UNIVERSITI PUTRA MALAYSIA

DECISION SUPPORT SYSTEM FOR WATER ALLOCATION IN A RICE IRRIGATION SCHEME UNDER CLIMATE CHANGE SCENARIOS

NKULULEKO SIMEON DLAMINI

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By

NKULULEKO SIMEON DLAMINI

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

May 2017

DEDICATION

This thesis is dedicated to;

My late parents for their endless love and wishes for their son to achieve this higher dream,

My wife lolo who has played a significant role during the journey of this study,

My dota Noma who endured hardships all the years without a father at home,and,

My best friend, Kenyatta, who has been a source of inspiration to me throughout my study.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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May 2017

Chairman : MD Rowshon Kamal, PhD
Faculty : Engineering

Irrigation is the major user of total water use in Malaysia for production of rice, its staple food, and therefore knowledge on future changes in irrigation demands due to climate change is critical for managing water allocations. General Circulation Models (GCMs) suggest that increase in emission of greenhouse gases will have significant implications on a number of hydrological processes at local scale including future streamflow fluctuations and evapotranspiration. These issues need to be quantified and accounted in future irrigation allocation and planning. The present thesis describes the development of a decision support system (DSS) tool for modelling water allocations in a local rice irrigation scheme under climate scenarios. The DSS is developed with climate outputs from GCMs, hydrological data, irrigation canal data and crop data. Four basic modules; Stochastic Rainfall Generator, Reference Evapotranspiration, Water Demand and Water Allocation Modules were developed and integrated in the MATALAB graphical user interface.

Future climate scenarios for the study area were extracted from ten global climate models (GCMs) under three Representative Concentration Pathways (RCPs) scenarios (RCP4.5, RCP6.0 and RCP8.5) obtained from the Program for Climate Model Diagnosis and Inter-comparison (PCMDI). Future projections of multi-GCMs in Upper Bernam River basin have shown that temperature will increase under scenarios, with the largest changes during the dry season months (February–June). Projected increase in maximum temperature ranges from 0.7–1.6 °C, 0.5–1.9 °C and 0.8–3.3 °C, under RCP4.5, RCP6.0 and RCP8.5, respectively. Rainfall projections showed variation between the two cropping seasons. The RCP4.5, 6.0 and 8.5 respectively projected average changes of –2.4%, –3.2% and –3.7% for the dry season months, and 1.0%, 0.8% and 2.4% for the wet season months. The results showed the watershed will likely experience warmer periods accompanied by dry climate during dry season months.

The impact of climate change on the flows of the Upper Bernam River Basin was studied using the SWAT hydrological model. The model was evaluated using 25 years of records (1981-2005). Results of the coefficient of determination, (R^2), Nasch-Sutcliff, (NSE) and Percent Bias, (PBIAS) were 0.67, 0.62 and -9.4 during calibration period, and 0.62, 0.61 and -4.2 during validation period. Future streamflow projections with the validated SWAT model showed that during the dry season months, annual streamflow is likely to decrease by up to (−6.6%) by the late century (2080s). Streamflow is predicted to increase by up to 11.4% in the same future period during the wet season. On the basis of these results, it can be inferred that the water resource of the Bernam River Basin could be sufficient up to the end of the century. However, these results also highlight some potential risk that climate change could impose on rice production during future dry season months. This requires integrated water management solutions to ensure sustainable rice production.

