SYMBOLIC REGRESSION MODEL FOR RELIABLE ESTIMATION AND PROJECTIONS OF EVAPOTRANSPIRATION

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DEDICATION

To My Parents, Wife and Family

For all your supports throughout my life

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ABSTRACT

Evapotranspiration (ET) plays a significant role in defining water demand, surface runoff, atmospheric moisture and precipitation. It is well recognized that ET is changing in regional and global scales due to rising temperature induced by global warming. Reliable estimation and future projections of ET with associated uncertainties are extremely important for agricultural and water resources development, planning and management. However, projections of ET using well-established empirical ET models suffer from large uncertainty due to their dependency on a large number of climatic variables. The major objective of the present study was to develop empirical ET models for reliable estimation and projection of ET in the context of global warming. Daily temperature, humidity, solar radiation, wind speed and pan evaporation data recorded at ten meteorological stations distributed over peninsular Malaysia was used for the development of four sets of ET models using Gene Expression Programming (GEP) based on a different combination of meteorological variables. The superiority of GEP generated ET models were established by comparing their performance with the most suitable ET model selected using compromise programming approach from the pool of existing ET models. A trend conserving perturbation approach was used to downscale the Global Climate Model (GCM) projected temperatures, which were then used for projection of future changes in ET using GEP generated temperature-based ET models for four Representative Concentration Pathways (RCPs) scenarios namely, RCP 2.6, 4.5, 6.0 and 8.5. The results revealed the Penman-Monteith as the most suitable method of estimation of ET followed by radiation-based Priestley and Taylor and the mass transfer-based Dalton and Meyer methods. Among the temperature-based methods, Ivanov was found the best. Comparison of GEP-based ET models with the existing most suitable empirical model in peninsular Malaysia showed better performance of GEP models in term of all standard statistics. The Nash Sutcliffe efficiency coefficients of GEP models were found more than 0.93 for all the GEP models during validation, which was higher than that obtained using existing empirical models. Downscaling of temperature revealed a continuous increase in minimum, maximum and average temperatures over the present century under all RCPs. The minimum temperature was projected to increase in the range 2.47–3.30°C, the maximum temperature in the range of 2.79–3.24°C, and the mean temperature in the range of 2.56–3.20°C during 2070-2099. The minimum temperature was found to increase more compared to maximum temperature in most of the stations. The ET in peninsular Malaysia was projected to change in the range of -4.35% to 7.06% under RCP2.6, -1.99% to 16.76% under RCP4.5, -1.66% to 22.14% under RCP6.0 and -0.91% to 39.7% under RCP8.5 during 2010-2099. Relatively more increase in ET was projected in the North compared to other parts of peninsular Malaysia. The rise in ET was found to follow the trend in temperature in most of the stations. The results also revealed high uncertainty in the projections of ET. The uncertainty in the rise of ET was found to increase with time and for higher RCPs. It can be expected that the methodology proposed in the present study can be useful in the reduction of uncertainty in the projection of ET which in turn can help in cost-effective adaptation and mitigation planning.

