UNIVERSITI PUTRA MALAYSIA

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

HADI GALAVI

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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

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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.

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همسر و همراه عزیزم، مریم، که عشق بی نظیر، حمایتهای همیشگی و مشورت های ارزشمند ایشان در طول این سفر از مهمترین سرمایه های من بودند.

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برادران و خواهران عزیزم، مصطفی، سعیده، صادق و حکیمه.

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

By

HADI GALAVI

December 2015

Chairman: Lee Teang Shui, PhD
Faculty: Engineering

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.

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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

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Salah satu penyataan utama daripada kesan perubahan iklim di satu kawasan tadahan air pada abad ke-21 adalah pemendakan—kekerapan dan keamatan—corak perubahan yang mungkin menyebabkan kekurangan air. Jadi ia adalah amat penting untuk mentakrifkan ciri-ciri hidrologi pada skala lembangan bawah perubahan iklim untuk pengurusan sumber air yang mampan untuk memuaskanpermintaan semasa dan masa depan. Perubahan spatial kekerapan pemendakan dan keamatan yang disebabkan oleh perubahan iklim boleh mempengaruhi kekerapan dan magnitud pengaliran sungai menyebabkan banjir dan kemarau terlampau bersama kesan tempatan dan serantau ketara yang berkenaan terhadap ekonomi. Penilaian kesan hidrologi perubahan iklim merangkumi ketidakpastian yang didapati daripada penggunaan Model Pengedaran Umum (GCM), Senario Pemancaran Gas Rumah Hijau (ES), kaedah-kaedah penskalaan rendah dan model hidrologi, yang mempunyai ketidakpastian semula jadi masing-masing. Penilaian ketidakpastian kesan perubahan iklim ke atas pengaliran sungai di Lembangan Hulu Langat merupakan objektif utama kajian ini. Namum begitu, Peralatan Penilaian Tanah dan Air (SWAT) digunakan untuk memodelkan sistem hidrologi kawasan tadahan. Ia ditentukurkan berdasarkan data sejarah pengaliran sungai di hilir kawasan tadahan. Satu kumpulan sebanyak 19 GCMs di bawah dua senario pemancaran digunakan untuk menyediakan pelbagai senario (ES) iklim yang mungkin berlaku pada masa hadapan. Kemudian, data pemendakan dan suhu daripada penskalaan rendah GCM yang diperbetulkan secara cenderung digunakan bersama model SWAT untuk menunjukkan kedua-dua iklim semasa dan masa hadapan. Senario pengaliran sungai yang diperolehi dianalisis berasaskan ketidakpastian yang sedia ada dalam ramalan. Parameter model hidrologi, senario pemancaran, dan ketidakpastian GCM dipermodelkan dengan menggunakan kaedah Reliability Ensemble Averaging (REA) dan kaedah Bootstrapped Ensemble Uncertainty Modeling (BEUM). Dalam simulasi iklim semasa, ketidakpastian parameter model hidrologi didapati lebih besar daripada yang dikaitkan dengan senario pemancaran, manakala GCMs merupakan sumber ketidakpastian yang terbesar. Bagaimanapun, ketidakpastian parameter model hidrologi adalah sumber yang paling kecil pada tempoh iklim masa hadapan, manakala GCMs dan senario pemancaran adalah sumber

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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 didapatiberbeza 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 dipakaiguna 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.

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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.

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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:

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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

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LIST OF NOTATIONS

SW_t	Total soil water content (mm water)
SW_0	Initial soil water content (mm water)
PRCP	Precipitation (mm water)
Q	Surface runoff (mm water)
ET	Evapotranspiration (mm water)
W_{seep}	Vadose zone water (mm water)
Q_{gw}	Return flow from lateral and ground water (mm water)
N	Number of behavioral parameter sets
$L(\theta_i)$	The likelihood function
P	Prediction percentile
φ_i	The i^{th} set of behavioral model parameter
$f(\varphi_i)$	The model for the i^{th} set of behavioral model parameter
$\hat{Z}_{t,i}$	The magnitude of parameter *Z* at time *t*
w_i	Weighted likelihood factor
$Q_{t_i,97.5\%}$	Upper band of the 95PPU
$Q_{t_i,2.5\%}$	Lower band of the 95PPU
t_i	Time interval
σ_{obs}	Standard deviation of observed data
F	CDF
F^{-1}	Inverse CDF
G	GCM
b	Baseline climate
p	Projection
X_{bc}	Bias-corrected value of X on the CDF of the future GCM
$\check{x}$	Time series of the observed rainfall above 0.1 mm
$\bar{x}_G$	Threshold for the GCM simulations applied for bias-correction
ΔQ	Simulations deviation from the observed mean annual flow
$\widetilde{\Delta Q}$	The ensemble average deviation from observations
R_i	Reliability measure of i^{th} GCM.
$R_{B,i}$	Model bias criteria
$R_{D,i}$	Model convergence criteria
ε_Q	Natural variability in the observed annual flow
B_i	i^{th} GCM absolute bias (ΔQ) from the observation

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D_i	Distance of *i*th GCM predictions from the ensemble average
$\delta_{\Delta Q}$	Root mean square difference
$\breve{H}_Q$	Hydrological model variability
$R_{mod,i}$	Overall reliability of ith GCM in the modified REA

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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

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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).

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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.

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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.

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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

Abbaspour, K. C., Faramarzi, M., Ghasemi, S. S., and Yang, H. (2009). Assessing the impact of climate change on water resources in Iran. *Water Resources Research*, *45*(10).

Abbaspour, K. C., Vejdani, M., and Haghighat, S. (2007). SWAT-CUP Calibration and Uncertainty Programs for SWAT. In *The fourth International SWAT conference* (pp. 1596–1602).