A user-friendly climate-smart decision support system (CSDSS) model was developed for modeling irrigation water allocation in Tanjung Karang Rice Irrigation Scheme (TAKRIS) under climate change scenarios. First, climate scenarios are downscaled within the system by perturbing observed series using change factors derived from GCMs outputs. The FAO-56 Penman-Monteith model was used for estimating reference evapotranspiration under future forcing. A stochastic rainfall model was adopted to simulate future rainfall series using the first-order two states Markov Chain Approach based on future emission scenario forcing. Then water demand model was developed from reference evapotranspiration and crop coefficient. Generated irrigation water requirements are converted into irrigation deliveries based on canal command area. The model is capable of generating several realizations of irrigation deliveries using individual GCMs and/or multi-models (ensemble) projections. The model was evaluated for irrigation deliveries at the study area using one year water supply data. The analyses showed that the average weekly irrigation supplies for measured supplies (without climate change) and simulated supplies (with climate change) under RCP4.5, RCP6.0 and RCP8.5 scenarios were respectively, 2.69 m^3/s, 2.00 m^3/s, 2.19 m^3/s and 1.94 m^3/s during off-season, and 2.55 m^3/s, 1.47 m^3/s, 1.76 m^3/s and 1.49 m^3/s during main-season. The results revealed that actual supply (without climate climate) was higher than the model simulated supplies (with climate change) for all the three climate scenarios in both cropping seasons. This could be suggestive of poor scheduling in the scheme, leading to undue excess water supply.

The application of the model in assessing long-term changes in irrigation water demands in response to the projected changes in reference evapotranspiration and effective rainfall is demonstrated using three future time slices (2020s, 2050s and 2080s) with respect to baseline period (1976-2005). The results generated from the DSS model suggest that monthly reference evapotranspiration is likely to increase in all scenarios up to 14.2% under RCP8.5 during February to July. Similarly, annual effective rainfall is predicted to slightly increase in future although with monthly variations. The irrigation water needs are projected to increase in the off season months and decrease during the main season months. At the present, the scheme requires a supply of 610 mm and 404 mm depth of water, for the respective off and main seasons, while future requirements will reach up to 675 mm and 376 mm under the highest scenario (RCP8.5). The results will be helpful for water managers in planning adaptation measures in those months where rainfall is predicted to be not sufficient to fulfill the crop water demands.

Based on the results, it can be inferred that the DSS can serve as a practical tool for simulating climate scenarios based on the outputs from global climate models (GCMs) to carry out standard calculations for reference evapotranspiration, rice water requirements and irrigation demands, for daily and/or periodic water allocations under climate scenarios. This will allow Water Management Authorities to assess climate change signals and thus promote adoption of appropriate adaptation strategies that could potentially lead to more sustainable water management at farm level. Additional beauty of the model is its flexibility updating future climate scenarios as new climate models become available, and also, with suitable locally derived data the tool can be extended to other geographical locations. Finally, the DSS has some application limitations which are highlighted in the thesis, and this form basis for future improvements.

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

SISTEM SOKONGAN KEPUTUSAN PERUNTUKAN AIR UNTUK SKIM PENGAIRAN PADI DI BAWAH SENARIO PERUBAHAN IKLIM

Oleh

NKULULEKO SIMEON DLAMINI

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Sektor pengairan merupakan pengguna utama air di Malaysia untuk penghasilan beras sebagai makanan ruji, oleh itu pengetahuan mengenai perubahan masa depan dalam keperluan pengairan yang berpunca daripada perubahan iklim adalah penting untuk menguruskan peruntukan air. Model Peredaran Umum ataupun dikenali sebagai General Circulation Models (GCMs) mencadangkan bahawa peningkatan dalam pelepasan gas rumah hijau akan mempunyai implikasi yang besar ke atas beberapa kitaran proses hidrologi pada skala tempatan termasuk perubahan aliran sungai dan evapotranspirasi pada masa depan. Isu-isu ini perlu dinilai dan diambilkira dalam peruntukan dan perancangan pengairan pada masa depan. Tesis ini menerangkan mengenai pembangunan alat sistem sokongan keputusan (DSS) untuk pemodelan peruntukan air di skim pengairan padi tempatan di bawah senario iklim. DSS ini dibangunkan berasaskan output iklim dari GCMs, data hidrologi, data terusan pengairan dan data tanaman. Empat modul asas telah dibangunkan dan diintegrasikan ke dalam pengaturcaraan MATLAB iaitu; generator hujan stokastik, penyejatpeluhan rujukan, modul keperluan air dan peruntukan air .