ABSTRAK

Evapotranspirasi (ET) memainkan peranan penting dalam menentukan permintaan air, larian permukaan, kelembapan udara dan hujan. Adalah diakui bahawa ET berubah dalam skala serantau dan global disebabkan peningkatan suhu dari pemanasan global. Anggaran yang boleh dipercayai dan unjuran ET yang akan datang dengan ketidakpastian yang berkaitan sangat penting untuk pembangunan, perancangan dan pengurusan pertanian dan sumber air. Walau bagaimanapun, unjuran ET menggunakan model ET empirikal yang mapan mengalami ketidakpastian yang besar disebabkan oleh pergantungan mereka terhadap banyak pembolehubah iklim. Objektif utama kajian ini adalah untuk membangunkan model empirikal ET untuk ramalan dan unjuran ET yang boleh dipercayai dalam konteks pemanasan global. Data suhu harian, kelembapan, sinaran suria, kelajuan angin dan kancah sejatan yang direkodkan di sepuluh stesen meteorologi yang di seluruh Semenanjung Malaysia digunakan untuk pembinaan empat set model ET menggunakan Pengaturcaraan Ekspresi Gen (GEP) berdasarkan kombinasi pemboleh ubah meteorologi yang berbeza. Keunggulan model ET yang dijana GEP dibuktikan dengan membandingkan prestasi mereka dengan model ET terbaik yang telah dipilih menggunakan pendekatan pengaturcaraan kompromi dari kumpulan model ET sedia ada. Pendekatan tren pelestarian perturbasi digunakan untuk menurunkan suhu yang diunjurkan oleh model iklim global (GCM), yang kemudiannya digunakan untuk unjuran perubahan ET pada masa depan menggunakan model GEP ET yang dijana berasaskan suhu untuk empat senario Laluan Konsentrasi Perwakilan (RCP) yang terdiri daripada RCP 2.6, 4.5, 6.0 dan 8.5. Hasilnya mendedahkan Penman-Monteith sebagai kaedah pengiraan ET yang paling sesuai diikuti oleh kaedah berasaskan radiasi Priestley-Taylor dan kaedah berasaskan pemindahan jisim Dalton dan Meyer. Antara kaedah yang berasaskan suhu, Ivanov didapati yang terbaik. Perbandingan model berasaskan GEP ET dengan model empirikal sedia ada yang paling sesuai di Semenanjung Malaysia menunjukkan prestasi model GEP yang lebih baik dari segi semua statistik standard. Koefisien kecekapan Nash Sutcliffe model GEP didapati lebih daripada 0.93 untuk semua model GEP semasa validasi, yang mana lebih tinggi daripada yang diperolehi menggunakan model empirik sedia ada. Penurunan suhu mendedahkan peningkatan berterusan dalam suhu minimum, maksimum dan purata sepanjang abad ini di bawah semua RCP. Suhu minimum diunjurkan meningkat dalam julat 2.47–3.30°C, suhu maksimum dalam julat 2.79–3.24°C, dan suhu min dalam julat 2.56–3.20°C untuk tempoh 2070-2099. Suhu minimum didapati meningkat lebih banyak berbanding suhu maksimum di kebanyakan stesen. ET di Semenanjung Malaysia dijangka berubah dalam lingkungan -4.35% kepada 7.06% di bawah RCP2.6, -1.99% hingga 16.76% di bawah RCP4.5, -1.66% hingga 22.14% di bawah RCP6.0 dan -0.91% ke 39.74% di bawah RCP8.5 semasa 2010-2099. Lebih banyak peningkatan dalam ET dijangka di bahagian Utara berbanding bahagian lain di Semenanjung Malaysia. Kenaikan ET didapati mengikuti tren suhu di kebanyakan stesen. Hasilnya juga menunjukkan ketidakpastian yang tinggi dalam unjuran ET. Ketidakpastian dalam peningkatan ET didapati meningkat seiring dengan masa dan untuk RCP yang lebih tinggi. Adalah dijangkakan bahawa metodologi yang dicadangkan dalam kajian ini berguna dalam pengurangan ketidaktentuan dalam unjuran ET, yang seterusnya dapat membantu dalam penyesuaian kos efektif dan perancangan mitigasi.

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LIST OF ABBREVIATIONS

AI	-	Artificial Intelligence
ANN	-	Artificial Neural Network
CMIP5	-	Couple Model Intercomparison Phase 5
CP	-	Compromise Programming
DDM	-	Data Driven Model
ESAT	-	Saturated Vapor Pressure
ET	-	Evapotranspiration
GA	-	Genetic Algorithm
GCM	-	Global Climate Model
GEP	-	Gene Expression Programming
hPa	-	Hectopascal
KGE	-	Kling-Gupta Efficiency
MAE	-	Mean Absolute Error
md	-	Modified Index of Agreement
ML	-	Machine Learning
MME	-	Multi-Model Ensembles
MOS	-	Model Output Statistic
NRMSE	-	Normalized Root Mean Square Error
NSE	-	Nash-Sutcliffe Efficiency
PBIAS	-	Percent Bias
RCPs	-	Representative Concentration Pathways
RH	-	Average Relative Humidity
RHOSAT	-	Saturated Vapor Density
rSD	-	Relative Standard Deviation
Tmin	-	Minimum Temperature
Tmean	-	Mean Temperature
Tmax	-	Maximum Temperature
SVM	-	Support Vector Machine