Ali, M. F., Rahman, N. F. A., Khalid, K., and Liem, N. D. (2014). Langat River Basin Hydrologic Model Using Integrated GIS and ArcSWAT Interface. *Applied Mechanics and Materials*, *567*, 86–91.

Allen, M., Stott, P., Mitchell, J., Schnur, R., and Delworth, T. (2000). Quantifying the uncertainty in forecasts of anthropogenic climate change. *Nature*, *407*(6804), 617–620.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., … Jha, M. K. (2012). Swat: Model Use, Calibration, and Validation. *American Society of Agricultural and Biological Engineers*, *55*(4), 1491–1508.

Arnold, J. G., Srinivasan, R., Muttiah, R. S., and Williams, J. R. (1998). Large area hydrologic modeling and assessment part i: model development. *Journal of the American Water Resources Association*, *34*(1), 73–89.

Ayub, K. R., Hin, L. S., and Hamidi, A. A. (2009). SWAT Application For Hydrologic and Water Quality Modeling For Suspended Sediments : A Case Study of Sungai Langat ' s Catchment in Selangor. In *International Conference on Water Resources*. Malaysia.

Bae, D.-H., Jung, I.-W., and Lettenmaier, D. P. (2011). Hydrologic uncertainties in climate change from IPCC AR4 GCM simulations of the Chungju Basin, Korea. *Journal of Hydrology*, *401*(1-2), 90–105.

Baldassarre, G. Di, Elshamy, M., Griensven, A. van, Soliman, E., Kigobe, M., Ndomba, P., … Uhlenbrook, S. (2011). A Critical Discussion of Recent Studies Evaluating the Impacts of Climate Change on Water Resources in the Nile basin. *Nile Basin Water Science & Engineering Journal*, *4*(2), 94–100.

Bastola, S. (2013). Hydrologic impacts of future climate change on Southeast US watersheds. *Regional Environmental Change*, *13*(S1), 131–139.

Bastola, S., Murphy, C., and Sweeney, J. (2011). The role of hydrological modelling uncertainties in climate change impact assessments of Irish river catchments. *Advances in Water Resources*, *34*(5), 562–576.

Beven, K., and Binley, A. (1992). The future of distributed models: model calibration and uncertainty prediction. *Hydrological Processes*, *6*(3), 279–298.

Beven, K., and Freer, J. (2001). Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *Journal of Hydrology*, *249*(1-4), 11–29.

© COPYRIGHT UPM

Boles, C. M. W. (2013). *Swat Model Simulation of Bioenergy Crop Impacts in a Tile-Drained Watershed* (Doctoral dissertation). Purdue University.

Boyer, C., Chaumont, D., Chartier, I., and Roy, A. G. (2010). Impact of climate change on the hydrology of St. Lawrence tributaries. *Journal of Hydrology*, *384*(1-2), 65–83.

Brands, S., Taboada, J., Cofiño, A., Sauter, T., and Schneider, C. (2011). Statistical downscaling of daily temperatures in the NW Iberian Peninsula from global climate models: validation and future scenarios. *Climate Research*, *48*(2), 163–176.

Brienen, S., Rust, H. W., Sauter, T., Themeßl, M., Venema, V. K. C., and Chun, K. P. (2010). Precipitation Downscaling Under Climate Change: Recent Developments to Bridge the Gap between Dynamical Models and the End User. *Reviews of Geophysics*, *48*(3), 1–34.

Brigode, P., Oudin, L., and Perrin, C. (2013). Hydrological model parameter instability: A source of additional uncertainty in estimating the hydrological impacts of climate change? *Journal of Hydrology*, *476*, 410–425.

Buytaert, W., Vuille, M., Dewulf, A., Urrutia, R., Karmalkar, A., and Célleri, R. (2010). Uncertainties in climate change projections and regional downscaling in the tropical Andes: implications for water resources management. *Hydrology and Earth System Sciences*, *14*(7), 1247–1258.

Carter, T. ., Hulme, M., and Lal, M. (1999). *Guidelines on the Use of Scenario Data for Climate Impact and Adaptation Assessment. Version 1*. Retrieved from http://www.ipcc-data.org/guidelines/TGICA_guidance_sdciaa_v1_final.pdf

Chen, J., Brissette, F. P., Chaumont, D., and Braun, M. (2013). Performance and uncertainty evaluation of empirical downscaling methods in quantifying the climate change impacts on hydrology over two North American river basins. *Journal of Hydrology*, *479*, 200–214.

Chen, J., Brissette, F. P., and Leconte, R. (2011). Uncertainty of downscaling method in quantifying the impact of climate change on hydrology. *Journal of Hydrology*, *401*(3-4), 190–202.

Christensen, J. H., Kjellström, E., Giorgi, F., Lenderink, G., and Rummukainen, M. (2010). Weight assignment in regional climate models. *Climate Research*, *44*(2-3), 179–194.

Chung, E.-S., Park, K., and Lee, K. S. (2011). The relative impacts of climate change and urbanization on the hydrological response of a Korean urban watershed. *Hydrological Processes*, *25*(4), 544–560.

Conway, D., and Jones, P. D. (1998). The use of weather types and air flow indices for GCM downscaling. *Journal of Hydrology*, *212-213*, 348–361.

Dawadi, S., and Ahmad, S. (2013). Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. *Journal of Environmental Management*, *114*, 261–75.

Devak, M., and Dhanya, C. T. (2014). Downscaling of Precipitation in Mahanadi Basin , India. *International Journal of Civil Engineering Research*, *5*(2),

© COPYRIGHT UPM

111–120.

