WATER SUPPLY RESERVOIR OPERATION IN THE FRAMEWORK OF CLIMATE VARIABILITY AND CHANGE

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To my beloved family…

mek
siti noor rashidah abdul rahim
muhammad nasrizal, muhammad irfan, muhammad imran
fatini, farzana
brothers, sisters, and in-laws

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ABSTRACT

The optimal planning and operation of a reservoir system is getting more crucial particularly in view of the recent awareness of potential climate change. In particular, the incorporation of hydrologic uncertainties due to climate change into reservoir operation system requires comprehensive and long-term hydrological database which rarely available in most of the conventional reservoir design. The prime objective of the study is to formulate a multiple approach on the long-term reservoir operation optimization under the scarcity of observed hydrological data and with the influence of climate change. A combined research method using IHACRES for hydrological simulation, HadCM3 for emission scenario and Statistical Downscaling Model were developed along with a Mixed Integer Linear Programming (MILP) for reservoir operation optimization. These approaches were applied to a single purpose Sg Layang Resevoir, that is one of the most prominent water supply reservoir located in Johor State, Malaysia. The climatic variables obtained from general circulation model (GCM) were downscaled corresponding to HadCM3 emission scenario and used in climate change impact analysis. The SDSM was used to produce 100 synthetic climate time-series for 90 years of the participating station, representing the climate change projection and baseline period. With respect to the baseline data, an apparent increase in temperature (1.2 degree Celsius between time periods) and rainfall was observed. The deterministic optimization exercise is performed repetitively for a number of case scenarios based on weekly reservoir's inflows derived from the projected climate change in a way to determine the optimal operation rule and policy which are based on total pumping volume and pumping cost. Corresponded to the future inflows, the pumping volume has shown an increase trend particularly during southwest monsoon, transition between seasons and autumn. Judged from the decreasing rate of the streamflows, a 34 to 40% increase in the projected monthly pumping volume is anticipated. An opposite scenario is observed during northeast monsoon season which shows a decreasing trend of 28% to 46%. At various degree of statistical reliability, the optimal operational pumping curves of the reservoir were established. These curves provide some basic information on the monthly pumping requirement from various sources of inflow to sustain the reservoir storage and demand. These operation curves are of very useful guidelines for reservoir operators in making decision to follow an optimal pumping operations schedule onsite. Such research findings were expected to generate a general awareness to the public water authorities on the potential long term effect of climate change to the reliability of reservoir operating system.

