UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A MATHEMATICAL MODEL FOR HYDROCLIMATOLOGICAL DROUGHT FORECASTING

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By

ALIREZA ESLAMI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2012

DEDICATION

Dedicated To:

All the Martyrs, Patient's Mother Bountiful and Father Kind-hearted Who, I Alive with His Memories Now and to My Wife "Masoumeh", My Lovely Girl "Faezeh" and Two My Sons "Foad and Farzad"

Abstract of thesis presented to the senate of Universiti Putra Malaysia in fulfilment of the requirements of the degree of Doctor of Philosophy

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Chairman: Assoc. Professor Abdul Halim Bin Ghazali, PhD

Faculty: Engineering

Knowledge of hydrological conditions and forecasting its occurrence for planning and for efficient use of water resources are essential. In this regard, the phenomenon of drought poses some destructive environmental effects on various aspects of hydrological processes. Anticipating the start of a drought phenomenon is very complex. Nevertheless, it is crucial to determine the most probable hydrological condition, after a certain condition of meteorological drought has occurred. Determining how long it will take for the hydrological conditions to be affected by the meteorological drought is also an important issue.

The main purpose of this research lies in attaining a method for predicting the occurrence of different hydrological conditions (states) according to various meteorological conditions for a time step ahead, in a basin. For this purpose, a stochastic model that comprises the hydro-climatological variables, based on Markov chain theory is developed. To accomplish this, meteorological and hydrological drought indices were employed. In this case, the time series of precipitation and streamflow were used to determine the different meteorological and hydrological

states. Performance of some of the well known meteorological drought indices were evaluated for the selected study area, which was the Semi-Mediterranean region in the North of Iran. Different meteorological and hydrological states were determined using the appropriate drought indices. Besides, the lag time between different meteorological and hydrological states was recognized using the monthly precipitation and streamflow time series. Probabilities of occurrence of different meteorological states were predicted via a one-dimensional transition probability matrix (ODTPM). Then, with the concept borrowed from the Markov chain theory and with regards to the basin lag time, the ODTPM was further developed into a two-dimensional transition probability matrix (TDTPM). This procedure led to a matrix as the main output of this study, which is called the Hydroclimatological Matrix (HCM). Thus, employing the ODTPM and TDTPM, probabilities of occurrence of different hydrological states were forecasted via a Prediction Matrix. Forecast verification was carried out via discrete predictors as a categorical method. Furthermore, the cross-validation approach and root mean square error (RMSE) methods were used for checking the consistence of probability shifts and robustness of the desired matrices. In particular, three study areas, which were Frizi, Joestan and Chalus Basins with various hydroclimatical variables were selected on which the proposed method could be implemented.

From this study, it is found that the non-parametric Deciles meteorological drought index method is the appropriate index. The flow duration curve (FDC) method was selected for categorizing the hydrological drought occurrence as an analogue method with the Deciles index. Following this, threshold levels in the range from Q_{50} to Q_{95} were adopted to distinguish corresponding levels of hydrological drought severity.

The Hydroclimatological matrices (HCM) have shown that a matrix with single-timescale is appropriate with a small basin like the Frizi, and in contrast, for large basins like the Chalus and Joestan, a multi-timescale matrix is more appropriate. Hence, the probabilities of occurrence of events in the Frizi Basin have indicated that hydrologic response of the river basin to climatic variation occurs in a short period of time. Comparison of the probability values related to the Frizi River has illustrated that the probability of occurrence of hydrological drought will increase by about 64.5% when the meteorological state changes from the 'Wet' to the 'Severe Dry' states for the following month in this basin. Notably, the 'Severe Drought' as another meteorological state has a significant impact on the occurrence of hydrological drought during the next three months in this case study. In the Joestan Basin, when the meteorological state changes from the Wet state to the Mild Drought, the river basin will have been trapped in drought with 76% probability. This process will continue with 58% probability, until the following four months for the river basin. In the case of the Chalus Basin, if the basin is attacked by the onset of a Severe meteorological drought in a given month, the hydrological drought streamflow will be experienced with 53.4% probability of occurrence with three months delay.

