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Conjunctive surface water and groundwater management under climate change

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Climate change can result in significant impacts on regional and global surface water and groundwater resources. Using groundwater as a complimentary source of water has provided an effective means to satisfy the ever-increasing water demands and deal with surface water shortages problems due to robust capability of groundwater in responding to climate change. Conjunctive use of surface water and groundwater is crucial for integrated water resources management. It is helpful to reduce vulnerabilities of water supply systems and mitigate the water supply stress in responding to climate change. Some critical challenges and perspectives are discussed to help decision/policy makers develop more effective management and adaptation strategies for conjunctive water resources use in facing climate change under complex uncertainties.

Keywords: conjunctive water management, surface water, groundwater, hydrology, climate change

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Introduction

Climate change can significantly affect regional and global surface water and groundwater resources. According to IPCC (2007a), climate change can result in increased temperature, widespread ice and snow melting, rising sea level, widespread changes in precipitation and evaporation patterns, and increased frequency and magnitude of extreme weather events such as flood, droughts, and heat waves (IPCC, 2007a,b; USGS, 2007; Gurdak et al., 2009; Ludwig et al., 2014). These changes can substantially affect water resources management practices. For examples, the observed and projected increases in temperature and evapotranspiration, decrease in precipitation, and more intense and longer droughts caused by climate change can lead to declined availability of water resources, aggravating the water scarcity problems (Schewe et al., 2014). This is especially true in semi-arid and arid areas where multiple water users are competing for limited and ever-decreasing water resources under projected future climates. It is desirable to develop effective management strategies for decision or policy makers for mitigating or reducing the negative impacts of climate change on water resources.

Conjunctive use of surface water and groundwater is of importance for integrated water resources management. It has provided an effective means to satisfy the ever-increasing water demands from different water users and deal with surface water shortage problems. Groundwater is a vital water resource especially in the regions with limited or no surface water supplies (Bovolo et al., 2009). Groundwater is relatively reliable and clean compared to surface water since it can be extracted even in the dry seasons and is less polluted than surface water in most cases (Kundzewicz and Doll, 2009). Using groundwater to compliment surface water supplies can help reduce vulnerabilities of surface water supply systems to climate change to a certain extent (Taylor et al., 2013). As pointed out by de Wrachien and Fasso (2002), properly managed integrated water resources systems can yield more water with more economic rates than those separately managed surface-water or groundwater systems. Conjunctive use of surface water and groundwater has been extensively studied and a number of methods/techniques have been reported for supporting conjunctive water use planning and management (Ejaz and Peralta, 1995; Başağaoğlu and Mariňo, 1999; Azaiez, 2002; Mohan and Jothiprakash, 2003; Pulido-Velazquez et al., 2008; Matrosov et al., 2011; Shi et al., 2012; Bejranonda et al., 2013; Khan et al., 2014). Although the existing water resources management systems have abilities to tackle interannual variability, they encounter difficulties in addressing long-term trends. Evaluating such long-term impacts of climate change on water resources is crucial to generate effective management strategies in the future (Serrat-Capdevila et al., 2007). Inadequacies or a lack of addressing the impacts of climate change could lead to biases in generated management strategies for conjunctive water use under future changing climatic conditions due to unequivocal characteristics of climate change. Investigation of all relevant literature is impractical and not the aim of the short review. The objective of this short review paper is to address some important issues in and provide insight into conjunctive management of surface water and groundwater resources under climate change with recent research.