Dibike, Y. B., and Coulibaly, P. (2005). Hydrologic impact of climate change in the Saguenay watershed: comparison of downscaling methods and hydrologic models. *Journal of Hydrology*, *307*(1-4), 145–163.

Dile, Y. T., Berndtsson, R., and Setegn, S. G. (2013). Hydrological Response to Climate Change for Gilgel Abay River, in the Lake Tana Basin - Upper Blue Nile Basin of Ethiopia. *PLoS ONE*, *8*(10), 12–17.

Dobler, C., Hagemann, S., Wilby, R. L., and Stötter, J. (2012). Quantifying different sources of uncertainty in hydrological projections in an Alpine watershed. *Hydrology and Earth System Sciences*, *16*(11), 4343–4360.

Dong, C., Schoups, G., and Giesen, N. Van De. (2013). Technological Forecasting & Social Change Scenario development for water resource planning and management : A review. *Technological Forecasting & Social Change*, *80*(4), 749–761.

Efron, B. (1979). Bootstrap Methods: Another Look at the Jackknife. *The Annals of Statistics*, *7*(1), 1–26.

Elshamy, M. E., Seierstad, I. a., and Sorteberg, a. (2008). Impacts of climate change on Blue Nile flows using bias-corrected GCM scenarios. *Hydrology and Earth System Sciences Discussions*, *5*(3), 1407–1439.

Etemadi, H., Samadi, S., and Sharifikia, M. (2014). Uncertainty analysis of statistical downscaling models using general circulation model over an international wetland. *Climate Dynamics*, *42*(11-12), 2899–2920.

Fang, G. H., Yang, J., Chen, Y. N., and Zammit, C. (2014). Comparing bias correction methods in downscaling meteorological variables for hydrologic impact study in an arid area in China. *Hydrology and Earth System Sciences Discussions*, *11*(11), 12659–12696.

Fowler, H. J., Blenkinsop, S., and Tebaldi, C. (2007). Linking climate change modelling to impacts studies : recent advances in downscaling techniques for hydrological. *International Journal of Climatology*, *27*, 1547–1578.

Fujihara, Y., Simonovic, S. P., Topaloğlu, F., Tanaka, K., and Watanabe, T. (2008). An inverse-modelling approach to assess the impacts of climate change in the Seyhan River basin, Turkey / Une approche de modélisation inverse pour évaluer les impacts du changement climatique dans le bassin versant de la Rivière Seyhan, Turquie. *Hydrological Sciences Journal*, *53*(6), 1121–1136.

Galván, L., Olías, M., Izquierdo, T., Cerón, J. C., and Fernández de Villarán, R. (2014). Rainfall estimation in SWAT: An alternative method to simulate orographic precipitation. *Journal of Hydrology*, *509*, 257–265.

Gassman, P. W., Reyes, M. R., Green, C. H., and Arnold, J. G. (2007). The Soil and Water Assessment Tool : Historical Development , Applications , and Future Research Directions. *American Society of Agricultural and Biological Engineers*, *50*(4), 1211–1250.

Gaur, A. (2013). *Climate change impact on flood hazard in the grand river basin, Ontario, Canada* (Doctoral dissertation). Western University, London, Ontario, Canada.

© COPYRIGHT UPM

Ghosh, S., and Katkar, S. (2012). Modeling Uncertainty Resulting from Multiple Downscaling Methods in Assessing Hydrological Impacts of Climate Change. *Water Resources Management*, *26*(12), 3559–3579.

Ghosh, S., and Misra, C. (2010). Assessing Hydrological Impacts of Climate Change : Modeling Techniques and Challenges. *The Open Hydrology Journal*, *4*, 115–121.

Ghosh, S., and Mujumdar, P. P. (2008). Statistical downscaling of GCM simulations to streamflow using relevance vector machine. *Advances in Water Resources*, *31*(1), 132–146.

Ghosh, S., and Mujumdar, P. P. (2009). Climate change impact assessment: Uncertainty modeling with imprecise probability. *Journal of Geophysical Research*, *114*(D18).

Giorgi, F., and Mearns, L. O. (2002). Calculation of Average, Uncertainty Range, and Reliability of Regional Climate Changes from AOGCM Simulations via the "Reliability Ensemble Averaging " (REA) Method. *Journal of Climate*, *15*(10), 1141–1158.

Goderniaux, P., Brouyere, S., Wildemeersch, S., Therrien, R., and Dassargues, A. (2015). Uncertainty of climate change impact on groundwater reserves – Application to a chalk aquifer. *Journal of Hydrology*, *528*, 108–121.

Greene, A. M., Goddard, L., and Lall, U. (2006). Probabilistic multimodel regional temperature change projections. *Journal of Climate*, *19*(17), 4326–4343.

Gupta, H. V., Sorooshian, S., and Yapo, P. O. (1999). Status of automatic calibration for hydrologic models: Comparison with multilevel expert calibration. *Journal of Hydrologic Engineering*, *4*(2), 135–143.

Hamlet, A. F., Salathé, E. P., and Carrasco, P. (2010). *Statistical Downscaling Techniques for Global Climate Model Simulations of Temperature and Precipitation with Application to Water Resources Planning Studies*. Retrieved from http://www.hydro.washington.edu/2860/products/sites/r7climate/study_report/CBCCSP_chap4_gcm_final.pdf

Hashmi, M. Z., Shamseldin, A. Y., and Melville, B. W. (2011). Statistical downscaling of watershed precipitation using Gene Expression Programming (GEP). *Environmental Modelling & Software*, *26*(12), 1639–1646.