The probability of detection (Hit rate) shows that the verification of forecast performance of the hydroclimatological matrix (HCM) can be adopted as satisfactory forecast. Likewise, results of the Cross-Validation approach and RMSE method exhibit the fact that the probability shifts are consistent in the matrices obtained, so that the HCM as a reference matrix has excelled in the robustness testing. Accordingly, in terms of the river basin management, the implementation of the proposed method for triggering warning towards an impending drought is its significant benefit.

Key words: Deciles Index, Hydrological Drought Index, Markov Chain, Lag Time, Transition Probability Matrix. Hydroclimatological Matrix, Prediction Matrix, Hydrological States

Abstrak tesis yang dikemukakan kepada senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN SATU MODEL MATEMATIK UNTUK RAMALAN KEMARAU HIDRO-IKLIM

Olah

ALIREZA ESLAMI

Mac 2012

Pengerusi: Profesor Madya Abdul Halim Bin Ghazali, PhD

Fakulti: Kejuruteraan

Pengetahuan tentang keadaan hidrologi dan ramalan berlakunya keadaan tersebut untuk tujuan merancang dan penggunaan sumber air yang berkesan adalah sesuatu yang dikira penting. Dalam hal ini, fenomena kemarau memberikan beberapa kesan pemusnahan persekitaran ke atas berbagai-bagai aspek proses hidrologi. Proses meramalkan permulaan fenomena kemarau adalah sesuatu yang sangat sukar. Namun begitu, adalah menjadi satu keperluan untuk mengesan keadaan hidrologi yang paling berkemungkinan, selepas satu kemarau meteorologi tertentu terjadi. Satu lagi isu penting ialah menentukan berapa lama masa yang diambil oleh keadaan hidrologi untuk menerima kesan dari kemarau meteorologi.

Tujuan utama kajian ini ialah membina satu kaedah untuk meramal keadaan hidrologi yang berbeza menurut pelbagai keadaan meteorologi, bagi suatu jarak masa ke hadapan, dalam sesuatu lembangan. Untuk tujuan ini. satu model stokastik yang

terdiri dari pembolehubah-pembolehubah hidro-iklim berdasarkan kepada teori rantaian Markov telah dibangunkan. Untuk mencapai tujuan ini, indeks kemarau meteorologi dan hidrologi telah digunapakai. Dalam hal ini, siri masa kerpasan dan aliran sungai telah digunakan untuk menentukan keadaan metereologi dan hidrologi yang berbeza-beza. Prestasi beberapa indeks metereologi yang terkenal telah dinilai untuk kawasan kajian yang telah dipilih, iaitu kawasan rantau separa-Mediterranean di Utara Iran. Keadaan metereologi dan hidrologi yang pelbagai telah ditentukan menggunakan indeks kemarau yang bersesuaian. Di samping itu, tempoh kelewatan di antara keadaan metereologi dan hidrologi yang berlainan telah dikenalpasti menggunakan siri masa kerpasan dan aliran bulanan. Kebarangkalian kejadian keadaan metereologi yang berlainan telah diramal melalui satu matriks kebarangkalian peralihan satu-dimensi (ODTPM). Kemudian, dengan konsep yang dipinjam dari teori rantaian Markov dan dengan mengambilkira masa keterlewatan lembangan, ODTPM telah dikembangkan kepada satu matriks kebarangkalian peralihan dua-dimensi (TDTPM). Prosedur ini membawa kepada matriks sebagai satu output utama kajian ini, yang dikenali sebagai Matriks Hidro-iklim, atau Hydroclimatological Matrix (HCM). Oleh itu, dengan menggunakan ODTPM dan TDTPM, kebarangkalian kejadian keadaan hidrologi yang berlainan telah diramal melalui Matriks Jangkaan. Pengesahan ramalan telah dijalankan melalui peramal nyata sebagai kaedah berkategori. Selain daripada itu, kaedah pengesahan rentas dan kaedah root mean square error (RMSE) telah digunakan untuk memeriksa konsistensi perubahan kebarangkalian dan kekuatan matriks yang dikehendaki. Secara khususnya, tiga kawasan kajian bernama Lembah Frizi, Joestan dan Chalus dengan pelbagai pembolehubah hidro-iklim telah dipilih di mana kaedah yang dicadangkan telah dilaksanakan.