LIST OF SYMBOLS

Δ	-	Slope of Saturation Vapour Pressure-Temperature Curve
λ	-	Latent Heat of Evaporation
γ	-	Psychrometric Constant
°C	-	Degree Celcius
e	-	Vapour Pressure
e_a	-	Actual Vapour Pressure
e_{ma}	-	Saturation Vapour Pressure at the Monthly Mean Daily Maximum Temperature
e_s	-	Saturation Vapour Pressure
ETa	-	Actual Evapotranspiration
ETo	-	Reference Evapotranspiration
$f(u)$	-	Function of Wind Speed
G	-	Soil Heat Flux
L_d	-	Daytime Length in Multiples of 12 h
mm	-	Milimeter
Oi	-	Observed Values
R^2	-	Coefficient of Determination
R_a	-	Extraterrestrial Radiation
R_n	-	Net Radiation
R_s	-	Solar Radiation
Si	-	Simulated Values
T	-	Temperature
u	-	Wind Speed
z	-	Elevation

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Evapotranspiration (ET) is the second most crucial component of the hydrological cycle after rainfall (Djaman et al., 2015). It has an important role in irrigation management (Shahid, 2011), water balance estimation (Jaber et al., 2016), surface water runoff modelling (Wigmosta et al., 1994), groundwater level fluctuation estimation (Salem et al., 2017), water stress assessment (Mohsenipour et al., 2018), reservoir operation (Ismail et al., 2017), surface flux modelling (Fisher et al., 2009), and climate change impact assessment (Shiru et al., 2018). Hence, ET is considered as one of the most important parameters for any hydrological and climatic study (Roudier et al., 2014). Rising temperature is one of the most imminent and certain impacts of global warming (Beniston et al., 2007). The major impact of the rising temperature of water resources will be through the alteration of ET. Therefore, accurate estimation of ET is very important for water resources development, planning and management in the context of global warming and climate change impact and adaptation studies.

Actual evapotranspiration can be measured using direct experimental methods such as using weighing lysimeter, remote sensing, eddy covariance, etc. or by indirect methods such as catchment water balance, hydrometeorological equations, energy balance, etc. (Rana and Katerji, 2000). Among these methods, direct estimation of actual evapotranspiration using a lysimeter is considered as the most accurate compared to other techniques (Gavilán et al., 2006; Tao et al., 2018). However, the estimation of evapotranspiration using lysimeter is often expensive and time-consuming in terms of accuracy in measurement and can only be fully exploited by well-trained personnel (Jensen et al., 1990). Furthermore, the limited area of a typical weather station enclosure does not provide sufficient fetch from a representative surface for these measurements to be meaningful (Sentelhas et al., 2010). Therefore, hydrometeorological empirical models are considered as the alternative for the estimation of ET (Djaman et al. 2015).

The difficulties in experimental measurements and the increasing availability of meteorological data have led to the development of a wide variety of empirical ET models. Several of these empirical formulations have been established for a specific climatic region and thus suitable for implementation in a specific region. However, there are a couple of empirical formulations which have been globally recognised such as Penman-Monteith method (Penman, 1948). The proficiency of this method had been examined over several climate regions including Malaysia and evidenced its potential for field measurement up to a certain level of reliability. The main limitations of this method are that it requires several meteorological variables, in addition to extensive data span to comprehend the ET pattern accurately. Furthermore, it is not possible to get long-term data of all the meteorological variables in most of the developing countries. Hence, it is highly essential to develop a robust and reliable model for estimation of ET with easily available meteorological variables.