Hassan, Z., and Harun, S. (2013). Impact of climate change on rainfall over Kerian, Malaysia with Long Ashton Research Station Weather Generator (LARS-WG). *Malaysian Journal of Civil Engineering*, *25*(1), 33–44.

Hay, L. E., Clark, M. P., Wilby, R. L., Gutowski, W. J., Leavesley, G. H., Pan, Z., … Takle, E. S. (2002). Use of Regional Climate Model Output for Hydrologic Simulations. *Journal of Hydrometeorology*, *3*(5), 571–590.

Hidalgo, H. G., Amador, J. a., Alfaro, E. J., and Quesada, B. (2013). Hydrological climate change projections for Central America. *Journal of Hydrology*, *495*, 94–112.

Huisman, J. a., Breuer, L., Bormann, H., Bronstert, a., Croke, B. F. W., Frede, H.-G., … Willems, P. (2009). Assessing the impact of land use change on

© COPYRIGHT UPM

hydrology by ensemble modeling (LUCHEM) III: Scenario analysis. *Advances in Water Resources*, *32*(2), 159–170.

IPCC. (1997). *The Regional Impacts of Climate Change: An Assessment of Vulnerability*. Retrieved from http://www.ipcc.ch/ipccreports/sres/regional/index.php?idp=0

IPCC. (2000). *Special Report Emissions Scenarios*. Retrieved from http://www.ipcc.ch/ipccreports/sres/emission/index.php?idp=0

IPCC. (2001). *Climate change 2001: The scientific basis*. Retrieved from http://www.grida.no/climate/ipcc_tar/wg1/index.htm

IPCC. (2007). *The physical science basis – summary for Policymakers. Contribution of WG1 to the Fourth assessment report of the Intergovernmental Panel on Climate Change*. Retrieved from http://www.ipcc.ch/publications_and_data/ar4/wg1/en/contents.html

Jajarmizadeh, M., Harun, S., Abdullah, R., and Salarpour, M. (2012). Using soil and water assessment tool for flow simulation and assessment of sensitive parameters applying SUFI-2 algorithm. *Caspian Journal of Applied Sciences Research*, *2*(1), 37–44.

Jiang, T., Chen, Y. D., Xu, C., Chen, X., Chen, X., and Singh, V. P. (2007). Comparison of hydrological impacts of climate change simulated by six hydrological models in the Dongjiang Basin, South China. *Journal of Hydrology*, *336*(3-4), 316–333.

Juahir, H. H. (2009). *Water quality data analysis and modeling of the Langat river basin* (Doctoral dissertation). University of Malaya.

Jung, I.-W., and Chang, H. (2011). Assessment of future runoff trends under multiple climate change scenarios in the Willamette River Basin, Oregon, USA. *Hydrological Processes*, *25*(2), 258–277.

Jung, I.-W., Moradkhani, H., and Chang, H. (2012). Uncertainty assessment of climate change impacts for hydrologically distinct river basins. *Journal of Hydrology*, *466-467*, 73–87.

Kabiri, R., Ramani Bai, V., and Chan, A. (2013). Regional precipitation scenarios using a spatial statistical downscaling approach for Klang watershed , Malaysia. *Journal of Environmental Research And Development*, *8*(1), 126–134.

Kannan, S., and Ghosh, S. (2010). Prediction of daily rainfall state in a river basin using statistical downscaling from GCM output. *Stochastic Environmental Research and Risk Assessment*, *25*(4), 457–474.

Karamouz, M., Asce, F., Ahmadi, B., and Zahmatkesh, Z. (2013). Developing an Agricultural Planning Model in a Watershed Considering Climate Change Impacts. *Journal of Water Resources Planning And Management*, *139*, 349–363.

Kay, a. L., Davies, H. N., Bell, V. a., and Jones, R. G. (2008). Comparison of uncertainty sources for climate change impacts: flood frequency in England. *Climatic Change*, *92*(1-2), 41–63.

Khalid, K., Ali, M. F., Rahman, N. F. A., and Mispan, M. R. (2016). Application

© COPYRIGHT UPM

on One-at-a-Time Sensitivity Analysis of Semi-Distributed Hydrological Model in Tropical Watershed. *IACSIT International Journal of Engineering and Technology*, *8*(2), 132–136.

Khan, M. S., Coulibaly, P., and Dibike, Y. (2006). Uncertainty analysis of statistical downscaling methods. *Journal of Hydrology*, *319*(1-4), 357–382.

Kingston, D. G., and Taylor, R. G. (2010). Sources of uncertainty in climate change impacts on river discharge and groundwater in a headwater catchment of the Upper Nile Basin, Uganda. *Hydrology and Earth System Sciences*, *14*(7), 1297–1308.

Kokic, P., Jin, H., and Crimp, S. (2013). Improved point scale climate projections using a block bootstrap simulation and quantile matching method. *Climate Dynamics*, *41*(3-4), 853–866.

Kriauciuniene, J., Jakimavicius, D., Sarauskiene, D., and Kaliatka, T. (2013). Estimation of uncertainty sources in the projections of Lithuanian river runoff. *Stochastic Environmental Research and Risk Assessment*, *27*, 769–784.

Kumar, N. (2014). *Impacts of Climate Change and Land-use Change on the Water Resources of the Upper Kharun Catchment , Chhattisgarh , India* (Doctoral dissertation). Rheinischen Friedrich-Wilhelms University.

Latif, M. (2011). Uncertainty in climate change projections. *Journal of Geochemical Exploration*, *110*(1), 1–7.

Lespinas, F., Ludwig, W., and Heussner, S. (2014). Hydrological and climatic uncertainties associated with modeling the impact of climate change on water resources of small Mediterranean coastal rivers. *Journal of Hydrology*, *511*, 403–422.

