UNIVERSITI PUTRA MALAYSIA

UNCERTAINTY ANALYSIS OF LANGAT RIVER FLOW PROJECTIONS USING IMPACT-BASED MULTI-MODEL ENSEMBLE APPROACHES

HADI GALAVI

FK 2015 88
UNCERTAINTY ANALYSIS OF LANGAT RIVER FLOW PROJECTIONS USING IMPACT-BASED MULTI-MODEL ENSEMBLE APPROACHES

By

HADI GALAVI

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

December 2015
To

My wife, Maryam, for her precious love, constant support and invaluable consultation during this journey.

My wonderful parents, Mohammad Galavi and Fatemeh Bahreh, for their love and patience.

My dear siblings, Mostafa, Saeedeh, Sadegh, and Hakimeh.

تقديم به:

همسر و همراه عزيزم، مریم، که عشق پی نظیر، حبیبی همیشگی و مشورت های ارزشمند ایشان در طول این سفر از سرمایه های سرمایه های من بودند.

پدر و مادر مرا اشهرم، محمد گلی و فاطمه عازده، که من در صورتی عشق و حبیتشان هستم.

برادران و خواهران عزیزم، مصطفی، سعیده، صادق و حکیمی.
Abstract of thesis presented to the senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

UNCERTAINTY ANALYSIS OF LANGAT RIVER FLOW PROJECTIONS USING IMPACT-BASED MULTI-MODEL ENSEMBLE APPROACHES

By

HADI GALAVI

December 2015

One of the major manifestations of the climate change impacts in the 21st century in a water catchment is the precipitation—frequency and intensity—pattern alteration that may result in water scarcity. It is important therefore to define the basin-scale hydrologic features under changing/variable climate for sustainable management of water resources. Spatial changes of precipitation frequency and intensity because of climate change may influence the streamflows frequency and magnitude causing intensified floods and droughts and the associated substantial local and regional impacts on the economy. Assessment of climate change hydrological impacts deals with uncertainties resulting from the application of General Circulation Models (GCM), Greenhouse Gasses Emission Scenarios (ES), downscaling methods, and hydrological models, each with their inherent uncertainty.

Uncertainty assessment of the climate change impacts on streamflow of the Hulu Langat Basin is the main objective of this study. To this end, the Soil and Water Assessment Tool (SWAT) is used to model the hydrological system of the catchment. It is calibrated based on the historical streamflow data of the catchment. An ensemble of 19 GCMs under two emission scenarios (ES) is used to provide a wide range of possible future climate scenarios. Next, bias-corrected GCM’s precipitation and temperature data were used to run the SWAT model for both the current and future climate. Uncertainty in obtained streamflow scenarios was analyzed with focus on hydrological model parameters, emission scenarios, and GCM uncertainties. This research has modified the existing uncertainty model of Reliability Ensemble Averaging (REA) to be applicable at impact level of climate studies; and a probabilistic ensemble approach that is referred to as Bootstrapped Ensemble Uncertainty Modeling (BEUM) was proposed for uncertainty modeling. In the baseline climate simulations, hydrologic model parameters uncertainty was found to be larger than the emission scenario uncertainty, while GCMs were the largest source of uncertainty. However, parameter uncertainty was the smallest source in future climate periods, while GCMs and emission scenarios were the larger sources with projections of 130% and 51% relative change in annual streamflow, respectively. The projected temporal pattern of monthly streamflow for 2070-2099 under emission scenario of RCP8.5 was found to be different from observed pattern, where the usual first
peak flow of the year in April is changed to May and the lowest flow rate happens in February instead of July and August. The temporal change in uncertainty sources may have to be taken into cognizance when implementing water resources projects in the future.

Based on the REA method, an approximately 3.5 and 2.9 m$^3$/s increase in mean monthly streamflow during the 2016-2045 period respectively under the emission scenarios of RCP4.5 and RCP8.5, are anticipated. The modification applied to the REA method accommodated the inclusion of hydrological model parameter uncertainty into the total uncertainty assessment. The modified REA method was able to embrace a more reliable prediction interval compared to the original REA. In addition, a full coverage of prediction intervals was possible in the proposed BEUM method, although it proved to be computationally expensive in comparison with the REA method.
Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ANALISIS KETIDAKPASTIAN UNJURAN ALIRAN SUNGAI LANGAT MENGGUNAKAN PENDEKATAN PELBAGAI MODEL YANG BERDASARKAN KESAN

Oleh

HADI GALAVI

Disember 2015

Pengerusi:  Lee Teang Shui, PhD
Fakulti:  Kejuruteraan

terbesar dengan unjuran 130% dan 51% perubahan relatif pengaliran sungai tahunan, masing masing. Corak pengaliran sungai bulanan yang diunjurkan untuk 2070-2099 dalam senario pemancaran RCP8.5 didapat berbeza daripada corak pemerhatian, di mana pengaliran kemuncak pertama tahunan biasa pada bulan April telah berubah ke bulan Mei dan kadar pengaliran terendah berlaku pada Februari dibandingkan biasanya berlaku pada Julai dan Ogos. Perubahan masa mungkin perlu diperhatikan dalam melaksanakan projek sumber air pada masa depan.

