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Impacts of climate change on groundwater level and irrigation cost in a groundwater dependent irrigated region

Golam Saleh Ahmed Salem[a,*], So Kazama[a], Shamsuddin Shahid[b], Nepal C. Dey[c]

[a] Department of Civil Engineering, Tohoku University, 6-6-06, Aoba-yama, Aoba, Sendai, 980-8579, Japan
[b] Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 Johor Bahru, Malaysia
[c] Research and Evaluation Division, BRAC.BRAC Centre, 75 Mohakhali, Dhaka 1212, Bangladesh

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ABSTRACT

The objective of the present study was to assess the impacts of climate change on irrigation cost in a groundwater dependent irrigated region in northwest Bangladesh. An ensemble of general circulation model (GCMs) were used for the projection of climate, an empirical hydrological model based on support vector machine (SVM) was used to simulate groundwater level from climatic variables, and a multiple-linear regression (MLR) model was used to estimate the irrigation cost due to the changes in groundwater level. The results revealed a declination of average groundwater level in the study area in the range of 0.45 – 01.19 m, 0.55–1.79 m, and 0.76–2.71 m under three representative concentration pathways (RCP) scenarios namely, RCP2.6, RCP4.5 and RCP8.5, respectively and therefore, an average increase in irrigation cost in the range of 1.61 to 9.82 USD/hectare at 95% confidence level. The maximum declination of groundwater level was projected in the northeast part of the study area in the range of 2.23–4.12 m by the GCM MIROC-ESM-CHEM which might cause an increase of irrigation cost in the range of 8.07 to 14.79 USD/hector. The study concludes that the impact of climate change-induced fluctuations in groundwater level on crop production cost is much less compared to other costs, but it may be significant in locations where groundwater level is declining fast.

1. Introduction

Groundwater is one of the primary sources of irrigation and food production in many countries of the World (Shahid et al., 2015; Siebert et al., 2010; Treidel et al., 2012). Despite its huge significance, groundwater resources are heading for a crisis in many regions mainly due to the huge exploitation of groundwater to extend irrigated agriculture to feed the growing population(Gandhi and Bhamoriya, 2011; Pengra, 2012). It is anticipated that climate change will pose another major threat to groundwater resources in the near future. Studies from different parts of the world show that increased temperature and changing rainfall patterns due to climate change will significantly affect groundwater recharge and accessibility (Davidson and Yang, 2007; Ranjan et al., 2006; Shahid et al., 2017; Shahid and Hazarika, 2010; Treidel et al., 2012). The lowering of the groundwater table due to changes in precipitation patterns and rises in temperature may reduce well yield and increase pumping cost, which may seriously affect the livelihood of farmers in the regions where groundwater is used as the major source of irrigation (Salem et al., 2017b). Mitigation of climate change impacts on groundwater resources to limit irrigation cost and ensure farmers' profits might be a major challenge in the near future, particularly in agricultural-based developing countries.

A number of studies have been conducted to assess climate change impacts on groundwater level (Davidson and Yang, 2007; Ranjan et al., 2006; Treidel et al., 2012), irrigation demand (Garrote et al., 2015; Shahid, 2011; Wang et al., 2016), and irrigation cost (Mulangu and Kraybill, 2015; Nelson et al., 2010). However, only a few studies have been conducted to assess the impact of declining groundwater level on irrigation cost (Kovacs and West, 2016; Medellín-Azuara et al., 2015; Narayanamoorthy, 2015; Nayak et al., 2015; Salem et al., 2017a; Srivastava et al., 2017). The majority of the studies was on economic assessment of declining groundwater level due to over exploitation (Narayanamoorthy, 2015). A few of studies mentioned changes in irrigation cost due to global warming induced changes in groundwater level. Shahid (2011) indicated that declination of groundwater level due to climate change would increase irrigation cost in Northwest Bangladesh. Nayak et al., (2015) assessed the impacts of different adaption measures to mitigate climate change impacts on irrigation cost. However, no study has been conducted to assess the possible changes in irrigation cost of groundwater-dependent irrigated crop for

* Corresponding author.
E-mail address: salem.golam.saleh.ahmed.c6@tohoku.ac.jp (G.S.A. Salem).

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different climate change scenarios. As groundwater is the major source of irrigation in many developing countries, understanding the impact of climate change on farmers' profits in a groundwater dependent irrigated region is very impotent. Furthermore, it is important for decision making towards adaptation and mitigation.