Understanding ongoing changes and possible future changes in ET are essential for the development of effective climate change adaptation policies for mitigation of climate change impacts on water resources (Wang et al., 2016). A reliable estimation of ET and the assessment of the changes in ET due to global warming can be useful for climate change impact assessment and the formulation of effective preparedness plans to combat water resources related challenges.

1.2 Problem Statement

Most of the ET estimation methods are developed for a particular region with a specific viewpoint, and therefore, they often found inefficient in estimating ET in other climatic zones. However, some methods are developed without focusing on any climatic region and have been found applicable over a wide range of climate. A large number of studies have been conducted to select the suitable ET model in different parts of the globe (Song et al., 2019; Tabari et al., 2013; Bogawski and Bednorz, 2014; Hosseinzadeh Talaee et al., 2014a; Lee et al., 2004; Ali and Shui, 2008; Muniandy et al., 2016). Different statistics have been used in previous studies for the assessment of the performance of ET for their ranking in a region (Muniandy et al., 2016; Muhammad et al., 2019). Statistical metrics often give contradictory results which make the ranking of ET estimation methods a challenging task (Nashwan et al., 2019c; Nashwan and Shahid, 2019b). Besides, the ranking of ET estimation methods for a given study area based on the rank at different stations is also a difficult task. This highlights the need for a statistically robust approach that does not depends on the outliers or distribution of data for the selection of most appropriate methods for the estimation of ET.

The difficulties in experimental measurements and the increasing availability of meteorological data have led to the development of a wide variety of empirical ET models. Though some of these empirical formulations have been globally recognised, the main limitations of the methods are requirements of several meteorological variables which are often not available at many locations in developing countries. This emphasizes the need for the development of models for reliable estimation of ET from easily available meteorological variables. Conventional non-linear regression methods generally used for the development of ET models from observed data often fail to capture the random variability of ET (Fahimi et al., 2016). Artificial intelligence (AI) techniques have been used to overcome the difficulties and development of new ET methods (Cobaner, 2011; Shiri et al., 2012; Gocić et al., 2015; Yao et al., 2017). Among all these AI models, symbolic regression models evidenced a remarkable capacity in modelling ET (Parasuraman et al., 2007; Shiri et al., 2014a; Shiri et al., 2014b; Guven et al., 2008; Traore and Guven, 2013; Kiafar et al., 2017; Mehdizadeh et al., 2017). The main advantage of the symbolic regression functionality is its distinguished capability to discover and mimic the hidden relationship between different meteorological variables and ET (Ferreira, 2006; Guven, 2009; Zuo et al., 2004). However, the major challenge appears due to different behaviours of climate in different regions which emphasizes the requirement of the development of regional-specific models. There is a major gap in research on the exploration of the capability of symbolic regression in modelling ET in a tropical region.

The global climate model (GCM) simulations are downscaled into much finer spatial resolution either using a statistical or dynamical downscaling approach for impact assessment. Compared to dynamical downscaling, statistical downscaling methods are often preferred for their simplicity, easiness, flexibility, quickness, and ability to provide local-scale information (Ahmed et al., 2015a; Pour et al., 2014). The statistical downscaling methods are subdivided into two large groups, perfect prognosis (PP) and model output statistics (MOS) (Maraun et al., 2010). The MOS models are able to explicitly account for GCM-inherent error and bias (Eden and Widmann, 2014) and therefore, found highly potential for climate change projections (Sunyer et al., 2015; Sa'adi et al., 2017; Eden and Widmann, 2014; Turco et al., 2011; Bi et al., 2017; Shirvani and Landman, 2016; Widmann et al., 2003). In recent years, regression-based MOS models have been developed to establish the relationship between GCM simulated variables and observed climate (Eden and Widmann, 2014; Abbasian et al., 2019; Bi et al., 2017; Shirvani and Landman, 2016; Eden et al., 2012; Moghim and Bras, 2017). The relationship between local climate and GCM hindcasts are often very complex. It is important to search sophisticated approach for modelling the relationship between local climate with GCM hindcast to improve the performance of MOS downscaling and reliability in climate change projections.