Berdasarkan kaedah REA, peningkatan lebih kurang 3.5 dan 2.9 m3/s pada purata pengaliran bulanan masing-masing dalam tempoh 2016-2045 untuk senario pemancaran RCP4.5 dan RCP8.5 dijangkakan. Satu ubahsuai telah dipakai kepada kaedah REA untuk menampung ketidakpastian model hidrologi dalam penilaian ketidakpastian berkeseluruhan. Kaedah REA terubahsuai mampu berkuatkuasa dalam satu selang ramalan lebih luas berbanding dengan REA asal. Satu liputan penuh selang ramalan boleh dilakukan dengan cadangan kaedah BEUM, walaupun dibuktikan bahawa ia lebih mahal berbanding dengan kaedah REA.
ACKNOWLEDGEMENTS

First and above all, I would like to thank God for providing me the opportunity to continue my post graduate studies and granting me motivation and capability to accomplish my goals.

I would like to express my deepest appreciation to my previous supervisor Prof. Dr. Lee Teang Shui who has retired recently, but continued to help and guide me through the last steps of my study. He has been a great mentor to me and I feel blessed for having the opportunity to be his student. I would also like to thank my current supervisor Dr. Md Rowshon Kamal for his kind assistance and support. I am grateful to Associate Prof. Dr. Abdul Halim Bin Ghazali and Dr. Liew Ju Neng, my co-supervisors, for their consultations.

I am also extremely thankful to Dr. Majid Mirzaei for his invaluable consultation, encouragement and guidance throughout my doctoral study. Despite his busy schedule at Universiti Tunku Abdul Rahman, Malaysia, he always made time for my questions.

Special thanks are due to the Department of Irrigation and Drainage (Kuala Lumpur) for providing very useful information in order to carry out this project.

Last but not least, I would like to express my sincere appreciation to the Ministry of Education (MOE), Malaysia, for their financial support of me under Malaysia International Scholarship (MIS) scheme.
I certify that a Thesis Examination Committee has met on 18 December 2015 to conduct the final examination of Hadi Galavi on his thesis entitled "UNCERTAINTY ANALYSIS OF LANGAT RIVER FLOW PROJECTIONS USING IMPACT-BASED MULTI-MODEL ENSEMBLE APPROACHES" in accordance with the Universities and University College Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(a) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Examination Committee were as follows:

**Desa bin Ahmad, PhD**
Professor Ir. Dr.
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

**Aimrun Wayayok, PhD**
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

**Badronnisa Yusuf, PhD**
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

**Md. Abdul Mojid, PhD**
Professor. Dr.
Department of Irrigation and Water Management
Bangladesh Agricultural University
Bangladesh
(External Examiner)

______________________________
**ZULKARNAIN ZAINAL, PhD**
Professor and Deputy Dean
School Of Graduate Studies
Universiti Putra Malaysia

Date:
This thesis was submitted to the senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the supervisory committee were as follows:

**Lee Teang Shui, PhD**  
Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**MD. Rowshon Kamal, PhD**  
Senior Lecturer  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Abdul Halim Bin Ghazali, PhD**  
Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Liew Ju Neng, PhD**  
Senior Lecturer  
Faculty of Science and Technology  
Universiti Kebangsaan Malaysia  
(Member)

---

**BUJANG BIN KIM HUAT, PhD**  
Professor and Dean  
School Of Graduate Studies  
Universiti Putra Malaysia

Date:
Declaration by graduate student

I hereby confirm that:

• this thesis is my original work;
• quotations, illustrations and citations have been duly referenced;
• this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
• intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
• written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
• there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: ________________________      Date: __________________

Name and Matric No.: Hadi Galavi, (GS29949)
Declaration by Members of Supervisory Committee

This is to 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) are adhered to.

Signature: ____________________________
Name of Chairman of Supervisory Committee: ____________________________

Signature: ____________________________
Name of Member of Supervisory Committee: ____________________________

Signature: ____________________________
Name of Member of Supervisory Committee: ____________________________