Li, H., Sheffield, J., and Wood, E. F. (2010). Bias correction of monthly precipitation and temperature fields from Intergovernmental Panel on Climate Change AR4 models using equidistant quantile matching. *Journal of Geophysical Research: Atmospheres*, *115*(10).

Liu, Y., Zhang, J., Wang, G., Liu, J., He, R., Wang, H., … Jin, J. (2012). Quantifying uncertainty in catchment-scale runoff modeling under climate change (case of the Huaihe River, China). *Quaternary International*, *282*, 130–136.

Lopez, A., Tebaldi, C., New, M., Stainforth, D., Allen, M., and Kettleborough, J. (2006). Two Approaches to Quantifying Uncertainty in Global Temperature Changes. *Journal of Climate*, *19*(19), 4785–4796.

Ludwig, F., van Slobbe, E., and Cofino, W. (2014). Climate change adaptation and Integrated Water Resource Management in the water sector. *Journal of Hydrology*, *518*, 235–242.

Lüthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., … Stocker, T. F. (2008). High-resolution carbon dioxide concentration record 650,000-800,000 years before present. *Nature*, *453*(7193), 379–382.

Mango, L. M., Melesse, A. M., McClain, M. E., Gann, D., and Setegn, S. G. (2011). Land use and climate change impacts on the hydrology of the upper

© COPYRIGHT UPM

Mara River Basin, Kenya: results of a modeling study to support better resource management. *Hydrology and Earth System Sciences*, *15*(7), 2245–2258.

Maurer, E. P. (2007). Uncertainty in hydrologic impacts of climate change in the Sierra Nevada, California, under two emissions scenarios. *Climatic Change*, *82*(3-4), 309–325.

Maurer, E. P., Hidalgo, H. G., Das, T., Dettinger, M. D., and Cayan, D. R. (2010). The utility of daily large-scale climate data in the assessment of climate change impacts on daily streamflow in California. *Hydrology and Earth System Sciences*, *14*(6), 1125–1138.

Mearns, L. O., Giorgi, F., Whetton, P., Pabon, D., Hulme, M., and Lal, M. (2003). Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments.

Mehta, V. K., Aslam, O., Dale, L., Miller, N., and Purkey, D. R. (2013). Scenario-based water resources planning for utilities in the Lake Victoria region. *Physics and Chemistry of the Earth*, *61-62*, 22–31.

Meinshausen, M., Smith, S. J., Calvin, K., Daniel, J. S., Kainuma, M. L. T., Lamarque, J., … van Vuuren, D. P. P. (2011). The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change*, *109*(1), 213–241.

Memarian, H., Balasundram, S. K., Abbaspour, K. C., Talib, J. B., Teh Boon Sung, C., and Sood, A. M. (2014). SWAT-based Hydrological Modelling of Tropical Land Use Scenarios. *Hydrological Sciences Journal*, *59*(10), 1808–1829.

Memarian, H., Tajbakhsh, M., and Balasundram, S. K. (2013). Application of SWAT for impact assessment of land use / cover change and best management practices : a review. *International Journal of Advancement in Earth and Environmental Sciences*, *1*(1), 36–40.

Mirzaei, M., Huang, Y. F., El-Shafie, A., and Shatirah, A. (2015). Application of the generalized likelihood uncertainty estimation (GLUE) approach for assessing uncertainty in hydrological models: a review. *Stochastic Environmental Research and Risk Assessment*, *29*, 1265–1273.

Mirzaei, M., Huang, Y. F., Lee, T. S., El-Shafie, A., and Ghazali, A. H. (2013). Quantifying uncertainties associated with depth duration frequency curves. *Natural Hazards*, *71*(2), 1227–1239.

Mondal, Y., Chiang, J. C. H., and Koo, M. S. (2014). Statistical downscaling of last glacial maximum and mid-holocene climate simulations over the continental United States. In *American Geophysical Union, Fall Meeting Abstracts* (pp. 3689–3690).

Moradkhani, H., Baird, R. G., and Wherry, S. a. (2010). Assessment of climate change impact on floodplain and hydrologic ecotones. *Journal of Hydrology*, *395*(3-4), 264–278.

Moriasi, D., and Arnold, J. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *American Society of Agricultural and Biological Engineers*, *50*(3), 885–900.

© COPYRIGHT UPM

MOSTI. (2015). General Climate of Malaysia.

Mujumdar, P. P., and Ghosh, S. (2008a). Climate change impact on hydrology and water resources. *ISH Journal of Hydraulic Engineering*, *14*(3), 1–17.

Mujumdar, P. P., and Ghosh, S. (2008b). Modeling GCM and scenario uncertainty using a possibilistic approach: Application to the Mahanadi River, India. *Water Resources Research*, *44*(6), 1–15.

Mujumdar, P. P., Ghosh, S., and Raje, D. (2009). Hydro-meteorological predictions from GCM simulations: downscaling techniques and uncertainty modelling. In *New approaches to hydrological prediction in data-sparse regions. Proceedings of Symposium HS. 2 at the Joint Convention of The International Association of Hydrological Sciences (IAHS) and The International Association of Hydrogeologists (IAH)* (pp. 165–175). Hyderabad, India: IAHS Press.

Nan, Y., Bao-hui, M., and Chun-kun, L. (2011). Impact Analysis of Climate Change on Water Resources. *Procedia Engineering*, *24*, 643–648.

Nash, E., and Sutcliffe, V. (1970). River flow forecasting through conceptual models part i- a discussion of principles. *Journal of Hydrology*, *10*, 282–290.