ABSTRAK

Kepentingan pengoptimuman operasi dan perancangan pengurusan sistem takungan telah meningkat terutamanya dengan kesedaran terhadap kesan potensi perubahan iklim. Khususnya, gabungan faktor ketidakpastian hidrologi disebabkan oleh perubahan iklim terhadap operasi sistem takungan memerlukan pengkalan data hidrologi yang komprehensif yang jarang terdapat dalam kebanyakan takungan konvensional. Objektif utama kajian ini ialah untuk merumuskan satu pendekatan pelbagai bagi pengoptimuman operasi takungan jangka panjang pada keadaan kekurangan data cerapan hidrologi dibawah pengaruh perubahan iklim. Gabungan kaedah kajian menggunakan IHACRES sebagai model simulasi hidrologi, senario pemancaran dari HadCM3 bagi model penurunan skala statistik (SDSM) telah dibangunkan bersama Program Integer Linear Bercampur (MILP) untuk menghasilkan operasi reservoir yang optimal. Pendekatan kajian ini diaplikasikan keatas takungan bertujuan tunggal Reservoir Sg Layang, iaitu satu takungan bekalan sumber air penting di Negeri Johor, Malaysia. Pemboleh-ubah iklim dari model peredaran umum (GCM) diturunkan skalanya selaras dengan senario HadCM3 bagi kegunaan didalam analisis impak perubahan iklim. SDSM dipilih untuk menghasilkan 100 siri data iklim sintetik bertempoh 90 tahun untuk setiap stesen pilihan yang mewakili ramalan perubahan iklim dan tempoh iklim dasar. Daripada rujukan terhadap data dasar, satu peningkatan jelas dalam suhu bagi semua musim (1.2 darjah Celsius antara sela masa) dan hujan telah ditunjukkan. Proses pengoptimuman dijalankan secara berulang bagi pelbagai kes senario dengan menggunakan siri data kadaralir mingguan yang dijanakan bagi memperolehi polisi operasi reservoir yang optimal berasaskan isipadu dan kos pengepaman. Hasil daripada aliran masuk masa depan yang dijanakan, jumlah isipadu pengepaman menunjukkan corak menaik terutama semasa monsun baratdaya, peralihan antara musim-musim dan musim luruh. Dinilai dari penyusutan kadar aliran sungai, satu unjuran peningkatan jumlah isipadu pengepaman bulanan diantara 34% hingga 40% telah dijangkakan. Sebaliknya pada musim timurlaut anggaran kadar pengepaman bulanan menurun diantara 28% hingga 46%. Dari berbagai tahap keboleh-harapan statistik, lengkung operasi optimal pengepaman ke takungan diterbitkan. Lengkung operasi ini menyediakan panduan operasi berkenaan keperluan pengepaman bulanan dari berbagai sumber aliran masuk bagi mengekalkan simpanan reservoir dan memenuhi permintaan semasa. Lengkung operasi ini juga boleh dijadikan sebagai garis panduan yang berguna kepada pengendali takungan untuk menentukan penjadualan operasi pengepaman yang optima ditapak. Hasil kajian ini dijangka mampu menjana kesedaran umum kepada pihak berkuasa bekalan air diatas potensi kesan jangka panjang dari perubahan iklim terhadap kebolehpercayaan sistem pengendalian takungan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

$\alpha^{(s)}$	-	Recession rate in linear module
$\beta^{(s)}$	-	Peak response in linear module
$\tau^{(s)}$	-	Slow flow time constant in linear module
ε_i	-	Modeling error
α_i	-	Weight from predictor-i (input) directly to output of skip layer connection
β_j	-	Connection weight from the *j*-th hidden node to the output node of ANN architecture
ω_{ji}	-	Bias weight in hidden layer of ANN architecture
β_o	-	Bias weight in output layer of ANN architecture
A_a	-	Area per unit active storage volume above dead storage
A_o	-	Reservoir surface area corresponding to the dead storage volume at 10m reservoir level
c	-	Mass balance parameter in non-linear module
e_t	-	Rate of evaporation
f		Temperature modulation parameter in non-linear module
h_j	-	Hidden node output of sigmoid function
Q_{in}	-	Total daily inflow
Q_t	-	Net surface inflow to reservoir during period *t*
t_w	-	Reference drying rate parameter in non-linear module
u_k	-	Effective rainfall
x_k	-	Streamflow
ΔS	-	Difference of reservoir storages
τ_k	-	Drying rate
ϕ_k	-	Soil moisture index

LIST OF ABBREVIATIONS

ANN	Artificial Neural Network
AOGCM	Atmosphere-Ocean General Circulation Model
DID	Malaysia Drainage and Irrigation Department
DP	Dynamic Programming
EC	Evolutionary Computation
EDA	Exploratory Data Analyses
FFNNSL	Feedforward Neural Network with skip layer connections
FFNN	Feedforward Neural Network without skip layer connections
GCM	General Circulation Model (Global Climate Model)
HadCM3	Hadley Center Coupled Model, version 3
INC	Malaysia's Initial National Communication
IPCC	Intergovernmental Panel on Climate Change
LAM	Limited-Area Model
LARS-WG	Long Ashton Research station Weather Generator
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MMD	Malaysia Meteorological Department
NC2	Second National Communication
NCEP	National Center for Environmental Prediction
NLP	Non-Linear Programming
RCM	Regional Climate Model
RegHCM-PM	Regional Hydrologic-atmospheric Climate Model of Peninsular Malaysia
RF1	Rainfall Station at Station No 1539136
RF2	Rainfall Station at Station No. 1539134
RF3	Rainfall Station at Station No. 1538117