Dari kajian ini, telah didapati bahawa indeks kemarau metereologi Deciles, iaitu satu kaedah bukan-parametrik merupakan indeks yang sesuai. Kaedah lengkuk tempoh masa aliran (FDC) telah dipilih untuk mengkategorikan kejadian kemarau hidrologi sebagai satu pendekatan analog dengan indeks Deciles tersebut. Berikutan ini, aras ambang dalam Q_{50} dan Q_{95} telah digunakan untuk membezakan aras-aras keseriusan kemarau hidrologi yang saling berkaitan.

Matriks Hidro-Iklim (HCM) menunjukkan bahawa satu matriks dengan satu skala-masa adalah bersesuaian dengan lembangan kecil seperti Frizi, dan sebaliknya, untuk lembangan besar seperti Chalus dan Joestan, satu matriks skala-pelbagai dikira lebih sesuai. Oleh itu, kebarangkalian berlakunya peristiwa di Lembangan Frizi telah menunjukkan bahawa respon hidrologi ke atas variasi iklim berlaku dalam jangkamasa yang pendek. Perbandingan nilai-nilai kebarangkalian berkaitan dengan Sungai Frizi telah menunjukkan bahawa kebarangkalian berlakunya kemarau akan bertambah sebanyak 64.5% apabila keadaan meterologi berubah dari 'Basah' kepada 'Sangat Kering' pada bulan berikutnya di lembangan ini. Jelaslah bahawa 'Kemarau Teruk' sebagai satu lagi keadaan metereologi mempunyai impak penting ke atas kejadian kemarau hidrologi semasa tiga bulan berikutnya dalam kajian kes ini. Di Lembangan Joestan, sewaktu keadaan metereologi berubah dari keadaan Basah kepada kemarau Sederhana, lembangan sungai itu akan dilanda kemarau dengan kebarangkaliann 76%. Proses ini akan berterusan dengan kebarangkalian 58%, sehingga empat bulan berikutnya di lembangan berkenaan. Dalam kes Lembangan Chalus, sekiranya lembangan itu dilanda dengan permulaan kemarau metereologi yang teruk dalam bulan tertentu, aliran sungai kemarau hidrologi akan berlaku, dengan kebarangkalian kejadian sebanyak 53.4% dengan tiga bulan penangguhan.

Kebarangkalian pengesanan (Kadar melanda) menunjukkan bahawa pengesahan prestasi ramalan matriks hidro-iklim (HCM) boleh diambil sebagai satu ramalan yang memuaskan. Demikian juga, keputusan daripada ujian kaedah pengesahan-rentas dan RMSE menampakkan perubahan kebarangkalian yang konsisten dalam matriks yang diperolehi, yang demikian HCM sebagai satu matriks rujukan tampil cemerlang dalam ujian keteguhan. Sewajarnya, dari sudut pengurusan lembah sungai, perlaksanaan kaedah yang dicadangkan ini dalam memberi amaran terhadap kemarau yang bakal berlaku merupakan satu faedah yang paling ketara.