Nawaz, N. R., and Adeloye, a. J. (2006). Monte carlo assessment of sampling uncertainty of climate change impacts on water resources yield in Yorkshire, England. *Climatic Change*, *78*(2-4), 257–292.

Nuri, A. Z., Farzaneh, M., and Espanayi, K. (2014). Assessment of climatic parameters uncertainty under effect of different downscaling techniques. *International Research Journal of Applied and Basic Sciences*, *8*(9), 1316–1320.

Okkan, U., and Inan, G. (2014). Statistical downscaling of monthly reservoir inflows for Kemer watershed in Turkey : use of machine learning methods , multiple GCMs and emission scenarios. *International Journal Of Climatology*.

Palizdan, N., Falamarzi, Y., Huang, Y. F., Lee, T. S., and Ghazali, A. H. (2013). Regional precipitation trend analysis at the Langat River Basin, Selangor, Malaysia. *Theoretical and Applied Climatology*, *117*(3-4), 589–606.

Park, J., Park, M., Ahn, S., Park, G., Yi, J. -E., Kim, G. S., … Kim, S. J. (2011). Assessment of future climate change impacts on water quantity and quality for a mountainous dam watershed using SWAT. *American Society of Agricultural and Biological Engineers*, *54*(5), 1725–1737.

Phillips, N. a. (1956). The general circulation of the atmosphere: A numerical experiment. *Quarterly Journal of the Royal Meteorological Society*, *82*(352), 123–164.

Poulin, A., Brissette, F., Leconte, R., Arsenault, R., and Malo, J.-S. (2011). Uncertainty of hydrological modelling in climate change impact studies in a Canadian, snow-dominated river basin. *Journal of Hydrology*, *409*(3-4), 626–636.

Prudhomme, C., and Davies, H. (2007). Comparison of different sources of uncertainty in climate change impact studies in Great Britain. In *Technical*

Document in Hydrology-UNESCO (pp. 183–190). Paris.

Prudhomme, C., and Jakob, D. (2002). Impact of climate change on flooding in the UK : a methodology for estimating uncertainty. In *Regional Hydrology: Bridging the gap between Research and Practice (FRIEND 2002)* (pp. 109–116).

Prudhomme, C., Jakob, D., and Svensson, C. (2003). Uncertainty and climate change impact on the flood regime of small UK catchments. *Journal of Hydrology*, *277*(1-2), 1–23.

Prudhomme, C., Reynard, N., and Crooks, S. (2002). Downscaling of global climate models for flood frequency analysis: where are we now? *Hydrological Processes*, *16*(6), 1137–1150.

Puncak Niaga Sdn. Bhd. (2008). *Annual report*. Putrajaya. Retrieved from http://www.puncakniaga.com.my/investorrelations/annual-report

Quintana-Seguí, P., Ribes, A., Martin, E., Habets, F., and Boé, J. (2010). Comparison of three downscaling methods in simulating the impact of climate change on the hydrology of Mediterranean basins. *Journal of Hydrology*, *383*(1-2), 111–124.

Rahmani, M.-A., and Zarghami, M. (2013). A new approach to combine climate change projections by ordered weighting averaging operator; applications to northwestern provinces of Iran. *Global and Planetary Change*, *102*, 41–50.

Rajan, S. (2014). *Statistical downscaling of GCM output, hydrological simulation and generation of future scenario using Variable Infiltration Capacity (VIC) model for the Ganga Basin, India* (Doctoral dissertation). Dept. of Space, Govt. of India Dehradun – Uttarakhand, India.

Raje, D., and Mujumdar, P. P. (2010). Constraining uncertainty in regional hydrologic impacts of climate change: Nonstationarity in downscaling. *Water Resources Research*, *46*(7).

Raneesh, K. Y., and Thampi-Santosh, G. (2011). A study on the impact of climate change on streamflow at the watershed scale in the humid tropics. *Hydrological Sciences Journal*, *56*(6), 946–965.

Rowell, D. P. (2011). Sources of uncertainty in future changes in local precipitation. *Climate Dynamics*, *39*(7-8), 1929–1950.

Rupa, C., Saha, U., and Mujumdar, P. P. (2015). Model and parameter uncertainty in IDF relationships under climate change. *Advances in Water Resources*, *79*, 127–139.

Samaniego, L., and Bárdossy, A. (2006). Simulation of the impacts of land use/cover and climatic changes on the runoff characteristics at the mesoscale. *Ecological Modelling*, *196*(1-2), 45–61.

Sarwar, S. (2013). *Reservoir life expectancy in relation to climate and land-use changes : case study of the Mangla reservoir in Pakistan* (Doctoral dissertation). The University of Waikato, New Zealand.

Schmidli, J., Frei, C., and Vidale, P. L. (2006). Downscaling from GCM precipitation: a benchmark for dynamical and statistical downscaling

© COPYRIGHT UPM

methods. *International Journal of Climatology*, *26*(5), 679–689.

Semenov, M., and Stratonovitch, P. (2010). Use of multi-model ensembles from global climate models for assessment of climate change impacts. *Climate Research*, *41*(Semenov 2007), 1–14.

Sharma, D., Das Gupta, a., and Babel, M. S. (2007). Spatial disaggregation of bias-corrected GCM precipitation for improved hydrologic simulation: Ping River Basin, Thailand. *Hydrology and Earth System Sciences Discussions*, *4*(1), 35–74.

Shashikanth, K., and Ghosh, S. (2013). Fine resolution indian summer monsoon rainfall projection with statistical downscaling. *International Journal of Chemical, Environmental & Biological Sciences*, *1*(4).

Shin, H.-J., Park, M.-J., Hwang, S.-J., Park, J.-Y., and Kim, S.-J. (2014). Hydrologic impact of climate change with adaptation of vegetation community in a forest-dominant watershed. *Paddy and Water Environment*, *12*(S1), 51–63.