Signature: ____________________________
Name of Member of Supervisory Committee: ____________________________
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRAK</td>
<td>iii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>APPROVAL</td>
<td>vi</td>
</tr>
<tr>
<td>DECLARATION</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xiii</td>
</tr>
<tr>
<td>LIST OF ABBREVIATIONS</td>
<td>xvi</td>
</tr>
<tr>
<td>LIST OF NOTATIONS</td>
<td>xvii</td>
</tr>
<tr>
<td><strong>CHAPTER</strong></td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Problem Statement</td>
<td>2</td>
</tr>
<tr>
<td>1.3 Research Objectives</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Scope of the Research</td>
<td>4</td>
</tr>
<tr>
<td>1.5 Significance of the work</td>
<td>5</td>
</tr>
<tr>
<td>2 LITERATURE REVIEW</td>
<td>6</td>
</tr>
<tr>
<td>2.1 Introduction – Climate Change and Water Resources</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Components of an Impact Study</td>
<td>7</td>
</tr>
<tr>
<td>2.2.1 Greenhouse Gases Emission Scenarios</td>
<td>7</td>
</tr>
<tr>
<td>2.2.2 General Circulation Models (GCM)</td>
<td>9</td>
</tr>
<tr>
<td>2.2.3 Downscaling</td>
<td>11</td>
</tr>
<tr>
<td>2.2.4 Hydrological Models</td>
<td>13</td>
</tr>
<tr>
<td>2.3 Uncertainty Analysis Methods</td>
<td>14</td>
</tr>
<tr>
<td>2.3.1 Generalized Likelihood Uncertainty Estimation</td>
<td>14</td>
</tr>
<tr>
<td>2.3.2 Multi-Model Ensemble</td>
<td>15</td>
</tr>
<tr>
<td>2.3.3 Bootstrap Confidence Intervals</td>
<td>17</td>
</tr>
<tr>
<td>2.4 Summary</td>
<td>17</td>
</tr>
<tr>
<td>3 METHODOLOGY</td>
<td>19</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>19</td>
</tr>
<tr>
<td>3.2 Study Area and Data</td>
<td>20</td>
</tr>
<tr>
<td>3.2.1 Climate Data and Surface Water Status</td>
<td>21</td>
</tr>
<tr>
<td>3.2.2 Land Use, Soil, and DEM Maps</td>
<td>24</td>
</tr>
<tr>
<td>3.2.3 GCM Data</td>
<td>26</td>
</tr>
<tr>
<td>3.3 Climate Modeling Phase</td>
<td>27</td>
</tr>
<tr>
<td>3.3.1 Greenhouse Gases Emission Scenarios Selection</td>
<td>28</td>
</tr>
<tr>
<td>3.3.2 Selection of GCMs</td>
<td>28</td>
</tr>
<tr>
<td>3.3.3 Bias Correction of the GCM Data</td>
<td>28</td>
</tr>
<tr>
<td>3.4 Hydrological Modeling - SWAT</td>
<td>30</td>
</tr>
<tr>
<td>3.4.1 Model description</td>
<td>31</td>
</tr>
<tr>
<td>3.4.2 Parameter Sensitivity Analysis</td>
<td>33</td>
</tr>
</tbody>
</table>
3.4.3 Model Calibration and Validation 34
3.5 Uncertainty Analysis of Hydrological Model Parameters 35
3.6 Statistical Evaluation Criteria 37
3.7 Climate Change Impacts on Streamflow 38
3.8 Contribution of Each Uncertainty Source 38
3.9 Overall Uncertainty Analysis and Modeling 40
   3.9.1 Reliability Ensemble Averaging 40
   3.9.2 Bootstrap Ensemble Uncertainty Modelling 43
3.10 Summary 45

4 RESULTS AND DISCUSSIONS 46
4.1 Introduction 46
4.2 Bias Correction of GCM data 46
   4.2.1 Bias-Correction of Rainfall Data - Baseline Climate 47
   4.2.2 Future Rainfall Projections 54
   4.2.3 Bias-Correction of Temperature - Baseline Climate 59
   4.2.4 Future Temperature Projections 63
4.3 SWAT Model 69
   4.3.1 Watershed delineation 69
   4.3.2 HRU definition 69
   4.3.3 Preliminary Model Simulations 70
   4.3.4 Parameter Sensitivity Analysis 71
   4.3.5 Calibration and Uncertainty Analysis 73
   4.3.6 Validation 75
   4.3.7 Selected SWAT Model for Impact Assessment 75
4.4 Climate Change Impacts on Streamflow 77
   4.4.1 GCM-Data-Driven Streamflow at Baseline Climate 77
   4.4.2 Future Streamflow Scenarios 79
4.5 Uncertainty Contribution of Each Source 83
4.6 The Uncertainty Models 85
   4.6.1 Original REA Method 85
   4.6.2 Modified REA Method 89
   4.6.3 Bootstrapped Ensemble Uncertainty Modeling 94
4.7 Summary 99