Kata Kunci: Indeks Deciles, Indeks Kemarau Hidrologi, Rantaian Markov, Masa Keterlewatan, Matriks Kebarangkalian Peralihan. Matriks Hidro-Iklim, Matriks Ramalan, Keadaan Hidrologi

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure **Page**

LIST OF ABBREVIATIONS

AGBM:	Australian Government Bureau of Meteorology
CMI:	Crop Moisture Index
CZI:	China Z-Index
DAI:	Drought Area Index
DI:	Deciles Index
DMCSEE:	Drought Management Centre for South-eastern Europe
DSIe:	Drought Severity Index
ED:	Extreme Drought
EDI:	Effective Drought Index
ESCAP:	Economic and Social Commission for Asia and the Pacific
EW:	Extreme Wet
FDC:	Flow Duration Curve
GPCC:	Global Precipitation Climatology Centre
HCM:	Hydro-Climatological Matrix
HDI:	Hydrological Drought Index
IDS:	Incipient Dry Spell
IPCC:	Intergovernmental Panel on Climate Change
IWMI:	International Water Management Institute
LOOCV:	Leave-one-out cross-validation
MA:	Moving Average

MAN:	Much Above Normal
MCM:	Markov Chain Model
MCZI:	Modified China Z-Index
MD:	Mild Drought
MDI:	Meteorological Drought Index
MRR:	Mediterranean Regional Roundtable
MRWC:	Mazandaran Regional Water Company
N:	Normal
NAO:	North Atlantic Oscillation
NCAR:	National Centre for Atmospheric Research
NCEP:	National Centres for Environmental Prediction
ODTPM:	One-Dimensional Transition Probability Matrix
PDF:	Probability Distribution Function
PDSI:	Palmer Drought Severity Index
PHDI:	Palmer Hydrological Drought Index
PNI:	Percent of Normal Index
POD:	Probability of Detection
RAI:	Rainfall Anomaly Index
RCS:	Reference Climate Station
RDI:	Reclamation Drought Index
RMSE:	Root Mean Square Error
SD:	Severe Drought

LIST OF NOTATIONS

v_i :	Volume of deficit
t_i :	Time of occurrence
d_i :	Duration
P_{ij} :	Transition probability from the *i* state to the *j* state
E_V :	Estimation or measure of the precision of the measurement
□ :	Mean of data
EF_{Qi}:	Exceedeance frequency
$P_{(N, W)}$:	Transition probability from the N to the W state
$[P_{ij}]$:	Transition Probability Matrix
ΔT:	Lag time
$(Tqi\text{-}Tpi\,';Ti)$	*i*th lag time of the Basin
D_m:	Meteorological Drought state
D_h:	Hydrological Drought state
$P_{(D_m, D_h)}$	Transition Probability from the D_m to D_h
s_{mi}:	i*th* meteorological state
s_{hi}:	j*th* hydrological state
fs_{mi}:	Frequency of occurrence of i*th* meteorological state
fs_{hi}:	Frequency of occurrence of j*th* hydrological state
H:	Hit rate
W_h:	Hydrological Wet state
D_h:	Hydrological Drought state
Dh | S.Dm	Hydrological Drought based on Severe meteorological drought

CHAPTER 1

INTRODUCTION

1.1 General

A good understanding of the natural drought phenomenon, as well as its meteorological and hydroclimatological causes, is essential for management of the limited water resources. Drought occurs in both low- and high-rainfall areas, in most regions of the world, and often on a yearly basis. It is important to identify the trend over time and to determine whether drought is becoming a more frequent and severe event. Concern exists that the threat of global warming may increase the frequency and severity of extreme climate events such as flood and drought in the future (IPCC, 2001). Basically, drought is a phenomenon that originates from a prolonged deficiency in precipitation over a region. Accordingly, meteorological drought is usually defined on the basis of the departure of precipitation from the normal condition or the long-term average amount and duration of the dry period. Meanwhile, hydrological drought is related to the effect of precipitation deficit on surface water, streamflow or groundwater, reservoirs and lake levels. In other words, it is a sustained and regionally extensive occurrence of below average natural water availability, and can thus be characterized as a deviation from the normal conditions of variables, such as precipitation, soil moisture, groundwater and streamflow (Tallaksen & Lanen, 2004). Due to the complexity caused by atmospheric and climatological phenomena, hydrological drought is a natural hazard and therefore cannot be prevented.