The GCM simulations of climate change fail to provide reliable information on spatial scales below about 200 km and therefore, it is important to downscale coarse resolution GCM simulated climatic variables to local scales for impact assessment (Su et al., 2016). Climate downscaling methods can be broadly classified into two major groups namely, (i) dynamical or physical downscaling, where high-resolution Regional Climate Models (RCMs) are employed (Gao et al., 2016; Laprise, 2008); and (ii) statistical downscaling (SD), where statistical relationships between local climatic variables and GCM variables are used (Do Hoai et al., 2011; Pour et al., 2014; Wilby et al., 2004). Compared to dynamical downscaling, statistical downscaling methods are often preferred for their simplicity, easiness, flexibility, quickness and ability to provide local-scale information (Ahmed et al., 2015; Pour et al., 2014). The statistical downscaling methods are subdivided into two large groups, perfect prognosis (PP) and model output statistics (MOS) (Maraun et al., 2010). In PP, a statistical relationship is established between observed climate variables (predictand) and observed large-scale predictors while in MOS, the GCM simulated predictors instead of observed predictors are used to establish statistical relationship with observed predictands (Eden and Widmann, 2013). The MOS models are able to explicitly account for GCM-inherent error and bias (Eden and Widmann, 2013; Turco et al., 2011) and therefore, found highly potential for climate change simulations (Eden and Widmann, 2013; Sa'adi et al., 2017; Shirvani and Landman, 2015; Sunyer et al., 2015; Turco et al., 2017; Widmann et al., 2003). A number of methods are available for correction of bias in GCMs. However, the quantile mapping (QM) method is widely used as it has the capability to correct systematic distributional biases present in GCMs (Argüeso et al., 2013; Cannon et al., 2015; Teutschbein and Seibert, 2013; Themeßl et al., 2012).

The objective of the study was to investigate the impacts of climate change on groundwater level and irrigation cost for different RCP scenarios. A climate downscaling model based on model output statistics (MOS), an empirical hydrological model based on support vector machine (SVM) and an econometric model based on multiple-linear regression (MLR) were integrated in this study for this purpose. The proposed modeling framework was applied to assess the impacts on climate change induced changes in groundwater and irrigation cost in Rajshahi district located in Northwest Bangladesh (Fig. 1), where groundwater is the only source of irrigation during dry season. Declination of the groundwater level is a major concern in the area in recent years. The methodology provided in this study can be used to assess the impact of climate change on irrigation cost of groundwater-dependent irrigated crop with associated uncertainties for any climatic and geographic region. The knowledge generated through the application of proposed methodological framework can be used for planning adaptation to climate change impacts on livelihoods and economy of vast rural population of developing countries depending on groundwater-based irrigate agriculture.

2. Materials and methods

2.1. Data and sources

The monthly rainfall and temperature simulated by eight GCMs (Table 1) for historical (1961–2005) and future (2010–2099) periods were used in this study. The choice of the selection of GCMs was based on the availability of projections for all the three RCP scenarios for Bangladesh. The long-term daily rainfall and temperature record (1961–2005) from a meteorological station located in the Rajshahi District (within the study area) were collected from the Bangladesh Meteorological Department (BMD). The bi-monthly data of groundwater level (the depth to groundwater table from the land surface) recorded at 10 observation wells across the study area (Fig. 1) during 1991–2009 were obtained from the Bangladesh Water Development Board (BWDB), while the irrigation cost, irrigated area, groundwater withdrawal, groundwater-well age and harvesting date were collected from the BRAC (Bangladesh Rural Advancement Committee) Research Centre.

2.2. Methods

The methodology adopted in the present study is shown by the flowchart in Fig. 2. The climate downscaling, hydrological and irrigation cost models were integrated to assess the impacts of climate change induced changes in groundwater level and consequent changes in irrigation cost. A MOS downscaling technique was used for the downscaling of GCM simulated rainfall and temperature. An empirical model was developed using SVM for the simulation of groundwater depth from surface using climate and other influencing factors. A MLR model was developed to predict irrigation cost from groundwater level and other factors. The empirical groundwater model was calibrated and validated using historical observed data. The projected rainfall and temperature by downscaling models were then used in the model to simulate groundwater levels for three RCP scenarios. Finally, the projected groundwater level data were used in calibrated MLR model to forecast the impacts of climate change on irrigation cost. The irrigation costs were computed for all the GCMs under three RCP scenarios. Finally, the mean and the 95% confidence intervals of irrigation cost were calculated to show the changes in irrigation cost with uncertainty for each RCP scenarios. A description of the methods used in the study is given in the following sections.

2.3. Climate downscaling and projections

The procedure used for statistical downscaling of rainfall and temperature was consisted of three steps as outlined below:

1 The GCM simulated rainfall and temperature at four GCM grid points surrounding the study area were used to interpolate the rainfall and temperature at the point of meteorological station within the study area.
2 The QM bias correction approach was used to correct the biases in GCM simulated rainfall (temperature) by comparing the simulated rainfall (temperature) with observed rainfall (temperature) for the period 1961–2005.
3 The estimated QM parameters to correct biases in historical rainfall (temperature) were used for correcting the biases in GCM simulations for period 2010–2099.

The QM is a non-parametric bias correction approach. The adjustment of data using QM can be represented as empirical cumulative density function (CDF) and its inverse as below (Fang et al., 2015),

$$P_{cor,m} = ecdf_{obs,m}^{-1}(ecdf_{raw,m}(P_{raw,m})) \quad (1)$$

Where, $P_{cor,m}$ is the bias corrected rainfall of m-th month; $P_{raw,m}$ is rainfall of m-th month before bias correction; $ecdf_{obs,m}$ is the empirical CDF of observed data of m-th month; and $ecdf_{raw,m}$ is the CDF of rainfall of m-th month before bias correction. Description of the QM and its application to correct biases in the GCMs can be found in Fang et al., (2015). In the present study, QM bias correction approach was used to correct the biases in each GCM simulated rainfall or temperature separately.