5 CONCLUSIONS AND RECOMMENDATIONS 101
5.1 Summary 101
5.2 Conclusions 101
5.3 Recommendations for Future Research 104

REFERENCES 105
APPENDICES 118
BIODATA OF STUDENT 141
LIST OF PUBLICATIONS 142
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>10</td>
</tr>
<tr>
<td>3.1</td>
<td>21</td>
</tr>
<tr>
<td>3.2</td>
<td>23</td>
</tr>
<tr>
<td>3.3</td>
<td>24</td>
</tr>
<tr>
<td>3.4</td>
<td>25</td>
</tr>
<tr>
<td>3.5</td>
<td>26</td>
</tr>
<tr>
<td>3.6</td>
<td>34</td>
</tr>
<tr>
<td>3.7</td>
<td>38</td>
</tr>
<tr>
<td>4.1</td>
<td>46</td>
</tr>
<tr>
<td>4.2</td>
<td>54</td>
</tr>
<tr>
<td>4.3</td>
<td>62</td>
</tr>
<tr>
<td>4.4</td>
<td>70</td>
</tr>
<tr>
<td>4.5</td>
<td>71</td>
</tr>
<tr>
<td>4.6</td>
<td>72</td>
</tr>
<tr>
<td>4.7</td>
<td>76</td>
</tr>
<tr>
<td>4.8</td>
<td>76</td>
</tr>
<tr>
<td>4.9</td>
<td>77</td>
</tr>
<tr>
<td>4.10</td>
<td>79</td>
</tr>
<tr>
<td>4.11</td>
<td>81</td>
</tr>
<tr>
<td>4.12</td>
<td>84</td>
</tr>
<tr>
<td>4.13</td>
<td>86</td>
</tr>
<tr>
<td>4.14</td>
<td>90</td>
</tr>
<tr>
<td>4.15</td>
<td>91</td>
</tr>
<tr>
<td>4.16</td>
<td>91</td>
</tr>
<tr>
<td>4.17</td>
<td>95</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>The general approach in climate change impact studies</td>
<td>6</td>
</tr>
<tr>
<td>2.2</td>
<td>RCPs referring to level of total radiative forcing</td>
<td>8</td>
</tr>
<tr>
<td>3.1</td>
<td>The study framework</td>
<td>20</td>
</tr>
<tr>
<td>3.2</td>
<td>Geographical location of the water bodies in the catchment</td>
<td>22</td>
</tr>
<tr>
<td>3.3</td>
<td>Mean monthly maximum (Max) and minimum (Min) temperature</td>
<td>22</td>
</tr>
<tr>
<td>3.4</td>
<td>Mean monthly rainfall data of the three stations</td>
<td>23</td>
</tr>
<tr>
<td>3.5</td>
<td>Land use map</td>
<td>24</td>
</tr>
<tr>
<td>3.6</td>
<td>Soil map of the catchment</td>
<td>25</td>
</tr>
<tr>
<td>3.7</td>
<td>Digital Elevation Model (DEM) of the catchment</td>
<td>26</td>
</tr>
<tr>
<td>3.8</td>
<td>Workflow in climate modeling phase</td>
<td>27</td>
</tr>
<tr>
<td>3.9</td>
<td>EDCDFm downscaling method (Li et al., 2010)</td>
<td>29</td>
</tr>
<tr>
<td>3.10</td>
<td>Workflow in Hydrological modeling phase using SWAT model</td>
<td>31</td>
</tr>
<tr>
<td>3.11</td>
<td>SWAT soil water movement structure (Bae et al., 2011)</td>
<td>32</td>
</tr>
<tr>
<td>3.12</td>
<td>The GLUE framework (Mirzaei et al., 2015)</td>
<td>35</td>
</tr>
<tr>
<td>3.13</td>
<td>Framework of uncertainty contribution analysis</td>
<td>39</td>
</tr>
<tr>
<td>3.14</td>
<td>The BEUM framework</td>
<td>44</td>
</tr>
<tr>
<td>4.1</td>
<td>Bias-corrected daily rainfall at Ulu-Langat Station - Baseline period</td>
<td>47</td>
</tr>
<tr>
<td>4.2</td>
<td>Number of wet days at the auxiliary stations compared with observations for the two emission scenarios and all the GCMs</td>
<td>49</td>
</tr>
<tr>
<td>4.3</td>
<td>Mean daily rainfall during wet days at auxiliary stations compared with observations for each emission scenario-GCM</td>
<td>50</td>
</tr>
<tr>
<td>4.4</td>
<td>Standard deviation of daily rainfall during wet days at auxiliary stations for each emission scenario-GCM compared with observations</td>
<td>51</td>
</tr>
<tr>
<td>4.5</td>
<td>Number of wet days and corresponding Mean daily rainfall at Ulu-Langat Station for each emission scenario and GCM compared with observation</td>
<td>52</td>
</tr>
<tr>
<td>4.6</td>
<td>Standard deviation of daily rainfall during wet days at Ulu-Langat Station for each emission scenario and GCM compared with observations</td>
<td>53</td>
</tr>
<tr>
<td>4.7</td>
<td>Bias-corrected future daily rainfall at Ulu-Langat Station</td>
<td>55</td>
</tr>
<tr>
<td>4.8</td>
<td>Future rainfall scenarios at Ulu-Langat Station for 2030s</td>
<td>56</td>
</tr>
<tr>
<td>4.9</td>
<td>Future rainfall scenarios at Ulu-Langat Station for 2080s</td>
<td>57</td>
</tr>
<tr>
<td>4.10</td>
<td>Comparison of the two emission scenarios in 2030s</td>
<td>58</td>
</tr>
<tr>
<td>4.11</td>
<td>Comparison of the two emission scenarios in 2080s</td>
<td>58</td>
</tr>
<tr>
<td>4.12</td>
<td>Bias-corrected daily temperature simulations - baseline period</td>
