nanchang County of Jiangxi Province, China the actual evapotranspiration values shows that Granger and Gray model performed better than Advection-Aridity model. Lui et al., (2010) further stated that the Advection-Aridity model has some systematic errors because of wind speed.

From Lui et al., (2010) study, Granger and Gray model estimated ET_a in the months of April as (69.3), May (88.0), June (93.2) July (104.2), August (92.8), September (75.7) and October (47.3). Comparatively their work has similar values as this work confirming a better performance of Granger and Gray model than the Advection-Aridity model.

Granger and Gray model has a lower RMSE value (2.03) than Advection-Aridity model (2.75) which confirms Lui et al., (2010) research that revealed that Granger and Gray model had smallest error among the three models estimated (CRAE, Granger and Gray and Advection-Aridity).

In a similar work by Anayah and Kaluarachchi (2014), estimating actual evapotranspiration from different complementary methods in a humid environment, the Granger and Gray model was slightly better than the AA model in terms of error estimates (RMSE). The average RMSE error was 35.2 for Advection-Aridity model and 27.1 for Granger and Gray model.

Both the Advection-Aridity model and Granger and Gray Model provided good estimates of Actual Evapotranspiration showing deterministic pattern. This conforms with Xu and Singh (2005|) who revealed that the complementary approaches (AA and GG) worked reasonably well in humid temperate regions. The original data variables (values) used provided good Actual Evapotranspiration estimates in temperate humid region of Sweden (Xu and Singh, 2005). This supports the use of original parameter values in this study.

CHAPTER SIX

6. CONCLUSION

The performance evaluation of these five Evapotranspiration estimation techniques done in this study is site specific (point estimation) and the results may vary from site to site. This study will help decision makers to select the best possible ET estimation technique with respect to data/cost constraints or accuracy constraints.

The meteorological data collected from the Nemcice Meteorological station, Czech Republic was used to estimate evapotranspiration using five models. First, potential evapotranspiration is computed using three models. Of the three potential evapotranspiration models, two are temperature- based methods (Turc model and Penman Monteith) and other one is radiation-based methods (Priestley–Taylor methods). Two complementary relationship methods (Advection-Aridity and Granger and Gray models) were used to estimate actual evapotranspiration.

The study revealed that Penman-Monteith has the strongest relationship with rainfall (R=0.84) whereas there was a negative correlation between Priestly-Taylor model and all the Data Input variables (R= -0.71; R= -0.59; R= -0.79) excluding Wind Speed. There was no relationship between Priestley-Taylor model and Wind Speed. The TUC model has the strongest relationship with solar radiation (R= 0.99) and Temperature (R= 0.96). This means that the Turc model is solely dependent on the amount of solar radiation.

The Penman-Monteith equation has proven to be the best method for estimating ET_p because of the deterministic pattern observed in the values in all the months.

Where the complementary relationship methods are concerned the Granger and Gray model shows direct dependency with Temperature (R= 0.93) and wind speed (R= 0.82). Moreover, the Advection-Aridity model had the strongest relationship with wind speed (R= 0.99).

In estimating actual evapotranspiration, the Granger and Gray model gives relatively good estimates especially in April, May, September and October and correlate very well with input parameters from the data than the AA model.

It is expected that the study will guide in selecting suitable methods for estimating and projecting ET in accordance to availability of meteorological data.

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APPENDICES

List of Figures

List of Tables

Table of Abbreviation

AA	Advection-Aridity
C_p	Specific heat of moist air
d	Displacement height
D	Vapor pressure deficit of the air

ET_a	Actual Evapotranspiration
ET_p	Potential Evapotranspiration
ET_o	Reference Evapotranspiration
E_{pan}	Evaporation pan
ET	Evapotranspiration
E_a	Drying power of air
e_s	Saturated vapor pressure
GG	Granger and Gray
G	Soil heat flux
g_s	Bulk surface conductance
K	Von Karman's constant
K_p	Pan coefficient
MAE	Mean average error
MSE	Mean square error
ME	Mean error
PET	Potential evapotranspiration
P	Atmospheric pressure
$RMSE$	Root mean square error
R_{ns}	Net solar Radiation
r_s	Bulk surface resistance
r_a	Aerodynamic resistance
U	Wind speed
Z_e	Height of the pressure instrument
Z_u	Height at which wind speed was measured
Z_{ov}	Roughness height for water vapor

Z_{om}	Roughness height for momentum

Symbols

γ	Psychometric constant
Δ	Slope of saturation vapor pressure temperature curve
λ	Latent heat
ρ_a	Mean air density
ρ_w	Density of water