Shrestha, R. R., Dibike, Y. B., and Prowse, T. D. (2012). Modelling of climate-induced hydrologic changes in the Lake Winnipeg watershed. *Journal of Great Lakes Research*, *38*(SUPPL. 3), 83–94.

Singh, H., Sinha, T., Sankarasubramanian, a, and Asce, M. (2009). Impacts of Near-Term Climate Change and Population Growth on Within-Year Reservoir Systems. *Journal of Water Resources Planning and Management*, 1–13.

Sivakumar, B., and Sharma, A. (2009). Climate change impacts on water resources planning and management: scientific challenges and beyond. In *18th World IMACS / MODSIM Congress* (pp. 3969–3975). Cairns, Australia.

Sperna-Weiland, F. C., van Beek, L. P. H., Kwadijk, J. C. J., and Bierkens, M. F. P. (2010). The ability of a GCM-forced hydrological model to reproduce global discharge variability. *Hydrology and Earth System Sciences*, *14*(8), 1595–1621.

Sperna-Weiland, F. C., van Beek, L. P. H., Weerts, A. H., and Bierkens, M. F. P. (2012). Extracting information from an ensemble of GCMs to reliably assess future global runoff change. *Journal of Hydrology*, *412-413*, 66–75.

Srivastava, P. K., Han, D., Rico-Ramirez, M. a., and Islam, T. (2014). Sensitivity and uncertainty analysis of mesoscale model downscaled hydro-meteorological variables for discharge prediction. *Hydrological Processes*, *28*(15), 4419–4432.

Stedinger, J. R., Vogel, R. M., Lee, S. U., and Batchelder, R. (2008). Appraisal of the generalized likelihood uncertainty estimation (GLUE) method. *Water Resources Research*, *44*(12), n/a–n/a.

Strauch, M., Bernhofer, C., Koide, S., Volk, M., Lorz, C., and Makeschin, F. (2012). Using precipitation data ensemble for uncertainty analysis in SWAT streamflow simulation. *Journal of Hydrology*, *414-415*, 413–424.

Sunyer, M. a., Madsen, H., and Ang, P. H. (2012). A comparison of different regional climate models and statistical downscaling methods for extreme

© COPYRIGHT UPM

rainfall estimation under climate change. *Atmospheric Research*, *103*, 119–128.

Tabor, K., and Williams, J. W. (2010). Globally downscaled climate projections for assessing the conservation impacts of climate change. *Ecological Applications : A Publication of the Ecological Society of America*, *20*(2), 554–65.

Tareghian, R., and Rasmussen, P. F. (2013). Statistical downscaling of precipitation using quantile regression. *Journal of Hydrology*, *487*, 122–135.

Tebaldi, C., and Knutti, R. (2007). The use of the multi-model ensemble in probabilistic climate projections. *Philosophical Transactions. Series A, Mathematical, Physical, and Engineering Sciences*, *365*(1857), 2053–75.

Tebaldi, C., Mearns, L. O., Nychka, D., and Smith, R. L. (2004). Regional probabilities of precipitation change: A Bayesian analysis of multimodel simulations. *Geophysical Research Letters*, *31*(24), 1–5.

Tebaldi, C., Smith, R. L., Nychka, D., and Mearns, L. O. (2005). Quantifying Uncertainty in Projections of Regional Climate Change : A Bayesian Approach to the Analysis of Multimodel Ensembles. *Journal of Climate*, *18*, 1524–1540.

Terray, L., and Boé, J. (2013). Quantifying 21st-century France climate change and related uncertainties. *Comptes Rendus Geoscience*, *345*(3), 136–149.

Teutschbein, C., and Seibert, J. (2012). Bias correction of regional climate model simulations for hydrological climate-change impact studies: Review and evaluation of different methods. *Journal of Hydrology*, *456-457*, 12–29.

Thompson, J. R., Green, A. J., Kingston, D. G., and Gosling, S. N. (2013). Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. *Journal of Hydrology*, *486*, 1–30.

Tian, Y., Booij, M., Zhu, Q., Pan, S., and Xu, Y. (2013). Uncertainties of the extreme high flows under climate change impact due to emission scenarios , hydrological models and parameters. *Geophysical Research Abstracts*, *15*, 2013.

Tisseuil, C., Vrac, M., Lek, S., and Wade, A. J. (2010). Statistical downscaling of river flows. *Journal of Hydrology*, *385*(1-4), 279–291.

Tong, S. T. Y., Sun, Y., Ranatunga, T., He, J., and Yang, Y. J. (2012). Predicting plausible impacts of sets of climate and land use change scenarios on water resources. *Applied Geography*, *32*(2), 477–489.

Touhami, I., Chirino, E., Andreu, J. M., Sánchez, J. R., Moutahir, H., and Bellot, J. (2015). Assessment of climate change impacts on soil water balance and aquifer recharge in a semiarid region in south east Spain. *Journal of Hydrology*, *527*, 619–629.

Tramblay, Y., Badi, W., Driouech, F., El Adlouni, S., Neppel, L., and Servat, E. (2012). Climate change impacts on extreme precipitation in Morocco. *Global and Planetary Change*, *82-83*, 104–114.

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Trzaska, S., and Schnarr, E. (2014). *A review of downscaling methods for climate change projections*. United States: United States Agency for International Development. Retrieved from http://www.ciesin.org/?documents/?Downscaling_?CLEARED_?000.?pdf

Van-Liew, M. W., and Garbrecht, J. (2003). Hydrologic Simulation of the little Washita River Experimental Watershed using SWAT. *Journal Of The American Water Resources Association*, *39*(2), 413–426.