<td>59</td>
</tr>
<tr>
<td>4.13</td>
<td>Bias corrected mean daily maximum and minimum temperature – baseline climate</td>
<td>60</td>
</tr>
<tr>
<td>Section</td>
<td>Title</td>
<td></td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>4.14</td>
<td>Standard deviation of bias-corrected daily temperature – baseline climate</td>
<td></td>
</tr>
<tr>
<td>4.15</td>
<td>Bias-corrected future temperature</td>
<td></td>
</tr>
<tr>
<td>4.16</td>
<td>Future maximum temperature changes as in 2030s under RCP4.5</td>
<td></td>
</tr>
<tr>
<td>4.17</td>
<td>Future minimum temperature changes as in 2030s under RCP4.5</td>
<td></td>
</tr>
<tr>
<td>4.18</td>
<td>Future Maximum Temperature changes in 2030s under RCP8.5</td>
<td></td>
</tr>
<tr>
<td>4.19</td>
<td>Future Minimum Temperature changes in 2030s under RCP8.5</td>
<td></td>
</tr>
<tr>
<td>4.20</td>
<td>Future Maximum Temperature changes in 2080s under RCP4.5</td>
<td></td>
</tr>
<tr>
<td>4.21</td>
<td>Future Minimum Temperature changes in 2080s under RCP4.5</td>
<td></td>
</tr>
<tr>
<td>4.22</td>
<td>Future Maximum Temperature changes in 2080s under RCP8.5</td>
<td></td>
</tr>
<tr>
<td>4.23</td>
<td>Future Minimum Temperature changes in 2080s under RCP8.5</td>
<td></td>
</tr>
<tr>
<td>4.24</td>
<td>Emission scenarios comparison in short-term period (2030s)</td>
<td></td>
</tr>
<tr>
<td>4.25</td>
<td>Emission scenarios comparison in long-term period (2080s)</td>
<td></td>
</tr>
<tr>
<td>4.26</td>
<td>Delineated watershed and stream network</td>
<td></td>
</tr>
<tr>
<td>4.27</td>
<td>The first model simulation result</td>
<td></td>
</tr>
<tr>
<td>4.28</td>
<td>Dotty plot of NSE coefficient against each aggregate SWAT parameters, NSE threshold of 0.60 (thick line)</td>
<td></td>
</tr>
<tr>
<td>4.29</td>
<td>Uncertainty band of the model predictions during calibration</td>
<td></td>
</tr>
<tr>
<td>4.30</td>
<td>The 95PPU range of the model simulations during validation</td>
<td></td>
</tr>
<tr>
<td>4.31</td>
<td>SWAT model simulations in calibration and validation periods</td>
<td></td>
</tr>
<tr>
<td>4.32</td>
<td>Annual GCMs data-driven streamflow simulations - baseline period</td>
<td></td>
</tr>
<tr>
<td>4.33</td>
<td>Streamflow changes under RCP4.5 in 2030s</td>
<td></td>
</tr>
<tr>
<td>4.34</td>
<td>Streamflow changes under RCP8.5 in 2030s</td>
<td></td>
</tr>
<tr>
<td>4.35</td>
<td>Streamflow changes under RCP4.5 in 2080s</td>
<td></td>
</tr>
<tr>
<td>4.36</td>
<td>Streamflow changes under RCP8.5 in 2080s</td>
<td></td>
</tr>
<tr>
<td>4.37</td>
<td>Comparison of different future streamflow scenarios using the ensemble raw average</td>
<td></td>
</tr>
<tr>
<td>4.38</td>
<td>Contribution of each uncertainty source at different periods</td>
<td></td>
</tr>
<tr>
<td>4.39</td>
<td>Uncertainty in 2030s under RCP4.5 by REA</td>
<td></td>
</tr>
<tr>
<td>4.40</td>
<td>Uncertainty in 2030s under RCP8.5 by REA</td>
<td></td>
</tr>
<tr>
<td>4.41</td>
<td>Uncertainty in 2080s under RCP4.5 by REA</td>
<td></td>
</tr>
<tr>
<td>4.42</td>
<td>Uncertainty in 2080s under RCP8.5 by REA</td>
<td></td>
</tr>
<tr>
<td>4.43</td>
<td>Uncertainty bounds in 2030s under RCP4.5 by modified REA</td>
<td></td>
</tr>
<tr>
<td>4.44</td>
<td>Uncertainty bounds in 2030s under RCP8.5 by modified REA</td>
<td></td>
</tr>
<tr>
<td>4.45</td>
<td>Uncertainty bounds in 2080s under RCP4.5 by modified REA</td>
<td></td>
</tr>
<tr>
<td>4.46</td>
<td>Uncertainty bounds in 2080s under RCP8.5 by modified REA</td>
<td></td>
</tr>
<tr>
<td>4.47</td>
<td>The monitoring points in BEUM</td>
<td></td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
<td>------</td>
</tr>
<tr>
<td>4.48</td>
<td>Uncertainty bounds using BEUM in 2030s under RCP4.5</td>
<td>96</td>
</tr>
<tr>
<td>4.49</td>
<td>Uncertainty bounds using BEUM in 2030s under RCP8.5</td>
<td>97</td>
</tr>
<tr>
<td>4.50</td>
<td>Uncertainty bounds using BEUM in 2080s under RCP4.5</td>
<td>97</td>
</tr>
<tr>
<td>4.51</td>
<td>Uncertainty bounds using BEUM in 2080s under RCP8.5</td>
<td>98</td>
</tr>
</tbody>
</table>
LIST OF ABBREVIATIONS