Senario iklim masa depan bagi kawasan kajian ini diambil daripada sepuluh model GCMs di bawah tiga senario RCPs iaitu RCP4.5, RCP6.0 dan RCP8.5 yang diperolehi daripada program perbandingan dan diagnosis antara model iklim (PCMDI). Unjuran masa depan pelbagai GCMs di hulu lembangan sungai bernam menunjukkan bahawa suhu dijangka meningkat di bawah semua senario, dengan perubahan terbesar pada bulan-bulan musim kering (Februari-Jun). Unjuran peningkatan julat suhu maksimum masing-masing adalah 0.7-1.6° C, 0.5-1.9° C dan 0.8-3.3° C, di bawah RCP4.5, RCP6.0 dan RCP8.5. Unjuran hujan menunjukkan perbezaan antara kedua-dua musim penanaman. Di bawah scenario RCP4.5, 6.0 dan 8.5 masing-masing dijangka perubahan purata -2.4%, -3.2% dan -3.7% untuk bulan-bulan pada musim kering, manakala 1.0%, 0.8% dan 2.4% untuk bulan-bulan pada musim hujan. Hasil kajian menunjukkan bahawa kawasan tadahan tersebut bermungkinan mengalami suhu yang lebih panas berserta iklim kering semasa musim kering.

Kesan perubahan iklim ke atas kadar alir bagi hulu lembangan Sungai Bernam telah dikaji menggunakan model hidrologi SWAT. Model ini telah dinilai dengan menggunakan rekod data selama 25 tahun (1981-2005). Keputusan pekali penentuan (R^2), Nash-Sutcliff (NSE) dan Peratus Pincang (PBIAS) adalah 0.67, 0.62 dan -9.4 semasa tempoh penentu-ukuran, dan 0.62, 0.61 dan -4.2 semasa tempoh pengesahan. Unjuran kadar alir sungai masa depan melalui model SWAT yang telah ditentu-sahkan menunjukkan bahawa ketika bulan-bulan musim kering, kadar alir sungai tahunan dijangka berkurangan sehingga (-6.6%) menjelang akhir abad (2080s). Kadar alir sungai dijangka meningkat sehingga 11.4% semasa musim hujan dalam tempoh masa depan yang sama. Berdasarkan keputusan ini, boleh disimpulkan bahawa sumber air di Lembangan Sungai Bernam dijangka mencukupi sehingga akhir abad ini. Walaubagaimanapun, keputusan ini juga mengetengahkan beberapa kemungkinan risiko yand disebabkan oleh perubahan iklim terhadap pengeluaran beras semasa bulan musim kering pada masa depan. Ini seterusnya memerlukan penyelesaian pengurusan air bersepadu untuk memastikan kelestarian pengeluaran beras.

Sebuah model sistem sokongan keputusan pintar iklim(CSDSS) yang mesra pengguna telah dibangunkan untuk permodelan peruntukan air pengairan di Skim Pengairan Padi Tanjung Karang (TAKRIS) di bawah scenario-scenario perubahan iklim. Pertamanya, scenario-scenario iklim diturun skala menggunakan sistem tersebut ke atas data-data cerapan dan teknik perubahan factor yang diterbitkan dari GCMs. Model Penman-Monteith FAO-56 telah digunakan untuk menganggarkan evapotranspirasi rujukan di bawah pendayaan masa depan. Sebuah model hujan stokastik telah digunakan untuk mensimulasi siri hujan masa hadapan menggunakan kaedah Markov Chain peringkat pertama berdasarkan senario pelepasan pendayaan masa depan. Kemudian model keperluan air dibangunkan berdasarkan kepada evapotranspirasi rujukan dan pekali tanaman. Keperluan air pengairan yang dijana ditukarkan kepada penghantaran pengairan berdasarkan kawasan perintah terusan. Model ini mampu menjana beberapa situasi agihan pengairan menggunakan unjuran GCMS individu dan / atau multi-model (ensemble). Model ini telah dinilai untuk agihan pengairan di kawasan kajian menggunakan data bekalan air selama satu tahun. Analisis menunjukkan bahawa purata bekalan pengairan mingguan untuk bekalan yang dicerap (tanpa perubahan iklim) dan bekalan simulasi (dengan perubahan iklim) di bawah scenario-scenario RCP4.5, RCP6.0 dan RCP8.5 masing-masing, adalah 2.69 m^3/s, 2.00 m^3/s, 2.19 m^3/s dan 1.94 m^3/s semasa luar musim, dan 2.55 m^3/s, 1.47 m^3/s, 1.76 m^3/s dan 1.49 m^3/s semasa musim utama. Keputusan mendedahkan bahawa bekalan sebenar (tanpa iklim) adalah lebih tinggi daripada bekalan model simulasi (dengan perubahan iklim) bagi ketiga-tiga senario iklim dalam kedua-dua musim penanaman. Ini menunjukkan bahawa mungkin ada isu-isu penjadualan yang kurang cekap dalam skim ini, yang membawa kepada pembaziran bekalan air secara berlebihan.