Besides, the impacts of droughts on environmental, natural resources and its other aspects can be reduced through mitigation and preparedness. Constant monitoring of the hydrological system, identification of drought characteristics, forecasting of drought occurrences, and their probability of recurrence, preferably built into an early warning system, can help in the preparation. In more specific, hydrological drought prevails after meteorological events within time lag. Hence, drought monitoring and forecasting can help to improve the decision making process for water resources management, drought mitigation and to reduce the negative impacts. The magnitude of drought impacts may increase in the future as a result of an increased frequency of the occurrence of the natural event (i.e. meteorological drought), changes in the factors that affect vulnerability, or a combination of these elements (Wilhite, 2002).

It is important to note that the characteristics of droughts are expressed in terms of drought index and intensity-duration-frequency. Many methods proposed for drought monitoring using indices, such as standardized precipitation index (SPI), Palmer Hydrological Drought Index (PHDI), and have been developed (Hayes *et al.*, 1999; Heim, 2000; Cancelliere *et al.*, 2007). As for the stochastic nature of climatological phenomenon like precipitation, some of the forecasting techniques for the characterization of meteorological drought have been developed and implemented, such as Markov chain (Isaacson and Madsen, 1976; Moreira *et al.*, 2006; Cancelliere *et al.*, 2007; Paulo, 2005, 2008). Similarly, knowledge of transition probabilities from a certain drought class to other drought conditions and its prediction for time scale ahead have also presented as a useful method (Cancelliere *et al.*, 2007; Paulo 2008). Therefore, a method that relates the hydroclimatological variables which enable hydrological drought to be analyzed based on meteorological drought, would be significant and valuable.

1.2 Statement of the Problem

In general, hydrological droughts arise after meteorological droughts. Hence, first meteorological drought occurs and its persistence over time and space leads to the occurrence of hydrological droughts. Accordingly, it takes more time for the precipitation deficiency to affect the components of the hydrological system, such as soil moisture, stream flow, reservoirs and groundwater levels. Meanwhile, the probability of occurrence of meteorological droughts and hydrological droughts varies accordingly.

Although from the viewpoint of meteorological droughts, the real extent of drought phenomenon is very useful, it does not bring attention to hydrological droughts as water managers are only involved with streamflow at the outlets of basins as points in space. In addition, because of the intricacy of the global hydrological cycle, it is virtually impossible to detect the source of droughts (Nalbantis & Tsakiris, 2009). Hence, forecasting the start of a drought event is practically a very complex issue, and for this reason, relevant investigations by researchers still have not shown any clear results. Some questions such as when a drought begins and when it finishes, how and what unfavourable effects it may cause and many other questions, have obviously not been answered or correctly addressed (Cordery & McCall, 2000; El Hassani, 2002). Meanwhile, identifying when a drought starts varies from place to place, and may also be based on different criteria. According to the above mentioned issues, there has been no index or a single pointer that can pinpoint the onset or severity and frequency of the occurrence of the drought event (ESCAP, 2010). So far, most studies have focused on meteorological droughts in the world. Researchers and hydrologists give more attention to the issue of how meteorological drought or shortage of precipitation will affect the hydrological system. In this respect, some important issues regarding the hydrological drought need to be investigated. The first one is determining how long it will take for the hydrological conditions to be affected by the meteorological drought. The second one is finding the probability of the occurrence of hydrological conditions with respect to lag time. Furthermore, it is crucial to determine the most probable hydrological condition, after a certain condition of meteorological drought has occurred.

1.3 Objectives of the Study

The main aim of this research is to attain a method to be used in predicting the probability of the occurrence of various hydrological conditions according to various meteorological conditions by employing appropriate drought indices. Accordingly, the objectives in this thesis work can be summarised in five key objectives elaborated by several specific tasks, as follows:

i. To determine the appropriate meteorological drought index (MDI);
ii. To estimate the different meteorological drought conditions using the properly selected index;
iii. To identify the proper hydrological drought index (HDI);
iv. To determine the lag time between meteorological and hydrological states and;
v. To forecast the probability of the occurrence of different hydrological states

based on various meteorological states according to their time lag.