IPCC Intergovernmental panel on climate change
CMIP5 Climate model intercomparison project phase 5
AR Assessment report
GCM General circulation model
ES Greenhouse gases emission scenario
PDF Probability distribution function
CDF Cumulative distribution function
REA Reliability ensemble averaging
BEUM Bootstrapped ensemble uncertainty modeling
EDCDFm EquiDistant cumulative distribution function matching
GLUE Generalized likelihood uncertainty estimation
NSE Nash–Sutcliffe model efficiency coefficient
HMPS Hydrological model parameter set
Sim Simulation
Obs Observation
abs Absolute
HRU Hydrologic Response Unit
RCM Regional Climate Models
### LIST OF NOTATIONS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SW_t$</td>
<td>Total soil water content (mm water)</td>
</tr>
<tr>
<td>$SW_0$</td>
<td>Initial soil water content (mm water)</td>
</tr>
<tr>
<td>PRCP</td>
<td>Precipitation (mm water)</td>
</tr>
<tr>
<td>Q</td>
<td>Surface runoff (mm water)</td>
</tr>
<tr>
<td>ET</td>
<td>Evapotranspiration (mm water)</td>
</tr>
<tr>
<td>$W_{seep}$</td>
<td>Vadose zone water (mm water)</td>
</tr>
<tr>
<td>$Q_{gw}$</td>
<td>Return flow from lateral and ground water (mm water)</td>
</tr>
<tr>
<td>N</td>
<td>Number of behavioral parameter sets</td>
</tr>
<tr>
<td>$L(\theta_i)$</td>
<td>The likelihood function</td>
</tr>
<tr>
<td>$P$</td>
<td>Prediction percentile</td>
</tr>
<tr>
<td>$\varphi_i$</td>
<td>The $i^{th}$ set of behavioral model parameter</td>
</tr>
<tr>
<td>$f(\varphi_i)$</td>
<td>The model for the $i^{th}$ set of behavioral model parameter</td>
</tr>
<tr>
<td>$\hat{Z}_{t,i}$</td>
<td>The magnitude of parameter $Z$ at time $t$</td>
</tr>
<tr>
<td>$w_i$</td>
<td>Weighted likelihood factor</td>
</tr>
<tr>
<td>$Q_{t_i,97.5%}$</td>
<td>Upper band of the 95PPU</td>
</tr>
<tr>
<td>$Q_{t_i,2.5%}$</td>
<td>Lower band of the 95PPU</td>
</tr>
<tr>
<td>$t_i$</td>
<td>Time interval</td>
</tr>
<tr>
<td>$\sigma_{obs}$</td>
<td>Standard deviation of observed data</td>
</tr>
<tr>
<td>$F$</td>
<td>CDF</td>
</tr>
<tr>
<td>$F^{-1}$</td>
<td>Inverse CDF</td>
</tr>
<tr>
<td>$G$</td>
<td>GCM</td>
</tr>
<tr>
<td>$b$</td>
<td>Baseline climate</td>
</tr>
<tr>
<td>$p$</td>
<td>Projection</td>
</tr>
<tr>
<td>$X_{bc}$</td>
<td>Bias-corrected value of $X$ on the CDF of the future GCM</td>
</tr>
<tr>
<td>$\bar{X}$</td>
<td>Time series of the observed rainfall above 0.1 mm</td>
</tr>
<tr>
<td>$\bar{X}_G$</td>
<td>Threshold for the GCM simulations applied for bias-correction</td>
</tr>
<tr>
<td>$\Delta Q$</td>
<td>Simulations deviation from the observed mean annual flow</td>
</tr>
<tr>
<td>$\bar{\Delta Q}$</td>
<td>The ensemble average deviation from observations</td>
</tr>
<tr>
<td>$R_i$</td>
<td>Reliability measure of $i^{th}$ GCM.</td>
</tr>
<tr>
<td>$R_{B,i}$</td>
<td>Model bias criteria</td>
</tr>
<tr>
<td>$R_{D,i}$</td>
<td>Model convergence criteria</td>
</tr>
<tr>
<td>$\epsilon_Q$</td>
<td>Natural variability in the observed annual flow</td>
</tr>
<tr>
<td>$B_i$</td>
<td>$i^{th}$ GCM absolute bias ($\Delta Q$) from the observation</td>
</tr>
</tbody>
</table>
\( D_i \) Distance of \( i^{th} \) GCM predictions from the ensemble average
\( \delta_{\Delta \dot{Q}} \) Root mean square difference
\( \bar{H}_Q \) Hydrological model variability
\( R_{\text{mod},i} \) Overall reliability of \( i^{th} \) GCM in the modified REA
CHAPTER 1