Penerapan model dalam menilai perubahan jangka panjang dalam permintaan air pengairan sebagai tindak balas kepada perubahan unjuran dalam evapotranspirasi rujukan dan hujan telah ditunjukkan dengan menggunakan tiga tempoh masa hadapan (2020-an, 2050-an dan 2080-an) berbanding dengan tempoh asas (1976-2005). Keputusan yang dijana daripada model DSS mencadangkan bahawa evapotranspirasi rujukan bulanan dijangka meningkat dalam semua senario sehingga 14.2% di bawah

RCP8.5 pada bulan Februari hingga Julai. Begitu juga, hujan tahunan berkesan diramalkan meningkat sedikit pada masa akan datang walaupun dengan variasi bulanan. Keperluan air pengairan dijangka meningkat pada bulan-bulan luar musim dan berkurang pada bulan-bulan musim utama. Pada masa ini, skim ini memerlukan bekalan di antara 610 mm dan 404 mm air, masing-masing untuk luar musim dan musim utama, manakala keperluan masa depan akan mencapai sehingga 675 mm dan 376 mm di bawah senario yang tertinggi (RCP8.5). Keputusan-keputusan ini akan membantu pengurus-pengurus air dalam merancang langkah-langkah penyesuaian pada bulan-bulan di mana hujan diramalkan sebagai tidak mencukupi untuk memenuhi permintaan air tanaman.

Berdasarkan kepada keputusan-keputusan tersebut, ia boleh disimpulkan bahawa DSS boleh berfungsi sebagai alat yang praktikal bagi simulasi scenario-scenario iklim berdasarkan output dari model-model iklim global (GCMs) untuk menjalankan pengiraan standard bagi evapotranspirasi rujukan, keperluan air tanaman padi dan keperluan pengairan, untuk agihan air harian atau berkala di bawah scenario-scenario iklim. Ini akan membolehkan Pihak Berkuasa Pengurusan Air menilai situasi perubahan iklim, dan dengan itu menggalakkan penggunaan strategi adaptasi yang sesuai serta berpotensi membawa kepada pengurusan air yang lebih mampan di peringkat kawasan tanaman. Kelebihan tambahan model ini adalah sifat fleksibilitinya dalam kemampuan mengemaskini senario iklim masa depan sekiranya terdapat model iklim baru yang tersedia, dan juga dengan data tempatan yang bersesuaian alat ini juga boleh dilanjutkan ke lokasi geografi yang lain. Akhir selaki, DSS ini turut mempunyai beberapa batasan penggunaan seperti yang diterangkan di dalam tesis, dan ini membentuk asas untuk penambahbaikan pada masa hadapan.

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Without my wife and daughter it would not have been easy for me to achieve this great work. It is through their love and sacrifice of numerous days without a husband and a father that this work was accomplished. Sincere gratitude goes to my late parents, siblings and friends for their love, affection and encouragement.