ET has attracted more attention in recent years due to increasing water demand, and limited and uncertain water supplies due to climate variability and changes (Mishra and Cherkauer, 2010). Numerous studies have been conducted to assess ET and understand the effects of climate change on water use in agriculture in the form of net irrigation requirements, demand, and crop water use (Azad et al., 2018; Brouziyne et al., 2018; Al-Najar and Ashour, 2013). However, attempts to develop a reliable approach for the projection of ET under climate change scenarios are limited. The higher ET can have a severe impact if it occurs during the crop-growing season (Ahmed et al., 2016; Alamgir et al., 2015). This emphasises the needs to assess climate change impacts on ET in the tropical region as higher ET under higher temperature can have severe implications including increasing water stress, reduction of crop yield and economic losses, particularly in agriculture-dependent regions.

1.3 Research Objectives

The major objective of the present study is to develop empirical models for reliable estimation of evapotranspiration and projection of evapotranspiration under climate change scenarios using limited meteorological data. The specific objectives of the research are:

1. To employ a robust approach for the comparison of the existing empirical ET models for selection of most suitable models

2. To apply a symbolic regression method for the development of ET models using different sets of meteorological variables

3. To perform downscaling and projection of temperature for different climate change scenarios using robust statistical downscaling methods

4. To project the changes in ET due to the change in climate using ET models with the least number of meteorological variables.

1.4 Scope of the Study

Empirical models have been developed for reliable estimation of ET and the assessment of the changes in climate on ET. The Peninsular Malaysia is used as the study area for the development and validation of the models.

Complete meteorological data are available only at 10 locations distribution over Peninsular Malaysia. Therefore, only the data of 10 sites were used for the development of ET models. The projections of ET were also performed in these 10 stations. The temperature and thus, ET in Peninsular Malaysia do not vary widely with space. Therefore, it was considered that the ETs of these 10 stations are sufficient to represent the whole of peninsular Malaysia.

The GCMs of Coupled Model Intercomparison Phase 5 (CMIP5) from each model developing centre that has projections in the study area for all the four RCP scenarios namely, RCP2.6, RCP4.5, RCP6.0 and RCP8.5 were only considered for the projection of climate and ET.

1.5 Significance of the Study

The novelty of the research lies in the robustness of the models developed in this study, particularly in the reduction of uncertainty in the estimation of ET and projections of ET. The methodology used in this study can be replicated in other regions of the development of reliable ET models for estimation and projections of ET from easily available meteorological variables.

Climate change is supposed to have strong negative effects on hydrology in many regions with significant implications on agriculture and livelihood of people. The methodological framework developed in the present study can be beneficial for the identification of reliable ET model by using robust statistical methods.

The knowledge generated in this study can help in guiding the operational responses of the various authorities, especially in terms of those interventions aimed at environmental risk reduction. The finding of the study will be beneficial to a number of stakeholders, particularly water resources and agricultural management, but also the development/planning authorities to improve their understanding of climate change and its impact of water resources.

1.6 Thesis Outlines

The thesis is divided into five chapters. Descriptions of the chapters are given below in brief.

Chapter 1 gives a general introduction comprising of the background of the study, problem statements, objectives of the study, scope of the work, and significance of the study.

Chapter 2 provides a general review of relevant literature of previous studies on empirical ET models, symbolic regression, and climate downscaling and projection.

Chapter 3 presents the methods used in the study. The chapter describes the methods used for estimation of ET, symbolic regression, gene expression programming, development of ET using symbolic regression, temperature downscaling, and estimation of ET under climate change scenarios.

Chapter 4 presents the results obtained in the study. The results are presented based on the objective of the study to clearly show how the objectives are achieved.

Finally, the conclusions made from the study are given in Chapter 5. Future research envisaged from the study is also discussed in this chapter.

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