INTRODUCTION

1.1 Background

The past climate used to be the leading guideline for future planning and management of water resources and other relevant events. However, since the inception of the Industrial Revolution, the climate conditions are perturbed because of the escalated volume of heat-trapping greenhouse gases. The current level of carbon dioxide concentration surpasses the past 650,000–800,000 years record (Lüthi et al., 2008) and in response, Northern Hemisphere average surface temperature has risen by 0.76°C over the past 150 years (IPCC, 2007). Consequently, the global atmospheric circulation pattern and the precipitation and temperature patterns have altered sequentially. In addition, the anthropogenic changes on land such as waterways channelization and land use change, which alter the nature of ecosystem and watershed hydrology, characterize climate changes at the local scale (Moradkhani et al., 2010).

One of the major manifestations of the climate change impacts in the 21st century in a water catchment is the precipitation—frequency and intensity—pattern alteration that may result in water scarcity. It is important therefore to define the basin-scale hydrologic features under changing/variable climate for sustainable management of water resources in order to satisfy both the current and future demands. Precipitation and temperature changes impacts on hydrologic processes negatively affect water resources and consequently all the water-reliant sectors (Jung and Chang, 2011). Notably, spatial changes of precipitation frequency and intensity because of climate change may influence the streamflows frequency and magnitude causing intensified floods and droughts with substantial local and regional impacts on the economy. Dependency of runoff variability on multi-year or -decadal scale variability of climate necessitates the study of key elements of the climate, temperature and precipitation. However, to define the major regional impacts of climate change, characteristics of a specific basin should be associated with the magnitude and distribution of changes in global scale (H. Xu et al., 2011).

General Circulation Models (GCMs), representing various earth systems including atmosphere and land surface based on general principles of fluid dynamics and thermodynamics, are the most credible tool for climate change modelling (Fowler et al., 2007). Climate change assessment practices require a global perspective of at least a century long. Practically, prediction of Greenhouse Gases emission for such a long horizon is impossible. Thus, the Intergovernmental Panel on Climate Change (IPCC) periodically introduces alternative emission scenarios representing storylines of the potential future developments in socio-economic systems and their corresponding emission level. GCMs—run using any of the IPCC emission scenarios—are powerful tools in capturing the large-scale global circulation pattern. However, the mismatch
between spatial resolution of GCMs and impact models (for instance a hydrological model in this research) limits the direct application of GCM outputs in impact assessment studies. Therefore, GCM simulations are downsized to a regional or basin-scale resolution using different downscaling techniques.

Every step in the climate change impact study—including GCMs run under any emission scenario, downscaling, and hydrological modeling—is inherently uncertain. Uncertainty in each assessment stage stems from model structure and parameters. Contribution of each uncertainty source towards the overall uncertainty envelop is significantly different. However, GCMs and emission scenarios are introduced as the largest sources of uncertainty in impact studies (Chen et al., 2013; Prudhomme et al., 2003). Emission scenarios due to their ill-understood systems are a fundamental source of uncertainty, although their uncertainty is most often assessed combined with GCM uncertainty. GCMs according to their model structure and associated assumptions produce different simulations of the same variable; thus, the choice of GCM highly influences the future projections of hydrologic components. Different approaches have been developed to analyze and quantify the GCM uncertainty and it is still at the forefront of the impact studies.

Hydrological models are frequently used to quantify the hydrological impacts of climate change using GCM data as inputs (Bastola, 2013; Ludwig et al., 2014; Vezzoli et al., 2013). Nevertheless, application of the model results with respect to future changes in runoff remains limited due to the large uncertainty stemming from GCMs, greenhouse gases emissions scenarios, downscaling methods, and hydrological models (Kingston and Taylor, 2010; Woldemeskel et al., 2014). Therefore, all the uncertainties have to be explored in order to draw a valid conclusion from the study (Quintana-Seguí et al., 2010). The major uncertainty source, however, is commonly believed to be the choice of GCM, where every GCM can project a different future climate condition (Buytaert et al., 2010). Therefore, many published studies and the IPCC embolden application of multiple GCMs in order to assess the GCM uncertainty (Chen et al., 2013; Ludwig et al., 2014).

1.2 Problem Statement

Up to date, uncertainty analysis has usually been limited to the climate part (e.g. Chen et al., 2013; Prudhomme and Davies, 2007), while many recent studies highlight that the uncertainty due to hydrological model parameters instability should not be ignored (Brigode et al., 2013; Goderniaux et al., 2015; Touhami et al., 2015). Because, hydrological model parameters are highly dependent on the climate properties of the catchment during model calibration period; thus, the highly variable model parameters can generate a wide spectrum of future scenarios when they are run by GCM data (Poulin et al., 2011). However, assessment of hydrological model structure uncertainty is deemed less informative when a large number of GCMs are applied in the study (Lespinas et al., 2014).
The common agreement within the climate research community is that the downscaling uncertainty is notably smaller than the GCM uncertainty (Chen et al., 2013; Prudhomme et al., 2003; Wilby and Harris, 2006), in which some studies have neglected it or incorporated it into the GCM uncertainty as one source (Liu et al., 2012; Mujumdar and Ghosh, 2008; Thompson et al., 2013). However, exploration of downscaling uncertainty is recommended in cases where only one GCM is applied for impact assessment (Chen et al., 2011). Selection of uncertainty modeling approach is believed to play an important role in quantifying the uncertainties involved in the impact study. Uncertainty modeling techniques are generally divided into probabilistic approaches, where equal probability is assigned to an ensemble of opportunities, and weighting approaches that assign different weights to different future scenarios (Lopez et al., 2006). Those methods analyze the uncertainty in GCM simulations of temperature and precipitation as the main climate variables and apply the quantified uncertainty to the impact models (Wang and Chen, 2013; H. Zhang et al., 2011). However, disregarding the impact level uncertainty and only applying the uncertainty models to the weather events under climate change scenarios is claimed to be the current gap in uncertainty analysis of integrated climate change impact studies (Fowler et al., 2007; Kumar, 2014; Yao et al., 2011).