This thesis was submitted to the senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by Members of Supervisory Committe

I hereby confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AR	Assessment Report
BRH	Bernam River Headworks
CMIP3	Climate Model Intercomparison Project Phase 3
CMIP5	Climate Model Intercomparison Project Phase 5
CSDSS	Climate-smart Decision Support System
CSDSS-RIMIS	Climate-smart Decision Support System for Rice Irrigation Management Information System
DID	Department of Irrigation and Drainage
DOA	Department of Agriculture
DR	Drainage Requirement
DSS	Decision Support System
P_{eff}	Effective Rainfall
ET_o	Reference Crop Evapotranspiration
FAO	Food and Agriculture Organization
GISS	Goddard Institute for Space Studies for the NASA
GCM	Global Circulation Model
GUI	Graphical User Interface
HRU	Hydrologic Response Unit
IPCC	Intergovernmental Panel on Climate Change
JICA	Japan International Cooperation Agency
NSE	Nash-Sutcliffe model Efficiency coefficient
PBIAS	Percent Bias
R^2	Coefficient of determination
RCP	Representative Carbon Pathways

TAKRIS	Tanjung Karang Rice Irrigation Scheme
TRH	Tengi River Headworks

CHAPTER 1

INTRODUCTION

1.1 Background

Water is one of the basic natural resources upon which sustainable development depends to satisfy daily requirements of the world's growing population. In recent years, competition for water has been on the increase to the point of physical scarcity of the resource (UN-Water 2010). According to global-scale water scarcity projection studies, up to two thirds of the world's population is likely to live in water stressed watersheds by the year 2025 (Shiklomanov 1998; Rijsberman 2004; Alcamo et al. 2007). The main driving force is attributed to the increasing demand for different land and water uses and the climate change phenomena.

Irrigated agriculture remains the largest consumer of water, accounting for some 70% of total water withdrawals in the world (FAO 2013). The agricultural sector is faced with the challenge of meeting future food requirements with limited water resources. With a population that is expected to increase significantly by the year 2025, it is estimated that agricultural production will have to increase by 60% by 2025 (FAO 2013) to satisfy the expected demands for food, fibers and other agricultural products. Although there are differences in opinions regarding exploring options for providing enough food, it is no doubt that irrigation will have to contribute significantly to increasing food production. At the World Food Summit in 1996, it was estimated that 60% of future food requirements would have to be met through irrigated agriculture. However, irrigation is being criticized for huge amount of water losses due to poor performance and low efficiencies. Linked to this, are the uncertainties associated with global climate change which have the potential to disrupt the hydrological parameters such as mean streamflows, crop water requirements, frequency and intensity of rainfall (Xu 1999a; IPCC 2001). These issues call for attention and suitable water management actions on many facades, which, if left unresolved, the severity of the water problem will only become acute with time.

Rice is the most common staple diet for more than half the world's population, rich in energy and protein sources, providing about 75% and 60% respectively. More than 142 million hectares are cultivated under rice, 90% of which is cultivated in the monsoon regions of Asia (De Wrachien 2003), and of this, 75% is produced from irrigated lands. In Malaysia, rice production is an important sub-sector in the national food security agenda. Presently, there are more than 300,000 rice farmers encompassing over 322,000 hectares under irrigation (Alam et al. 2010). All the key rice-growing areas have irrigation and drainage facilities with an average yield of 3.5 tons per hectare (Agriculture Statistical Handbook, 2008), with a potential yield of 7.2 tons per hectare (Singh et al. (1996). Rice is cultivated during dry season and wet season (double cropping) under irrigation schemes.

The irrigation sector has the greatest annual water withdrawals, with more than 80% of Malaysia's water demands accounted for by rice irrigation use. To ensure sustainability of this sub-sector, the Federal Government developed the National Agricultural Policy which sets to transform the agricultural sector into a more efficient commercial sector to address three objectives; (1) to ensure attractive price to paddy farmers to produce rice, (2) to achieve a certain level of self-sufficiency in rice production, and (3) to ensure a stable and high quality of rice to consumers (NAP3 2010; Bala et al. 2014). Through this policy, rice productivity in the eight designated granary areas has seen a significant increase to about 72% self-sufficiency level (Bala et al. 2014). Figure 1.1 shows the location of these granary areas in Peninsular Malaysia.