RF_{avg}	Average Rainfall
SDSM	Statistical Down-Scaling Model
SRES	Special Report on Emissions Scenario
T_{avg}	Average Temperature
TLFN	Time Lagged Feedforward Neural Network
T_{max}	Maximum Temperature
T_{min}	Minimum Temperature
UNFCCC	United Nations Framework Convention on Climate Change

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Urbanization processes is a continuing phenomenon not only in developing countries but also in developed countries. There has been increasing interest and concern on the use of our natural resources specifically water, that has been accorded as the highest priority in the global development agenda. Forests, plantations, grasslands and others are being continually converted into residential areas, commercial and industrial complexes, shopping centers and other facilities. One of the consequences of urbanization with which engineers, planners and decision makers should deal with is the increase demand of water supply for domestic and industrial usage that requires a greater emphasis in managing the water resources and water supply in an integrated manner.

The demand for a proper and appropriate water resources development and water supply services has increased steadily as a result of the rapid socio-economic development and environmental consciousness. As the population expands, rapid urbanization, industrial expansion and climate change, besides contributing to rising water pollution, the strains places on the earth's natural resources also increase.

There is a strong agreement among the scientific community that the climate change is taking place with evidence from the increase in earth's surface temperature due to greenhouse gas emissions. The Intergovernmental Panel on Climate Change (IPCC) for instance has reported that the average global temperature increases of

about 0.2°C per decade is anticipated over the next twenty years from the previous assessment of 0.6°C to 0.74°C (IPCC 2007). Changes in global climate would have significant impact on regional and local hydrological regimes in terms of key climatic variables, which in turn will affect the future water supply sources in the region. The Malaysia's Initial National Communication (INC) to the United Nations Framework Convention on Climate Change (UNFCCC) describes the quantitative impact of climate change to surface runoff. For instance, with 10% less rainfall and a 1°C increase in temperature the runoff would reduce between 13% to 35% and 14% to 43% during the wet and dry months, respectively. Similarly, when temperature rises by 3°C, the reduction in runoff ranges between 13% to 48% and 17% to 53% during the wet and dry periods, respectively (MOSTE, 2000). In the Second National Communication (NC2) report (NRE, 2010), emphasis is given to the water resources sector as a result of climate change projections that states the disruption of water supply is expected to occur in urban areas during extreme drought events.

With such climatic variation trend, it would be a great challenge for water resources managers to develop a comprehensive understanding of the expected impacts on climatic variability and change and its consequences to the water supply system. Subsequently, an optimal reservoir operation and management systems shall be planned in order to improve the management strategies for reliable water supply particularly during the long dry spells. The factors of future land used pattern and the predicted climatic conditions could be considered to accommodate the ever growing demand of freshwater supply as well as to avoid water shortages that may disrupt overall economic activities.

1.2 Statement of the Problem

As the total quantity of available water is finite with increasing demand at geometrical rates, Malaysia, a tropical country relatively rich in water resources, is not exempted from facing numerous water related problems, such as water shortages,

water pollution, and floods. It is reported that 98% of the total national water resources originates from surface water which easily be affected by long dry spells. A few incidents in the past where drought caused serious water rationing and hardship to 1.8 million residents of Kuala Lumpur and other townships in Klang Valley in 1998. In similar case, Malacca state also experienced water rationing in most part of the state when the level at Durian Tunggal Dam recedes to a critical level, i.e. the main water supply reservoir of the state, reached 50% of its capacity in 1991.