The Reliability Ensemble Averaging (REA) method (Giorgi and Mearns, 2002) is one of the most credible weighting approaches that has been proved a promising method to reduce uncertainty in climate studies (Mearns et al., 2003; Tebaldi and Knutti, 2007; Tebaldi et al., 2005), but it has very rarely been applied at impact level of climate change studies. To the best of the author’s knowledge, only Sperna-Weiland et al. (2012) used REA method at impact level in their study where the total uncertainty is represented in streamflow scenarios. Unlike the Sperna-Weiland et al. (2012) study, however, this research argues that application of REA method at impact level requires inclusion of hydrologic (impact) model uncertainty into the method’s structure. Therefore, the present research analyzes the possibility of hydrological model uncertainty inclusion to the REA method.

Probabilistic approaches, on the other hand, have shown to be effective at demonstrating the likelihood of climate change scenarios and impacts (Chen et al., 2013; Fowler et al., 2007; Raje and Mujumdar, 2010), despite being generally applied at climate level. A resampling method is often used to generate a large number of future climate scenarios and quantify the uncertainties through defining a confidence interval for the likelihood of climate projections. Wilby and Harris (2006) have claimed that application of an integrated system of GCM/downscaling/hydrological-model for uncertainty quantification might conceal the individual uncertainty sources influence on the final Cumulative Distribution Function (CDF). In response, this research postulates that by altering the probability of occurrence of obtained impacts (streamflow) from an ensemble of integrated systems, individual components’ uncertainty would be manifested in the final ‘uncertainty band’ instead of a single CDF. Thus, climate change hydrological impact uncertainty is to be quantified by bootstrapping each integrated systems output and defining a probabilistic uncertainty band.
1.3 Research Objectives

According to the stated research gaps in uncertainty analysis of climate change hydrological impacts amidst increasing water scarcity, which necessitates a precise impact assessment of climate change scenarios; the main objective of this study is to assess impact-based multi-model ensemble approaches for uncertainty analysis of climate change impact studies. Consequently, to achieve this aim, the following sub-objectives are delineated:

1- To study climate change impacts on climate variables of the case study by generating a large ensemble of future scenarios using 19 GCMs’ bias-corrected simulations under two emission scenarios.

2- To simulate the hydrology cycle of the case study using Soil and Water Assessment Tool (SWAT) model and assess climate change impacts on streamflow of the basin.

3- To quantify uncertainty contribution of each component in the impact study inclusive of GCMs/downscaling, emission scenarios, and hydrological model parameter set.

4- To modify the uncertainty modeling method of Reliability Ensemble Averaging (REA) for an impact wise assessment of uncertainties, and compare it with a new impact-based probabilistic approach.

1.4 Scope of the Research

Climatological, hydrological, and statistical considerations are the three main aspects of this research that are integrated for uncertainty modeling of the climate change impacts on streamflow of the Hulu Langat Basin. Downscaling of 19 GCMs’ output under two greenhouse gases emission scenarios to run the calibrated hydrological model for assessment of climate change impacts on streamflow is followed by the analysis and modeling of the uncertainty in obtained streamflow scenarios. Uncertainty modeling is accomplished using two methods; one based on weighting the streamflow scenarios and the other follows a probabilistic approach. The analysis of the effect of climate change at two time periods of 2016-2045 as the near-future climate represented by 2030s, and 2070-2099 as the long-term climate represented by 2080s serve as the main draw of the work. The physical characteristics of the catchment are represented with the calibrated hydrological model. In both phases of the study, climate and hydrology, data availability constraint has been dealt with by changing periods’ length. In addition, posterior distribution of hydrological parameters were used in hydrological modeling to conceptualize land use changes effect on hydrological modeling in future periods.
1.5 Significance of the work

The future challenge in adapting to climate changes is quantification of uncertainties involved. In comparison with other studies in this context, two common uncertainty-modeling approaches are applied at the impact level of the study. The results would be integrated uncertainty modeling methods that encapsulate climate components (GCM, emission scenario) uncertainty and hydrological modeling uncertainty within a lump system. The reliability ensemble averaging method in the class of multi-model ensemble approaches is modified to take into account the effect of hydrological model parameter uncertainty, which then encircles all the uncertainty sources and portrays them within a prediction interval without overlooking any uncertainty component. Moreover, in the class of probabilistic approaches, application of bootstrapped ensemble of streamflow scenarios is promoted as a new approach that can stand for all the uncertainty sources in an impact study. Thus, uncertainty level can be reduced by ranking future streamflow scenarios based on their reliability measures or probability of occurrence. The more pragmatic realizations of future climate can be then selected to appoint adaptation strategies and approximate the future compatibility between water demand and resources available.
REFERENCES