Van-Liew, M. W., and Veith, T. L. (2010). *Guidelines for Using the Sensitivity Analysis and Auto-calibration Tools for Multi-gage or Multi-step Calibration in SWAT*. Retrieved from http://www.heartlandwq.iastate.edu/NR/rdonlyres/E1A 7 4 7 FB-4B95-485C-9 7 C4-AO5 5CD4DBEF2/13689 2/Guidelines for Sensitivity and auto-calibrations wat. pdf.

Velázquez, J. a., Schmid, J., Ricard, S., Muerth, M. J., Gauvin St-Denis, B., Minville, M., … Turcotte, R. (2013). An ensemble approach to assess hydrological models' contribution to uncertainties in the analysis of climate change impact on water resources. *Hydrology and Earth System Sciences*, *17*(2), 565–578.

Vezzoli, R., Mercogliano, P., Pecora, S., and Zenoni, E. (2013). Impact simulations of climate change on hydrological extremes in the Po basin. *Geophysical Research Abstracts*, *15*.

Vidal, J.-P., and Wade, S. D. (2008). Multimodel projections of catchment-scale precipitation regime. *Journal of Hydrology*, *353*(1-2), 143–158.

Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., … Rose, S. K. (2011). The representative concentration pathways: an overview. *Climatic Change*, *109*(1-2), 5–31.

Wang, L., and Chen, W. (2013). A CMIP5 multimodel projection of future temperature, precipitation, and climatological drought in China. *International Journal of Climatology*, *2078*(September 2013), 2059–2078.

Wilby, R. ., Charles, S., Zorita, E., and Timbal, B. (2004). *Guidelines for use of climate scenarios developed from statistical downscaling methods*. Retrieved from http://www.narccap.ucar.edu/doc/tgica-guidance-2004.pdf

Wilby, R. ., Dawson, C. ., and Barrow, E. . (2002). Sdsm — a Decision Support Tool for the Assessment of Regional Climate Change Impacts. *Environmental Modelling & Software*, *17*(2), 145–157.

Wilby, R. ., and Harris, I. (2006). A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. *Water Resources Research*, *42*(2).

Woldemeskel, F. M., Sharma, a., Sivakumar, B., and Mehrotra, R. (2014). A framework to quantify GCM uncertainties for use in impact assessment studies. *Journal of Hydrology*, *519*, 1453–1465.

Wood, a. W., Leung, L. R., Sridhar, V., and Lettenmaier, D. P. (2004). Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs. *Climatic Change*, *62*(1-3), 189–216.

Wu, H., and Chen, B. (2014). Uncertainty analysis for propagation effects from

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statistical downscaling to hydrological modeling. In *The 2014 International Conference on Marine and Freshwater Environments*. Canada.

Xu, C. (1999). Climate Change and Hydrologic Models : A Review of Existing Gaps and Recent Research Developments. *Water Resources Management*, *13*(5), 369–382.

Xu, C., Widén, E., and Halldin, S. (2005). Modelling hydrological consequences of climate change—Progress and challenges. *Advances in Atmospheric Sciences*, *22*(6), 789–797.

Xu, H., Taylor, R. G., and Xu, Y. (2011). Quantifying uncertainty in the impacts of climate change on river discharge in sub-catchments of the Yangtze and Yellow River Basins, China. *Hydrology and Earth System Sciences*, *15*(1), 333–344.

Xu, Y.-P., Zhang, X., Ran, Q., and Tian, Y. (2013). Impact of climate change on hydrology of upper reaches of Qiantang River Basin, East China. *Journal of Hydrology*, *483*, 51–60.

Xue-jie, G. a O., Mei-li, W., and Giorgi, F. (2013). Climate Change over China in the 21st Century as Simulated by BCC _ CSM1 . 1-RegCM4 . 0. *Atmospheric and Oceanic Science Letters*, *6*(5), 381–386.

Yang, J., Reichert, P., Abbaspour, K. C., Xia, J., and Yang, H. (2008). Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China. *Journal of Hydrology*, *358*(1-2), 1–23.

Yao, F., Qin, P., Zhang, J., Lin, E., and Boken, V. (2011). Uncertainties in assessing the effect of climate change on agriculture using model simulation and uncertainty processing methods. *Chinese Science Bulletin*, *56*(8), 729–737.

Yin, C. (2011). *Applications of self-organizing maps to statistical downscaling of major regional climate variables* (Doctoral dissertation). The University of Waikato, New Zealand.

Zarghami, M., Abdi, A., Babaeian, I., Hassanzadeh, Y., and Kanani, R. (2011). Impacts of climate change on runoffs in East Azerbaijan, Iran. *Global and Planetary Change*, *78*(3-4), 137–146.

Zhang, H., Huang, G. H., Wang, D., and Zhang, X. (2011). Uncertainty assessment of climate change impacts on the hydrology of small prairie wetlands. *Journal of Hydrology*, *396*(1-2), 94–103.

Zhang, X., Srinivasan, R., and Hao, F. (2007). Predicting hydrologic response to climate change in the luohe river basin using the swat model. *American Society of Agricultural and Biological Engineers*, *50*(3), 901–910.

Zhang, X.-C., Liu, W.-Z., Li, Z., and Zheng, F.-L. (2009). Simulating site-specific impacts of climate change on soil erosion and surface hydrology in southern Loess Plateau of China. *Catena*, *79*(3), 237–242.

Zhou, Y., Zwahlen, F., Wang, Y., and Li, Y. (2010). Impact of climate change on irrigation requirements in terms of groundwater resources. *Hydrogeology Journal*, *18*(7), 1571–1582.

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