1.4 Significance of the Study

The results of this study are significant in predicting the probability of occurrence for the different hydrological status based on the meteorological conditions for longer time step. In other words, the time lag of the hydrological drought occurrence after an onset of a meteorological drought has been analyzed. Hence, the implementation of this particular method is an important step and a good opportunity for risk reduction and management of water resources. A lot of resources and methods for analyzing meteorological drought have been discussed and proposed (Gibbs & Maher, 1967; Mckee *et al.*, 1993; Hayes *et al.*, 1999; Lloyd and Saunders, 2002; Tsakiris & Vangelis, 2005; Paulo *et al.*, 2007). On the contrary, hydrological drought indices such as Palmer Hydrological Drought Index (PHDI), or Surface Water Supply Index (SWSI) are, overall, data requiring and computationally intensive (Nalbantis & Tsakiris, 2009). It is important to highlight that forecasting hydrological droughts that follow meteorological droughts with a lag time can improve the decision making process for water resources management, drought mitigation and so on. Due to its complexity, however, there are only a few investigations carried out on this issue, and the focus has always been on the meteorological droughts. Recently, several studies were done to obtain a simple and effective hydrological drought index (see for example, Nalbantis, 2008; Nalbantis & Tsakiris, 2009). Similarly, reviews and studies on this issue are also in progress. Therefore, finding a method that focuses on hydrological droughts, based on hydroclimatological variables, is apparently valuable. Meanwhile, the lack of streamflow data or its insufficiency is of major concern for hydrological condition simulation via time series analysis. In those cases where data are adequate, the governing of its probability distribution function (PDF) is an important constraint that makes the technique inefficient. Hence, when the precipitation time series is available, applying the result of such study will be very useful. Apparently, a generalized model for the areas of hydroclimatological homogeneity would be an efficient approach.

1.5 Scope of the Study

The scope of this study covers the development of a model to predict the transition probability of different meteorological states to different hydrological states. For this purpose, the methodology was employed in three regions located in the north, north-west and north-east of Iran with different aspects of size, climate and length of records. The first region is the Joestan watershed, with a semi-wet climate, an annual precipitation of 547 mm, and a drainage area of 412 km^2 located in the north-west of Tehran, the capital of Iran. The second region is the Chalus watershed, with a semi-arid temperate climate, an annual precipitation of 318 mm, and drainage area of 1600 km^2 located in the north of Iran near the Caspian Sea. Meanwhile, the third region is the Frizi watershed, with a semi-arid cold climate, an annual precipitation of 372 mm, and a drainage area of 273 km^2. The following describes the detailed scope of this study:

i. Collecting the daily precipitation and discharge time series data at the related stations and extracting of monthly and yearly data.

ii. Determining the meteorological drought classes using various indices.

iii. Selecting the appropriate meteorological drought index.

iv. Determining the transition-probability matrix (TPM) in different meteorological status by employing the stochastic method (Markov Chain Model: MCM).

v. Determining different classes of hydrological drought using a proper index.

vi. Developing the model of one-dimensional transition-probability matrix (ODTPM) by converting it into two-dimensional (TDTPM)

vii. Employing the model developed for forecasting the probability of occurrence of each hydrological state based on different meteorological states using precipitation and streamflow time series.

1.6 Limitation of the Study

A significant or negligible probability value depends on the sufficient frequency and distribution of events in each class. In this study, two sub-category of drought were considered in the extraction of a two-dimensional matrix. Clearly, more separation of classes for the meteorological/hydrological drought period based on the proposed methodology, a very long-term coincident time series of precipitation and streamflow are demanded. Hence, this theme can be seen as a limitation in the case of this current study.

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