Recent local studies also suggest that due to climate change there is a likelihood of a uniform annual increase in temperature and caused the regional precipitation patterns vary considerably (Zakaria and Shaaban, 2007; Shaaban *et al*., 2011) for most of the watersheds of the country. Regarding the annual rainfall, the east coast region is expected to experience 10% increase while the west coast and southern areas may drop by 5% (Zakaria and Shaaban, 2007). Similarly, the projected increase of annual surface temperature in between 1.0°C to 1.5°C for a future period of 25 years (Salmah and Liew, 2008; Tangang *et al*., 2007) over all regions may have directly influenced the potential evapotranspiration and subsequently the quantity of the runoff component. Consequently, the availability of water resources in the region would be affected whereby in the past, many operational decisions depend explicitly on the assumptions about future climatic conditions. A few studies have been carried out to incorporate the variation of climate change factor in reservoir planning and operation (Eum and Simonovic, 2010; Karamouz *et al*., 2012). Therefore there is a need to develop an integrated approach to consider these factors on climate change impact on streamflow and derive adaptive policies for possible optimal reservoir operation.

Considering the continual growth of urbanization and industrialization and the effect of climate change, an optimal operation of a water supply reservoir demands an immediate attention to ensure a long term availability and sustainability of water supply, including the conservation of water in future.

The reliability of a water supply reservoirs system depends on the appropriate rule for optimal operation. It is presumably a function of multiple and complex factors which basically governed by hydrologic uncertainties due to both supply-demand and climatic variability and change. Such generic understanding become the impetus of the present study with primary aim is to provide detail understanding through a case study of Sg Layang Reservoir.

1.3 Objectives of the Study

The principal objective of this study is to derive more realistic and reliable operational rules for a water supply reservoir system with multi-source dependent in a way to reduce the gap between theoretical assumptions and practical implementations. The specific objectives of this study that lead to a logical progression through the thesis have been identified and are summarized as follows:

1. To generate a long-term streamflow data of the study area for climate change scenario using conceptual model

2. To generate rainfall and temperature at catchment scale for climate change scenario using statistical downscaling model by employing climate variables of Global Circulation Model (GCM).

3. To evaluate the probable reservoir inflows in a way to investigate the possible changes in water availability under the framework of future climate variability and variation in pumping operation of multi-source reservoir system.

4. To develop a reservoir optimization model based on mixed integer linear programming algorithm to produce an optimal reservoir operation rules.

1.4 Research Approach and Scope of Work

The scope of the study is focused on the development of optimization model to derive a general monthly reservoir operating policy using historical data and to account the impacts of climate change and the uncertainties of inputs arise from the random nature of the inflows to the system in addition to other various sources.

The specific aims that lead to the model development and analysis of the proposed work can be summarized as follows:

- To assess the actual performance of the current reservoir operating policy.
- To evaluate the historical trends in precipitation as the basis of selecting the local representative station
- To develop a rainfall-runoff model and model selection to simulate historical and future streamflows under current and future climate scenarios.
- To evaluate the performance of downscaling models for their ability to convert large-scale GCM outputs into finer resolution daily time series of local precipitation and temperature at local meteorological stations.
- To simulate the daily inflows to Sg Layang Reservoir for both current climatic conditions and future climate scenarios using daily rainfall and temperature time series generated from the calibrated downscaling model and the corresponding GCM predictors and analyze the inflow variation due to climate change.
- To develop a deterministic optimization model formulated based on mixed integer linear programming algorithm in order to produce an optimal reservoir operation policy of the Sg Layang Reservoir system with the overall objective is to minimize the operational pumping costs from different sources considering the peak and off-peak power prices.
- To derive an optimal reservoir operation policy based on the above optimization model that takes an account of population increase and climate change.
- To compare the operational results obtained from the simulation models with the

actual operational curve produced from historical operation of the reservoir for the evaluation of the usefulness of optimal operation policies based on performance criteria.