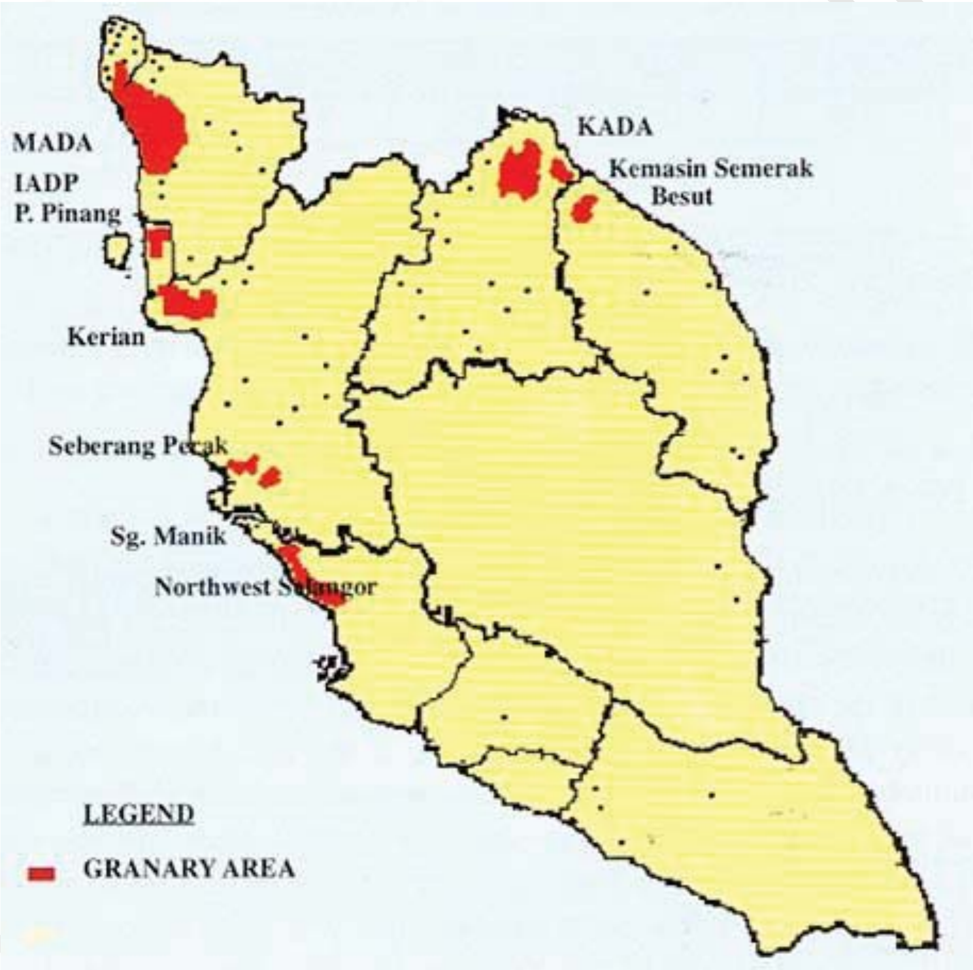

Figure 1.1 : Location of rice granary areas in Peninsula Malaysia
(Source: Department of Irrigation and Drainage, Malaysia, 2014)

Agriculture is vulnerable to changes in weather conditions and future climate change could be unfavorable for rice production. Hydrologic changes are the most important impacts of climate change in the Southeast Asia region (Christensen et al. 2007; IPCC 2007), to which Malaysia is a part. The recent assessment report (AR5) based on the CMIP5 simulations has shown that future rainfall projection changes are qualitatively similar to those in the previous assessment report (AR4) (IPCC 2013). The report further highlight that in Peninsular Malaysia rainfall intensity increased during the southwest monsoon season, whilst during the northeast monsoon, total rainfall, frequency of extreme rainfall events, and rainfall intensity all increased. At the same time, higher temperatures in the region are predicted which will demand higher irrigation water requirements.

Although Malaysia is blessed with rainfall throughout the year with an average of 2,420 mm (Alansi 2010), it is however, not yet clear how these supposed changes will affect the country's water resources systems for rice production in future. Quantitative studies are scarce, and the country's climate change policy is still being developed. Current adaptive strategies by local farmers are largely generic and are based on information derived from regional studies despite clear variations in local and regional-scale climates. Effective adaptive measures require good understanding of the uncertainty of climatic variables at local levels. Application of hydrologic modeling on basin-wide assessments is becoming a basis for understanding the repercussions of climate change to ensure effective adaptation measures and resilience to these changes (Xu 1999b; Fowler et al. 2007). Coupled with these models, are climate change-based decision support tools for modeling uncertainties in water allocations. Such tools therefore rely on existence of climate information consistent with the future for successful implementation.

1.2 Problem Statement

Rice is one of the major crops grown in many irrigation schemes in Malaysia as it constitutes a major portion of diet for a large population. Its demand for irrigation water is relatively high and differs from that of other field crops. Successful irrigation water management approaches used by water managers should aim at managing irrigation water deliveries in a more efficient way, and consistent with the prevailing climate conditions.

Many irrigation schemes suffer from water shortages in certain period in the cropping seasons, and the Tanjung Karang Irrigation Scheme (TAKRIS) is no exception. The inadequate and unreliable water deliveries in the main supply system often cause farmers to face regular water shortages for their rice fields, resulting in reduced yields and incomes. A feasibility study report and other previous studies have highlighted some of the water management issues faced by the scheme. Frequent water shortage especially during the dry season months is one of the key challenges facing the scheme. In addition, problems are being encountered in distributing water evenly over the command area, and also water management practices that lead to inefficient use of water.

Compounding problem is the impact associated with climate change in managing irrigation water management under climate scenarios. In its assessment over the past few decades, the Inter-governmental Panel on Climate Change (IPCC) reported three undeniable signals of climate change, that is, gradual changes in global average temperatures, rainfall patterns, and rise in sea levels (IPCC 2001; 2007). These have direct implications on a number of hydrological processes including streamflow fluctuations, groundwater recharge, reservoir levels and irrigation demand. Changes in temperature directly impacts on evapotranspiration and changes in rainfall affects streamflow and irrigation demand patterns at catchment scale. This will likely bring changes in rice water demands and put additional strain on the limited available water resources of the Bernam River, which is a source of irrigation water for the scheme. Local studies by the National Hydraulic Research Institute of Malaysia (NAHRIM) on the impacts of climate change at country level confirmed potential increase in future temperature and changes in rainfall patterns (NAHRIM 2006; 2014).

These issues therefore need to be quantified and accounted in future irrigation water allocation and planning. Current approaches at the scheme do not account for climate change related issues in water allocation for irrigation. Computer models such as decision support systems (DSS) are powerful tools can be used in combination with outputs from global climate models (GCMs) to simulate irrigation requirements and translate them to water deliveries under climate scenarios. However, current existing decision support system models, including those developed for local rice schemes, such as, RWM-DSS (Haque 2004), RIMIS (Rowshon 2006), PIM (Deepak 2011), SWAMP (Mohd 2014), have limitations as they do not account for climate scenarios in their modeling. This study, therefore, attempts to develop a decision support system (DSS) to model water demand and allocations in a rice irrigation scheme under climate scenarios by using outputs from the global climate models (GCMs). The tool will serve as a practical tool to generate climate scenarios based on the outputs from global climate models (GCMs) to carry out standard calculations for reference evapotranspiration, rice water requirements and irrigation demands, for daily and/or periodic water allocations under climate scenarios. This will allow Water Managers to assess climate change signals and thus promote adoption of appropriate adaptation strategies that could potentially lead to improved water use and management at farm level.

1.3 Goals and Objectives of Study

The primary goal of the present study is to develop a water management tool to generate local climate scenarios for modeling of water demands and allocation, and thereby facilitates development of mitigation measures at a local irrigation command area (Tanjung Karang Irrigation Scheme). To achieve this goal, the study was undertaken with the following specific objectives;

1. To develop local projected climate scenarios using the delta change factor methodology for streamflow modeling and water demand projections.
2. To assess streamflow of the Bernam River Catchment in response to climate change impacts using the SWAT model.
3. To develop a decision support system (DSS) for modeling irrigation demands and deliveries in rice field tertiary canals of the command area under climate change scenarios.
4. To assess impacts of climate change on the irrigation demands for the rice irrigation command area.