- To analyze the operating policy to take into account of the system maximum capacity and future increase in water demands.
- To develop reservoir pumping operating curve involving different confidence intervals and change in future demands which are more appropriate for practical applications.

1.5 Significance of the Study

Optimal operation of reservoir has been an active area of water research over the years. Various techniques have been developed and adopted for reservoir operation by incorporating the aspect of uncertainties due to stochastic nature of inflows and demands.

For a reservoir that depends not only upon catchment runoff but other sources of hydrologic inflow, the available and effective volume is subjected to numerous constraints including reservoir inflow conditions, increasing water demands, pumping, and reservoir storage. These constraints vary and may change considerably during the project life which calls for a modified operational policy.

Most of reservoirs found in Malaysia are single purpose reservoirs managed by separate authorities mainly either for the purposes of hydropower generation, water supply, flood control or irrigation. They are operated based on the skill and experience of the reservoir managers that generally provides operation strategies in the form of general operating curve for reservoir releases and pumping according to the current reservoir level, hydrological conditions and water demands. Such operating practices, however, were found not adapted well to changing in hydrologic and climatic conditions. In addition, due to the lack of information on inflows into

the reservoir various hydrologic variables, a more systematic and acceptable approach is crucial to establish for optimization of the operation.

One of the most prominent water supply reservoirs found in the southern region of the country is Sg Layang Reservoir. The general annual water supply-demand analysis of the Sg Layang reservoir system characteristics has shown that in general, the current supply exceeds the demand, which could be due to an excessive pumping during the unsuitable period. If we were based on the current supply trend the future demand could be increased by 40%. As such, the current practice must be enhanced by considering the followings:

- optimizing pumping operation with respect to the demand
- developing a specific reservoir operation technique by incorporating the factor of uncertainties due to stochastic nature of inflows and demands
- developing an optimal operation rule of the reservoir in response to both nonclimatic and climatic changes

Considering the need of future reservoir system expansion, analysis based on annual averages with the upper bound supply level, the current demand can probably be extended by 1.56 times of the present system characteristics. However, monthly variations due to pumping restrictions, river depth, lower reservoir uncertainties, and inflow from watershed, the pumping cost could reduce significantly. Therefore, there is an opportunity to investigate and optimize the water supply reservoir operation in the framework of climate variability and change to establish a more reliable reservoir operating policies for utilizing water of desired quantity over the operational period.

1.6 Thesis Outline

The thesis is organized in six chapters (including the introduction as Chapter 1) as follows;

Chapter 2 presents a summary of the available literatures which are relevant to the development of the optimal operation of reservoir system in the framework of climate variability and change. It briefly introduces a review of rainfall-runoff models, downscaling methods and model selection for assessing climate change impacts on reservoir systems, and mathematical programming related to the optimization of reservoir systems. Emphasized is given to climate change and downscaling methods, describing advantages and limitation of each method and highlighting several comparative studies and models applications that are related to the current study.

Chapter 3 provides a description of study area and availability of data. A comprehensive data collection includes the historical hydrometeorological data for the hydrological and climate downscaling models calibration and analysis, and climate scenario predictor variables consisting of re-analysis data and large-scale atmospheric variables used for statistical downscaling model input.

Chapter 4 describes the methodology used to select the hydrological modeling approach to simulate inflows to the study reservoir, evaluate the downscaling models, develop future climate change scenarios, and derive an optimal operation policy for the reservoir.

Chapter 5 provides the results of a comprehensive assessment of uncertainty for the selection of the best downscaling model to generate the possible future scenarios of local meteorological variables of precipitation and rainfall at representative local station. The results of climate downscaling become the inputs to the calibrated hydrologic model to generate daily streamflow for the investigation on

how changes in water availability under future climate scenarios will effect the optimal operation of pumping of multi-source reservoir system.

Chapter 6 concludes the major findings of the work described in the thesis and recommendations for future study.

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