1.4 Relevance and Scope of the Study

Tanjung Karang is one of the rice irrigation schemes that contribute significantly to the rice food for the large population of Malaysia. General issues such as regular water shortage during dry season months and poor water management practices are some of the challenges reported by local water managers and previous feasibility studies. Climate change is a new threat in agricultural water management. Climate change is a global problem which cascade its impacts to regional and local-scale. The current existing approaches with regards to water management for irrigation to the scheme do not account for climate change scenarios. Instead water is supplied based on some design discharge originally designed for transplanted rice, and the climate change factor is not considered. Since this is still a run-of-the-river scheme, it is critical that we understand the impacts of climate change so that appropriate mitigation strategies could be developed for sustainable production.

The scope of work includes the following tasks;

- Collection of relevant information on the history, operation and maintenance of the paddy schemes.
- Collection of spatial maps (landuse, soils, DEM) from various government agencies and generating (digitizing) new maps (shapefiles).
- Collection of observed hydro-meteorological data from different stations within the study area and the watershed for calibration and validation of a hydrological model
- Downloading and extraction of GCM data from .nc file format to .mat file format using MATLAB Programme
- Detailed study of/and selection of climate change downscaling techniques and predictor variable suitable for the study purpose.
- Downscaling the climate variables through a specified downscaling domain with coordinates
- Simulation of future streamflow of the Bernam river basin considering the effects of climate change on the hydrology using multiple GCMs.
- Development of stochastic rainfall generator model for daily rainfall simulation under climate change scenarios using first-order Markov chain based on multiple GCMs and emission scenarios.
- Development of codes, functions and user interface using MATLAB platform for integrating all modules of the decision support system.
- Collection of irrigation supply data for evaluation of the decision support system.

1.5 Limitations on the Scope of Study

Although the study has achieved its objectives as set out, the following limitations on the scope of the study are highlighted. First, for streamflow modeling, future changes in landuse or vegetation cover was assumed to be stationery. However, land use change is generally considered one of the main factors affecting the rainfall-runoff relationship. It is believed that changes in landuse in the future will have a corresponding impact on streamflow. Second, the study was conducted using only the simulation outputs from climate models (GCMs) data based on the driving carbon emission scenarios. A combination of GCMs data with real-time simulation data would be ideal in a future study. Third, the study has assumed unconstrained supply for irrigation water. Future modelling studies should investigate the impacts of future changes in reliability of water supply for irrigation at certain times during the season, for instance, due to low flows or seasonal droughts. Fourth, channel routing modeling to evaluating the hydraulic performance of the conveyance system was not carried out. Canal simulations is essential in future studies to better synchronize both the upstream (water supply) and downstream (water demand) sides.

1.6 Outline of the Thesis

The thesis is organized into 5 chapters as follows: Chapter 1 provides the overview of the pivotal role of water in food production particularly rice, highlighting the problem faced by the agriculture sector on having to increase production with limited water resources, and the need for the sector to develop scientific tools for optimizing the use of irrigation water. The specific objectives of the study and its contribution to water management are also highlighted in this chapter.

The relevant literature to methods, techniques and approaches used in the study is reviewed in Chapter 2. The chapter includes an in-depth discussion of the concept of climate change, downscaling techniques and their applications to hydrologic modeling and future irrigation water demands. Applications of decision support systems as relate to water management are further reviewed in this chapter.

Chapter 3 presents the methodology with background information on the study area, data collection and a summary of the methods used to downscale future climate data, models applied in assessing future streamflow and developing stochastic rainfall model, irrigation water demand and development of decision support system from climate projections.

Chapter 4 presents the results of the study including climate change impacts on the future streamflow, application of the climate-smart decision support system in modeling water demands projections and allocation for rice tertiary canals which will be useful to farmers and water authorities for implementing allocation measures of irrigation water during climate change conditions.

Chapter 5 concludes the study highlighting its contribution and methodological limitations and suggests some recommendations for future work.

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