Impacts of Climate Change on Water Resources

Climate Change Impacts on Surface Water

Climate change has direct effects on surface water through modification of long-term climate variables (Jyrkama and Sykes, 2007). Investigations of the impacts of climate change on surface water resources have mushroomed previously (Middelkoop et al., 2001; Zhu et al., 2005; de Wit and Stankiewicz, 2006; Burns et al., 2007; Hagg et al., 2007; Brikowski, 2008; Matthews and Quesne, 2008; Ficklin et al., 2009; Hay and McCabe, 2010; Arnell, 2011; Gosling et al., 2011; Kuhn et al., 2011; Georgakakos et al., 2012; Koutroulis et al., 2013; Selek and Tuncok, 2014). Changes of temperature and precipitation caused by climate change could lead to increased water demand and reduced water resources availability (Chen et al., 2001; Kamga, 2001). Recently, Milly et al. (2005) quantitatively assessed the impacts of climate change on global water resources availability using 12 climate models. Their results indicated that runoff in eastern equatorial Africa, high latitudes of North America and Eurasia, and the La Plata basin of South America would increase by 10–40%, while that in southern Europe, the Middle East and mid-latitude western North America, and southern Africa would decrease by 10–30% in 2050. Lee and Chung (2007) studied the impacts of climate variability, groundwater withdrawal and land use on dry-weather streamflows in a small Korean watershed located in Gyeonggi province by using SWAT. The study watershed had a monsoon climate cycle with strong seasonality, similar to many East Asian river systems. The increases of temperature and solar radiation could significantly decrease streamflows in the dry period. The increased groundwater withdrawal would result in the decreased streamflows, while the effects of land use changes on streamflows in the dry period were not significant. Serrat-Capdevila et al. (2007) investigated the climate change impacts on water resources in the San Pedro River Basin, a semi-arid transboundary basin in southeastern Arizona and northern Sonora. Their multi-model projections predicted a decreased recharge and a decreased mean net stream gain (i.e., base flow) across the Basin. Brikowski (2008) predicted a continued decline of streamflow at historical rates on the Great Plains under future climate change. Such a decline would worsen the imbalance between water supply and demand. Chiew et al. (2009) used 15 GCMs (General Circulation Models) for future climate projections corresponding to 0.9°C increase in global average surface air temperature, most of which predicted less runoff in southeast Australia. However, their results were associated with a number of uncertainties since the modeled mean annual runoff averaged in the whole study area would vary from a reduction of 17% to an increase of 7%. Ficklin et al. (2009) investigated the effects of climate change on a highly agricultural San Joaquin watershed in California. Their studies showed that the watershed hydrology was highly sensitive to climate change. Local water yield, evapotranspiration, irrigation water use, and stream flow would be significantly affected by projected changes of atmospheric CO_2, temperature, and precipitation. Young et al. (2009) evaluated the hydrological effects of climate change on snow pack and initiation of snowmelt in the Sierra Nevada in California, covering watersheds from the Feather River in the north to the Kern River in the south. A reduction in snow pack was found, resulting in a shift in runoff center of mass to earlier dates. Manning et al. (2009) pointed out that water availability in the Thames watershed would be substantially reduced based on an ensemble of climate models. Zhang et al. (2011a) evaluated hydrological responses of the Assiniboia watershed, an isolated small one in the Canadian Prairies, to climate change. Two regional climate models, two weather generators and a distributed hydrological model were incorporated into a general research framework. Annual reservoir storage would be reduced while annual water yield and evapotranspiration in 2050s would keep unchanged.

More recently, Candela et al. (2012) reported a maximum of 56% reduction of water resources availability in the Siurana catchment in Spain under climate change. Kienzle et al. (2012) used five different GCMs to simulate the effects of climate change on water yield, streamflow extremes, and streamflow regimes in the Cline River watershed which accounted for over 40% of the North Saskatchewan River streamflows in Alberta, Canada. All of the five climate models predicted the increases in mean annual potential and actual evapotranspiration, soil moisture, groundwater recharge, and streamflow due to increased temperature and precipitation. Koutroulis et al. (2013) quantified the impacts of climate change on water availability in the Crete Island in Greece using three GCMs and 10 RCMs (Regional Climate Models) with three emission scenarios (i.e., B1, A2, and A1B) for future precipitation and temperature projections. A trend of decreasing water availability was predicted considering the combinations of emission, demand and infrastructure scenarios. In the investigation of climate change impacts on water availability in the snow-glacier dominated Mendoza river watershed in Argentina by Schwank et al. (2014), a reduction of water availability due to climate change was projected, intensifying future water resources management stress. Future water management strategies are suggested by adjusting and balancing the needs of different water users such as irrigation, industrial, and domestic ones during the long-term planning periods. Changes of availability of water resources will considerably affect future water resources planning, management and adaptation strategies, and policies to climate change.

Climate Change Impacts on Groundwater

Studies on impacts of climate change on groundwater are relatively limited compared to surface water (Allen et al., 2004; Brouyère et al., 2004; Hsu et al., 2007; Bates et al., 2008). Surface water shortages caused by future climate change stress more on groundwater (Brikowski, 2008). Groundwater can alleviate the stress on surface water by complimenting surface water supplies under climate change in the regions with sufficient and unpolluted groundwater resources or where groundwater recharge will not decrease significantly due to changing climate (Kundzewicz and Doll, 2009). Groundwater is relatively more robust in responding to climate change than surface water due to its higher storage capacity in most cases (Kundzewicz and Doll, 2009). Climate change will directly affect groundwater mainly through changing groundwater recharge, resulting in changing groundwater tables or levels (Chen et al., 2004; Scibek and Allen, 2006; Dzhamalov et al., 2008; Aguilera and Murillo, 2009; Kundzewicz and Doll, 2009; Mileham et al., 2009; Allen et al., 2010; Taylor et al., 2013). In addition, changes in land use and land cover have indirect effects on groundwater through changes in groundwater use (Taylor et al., 2013).

Recently, Croley and Luukkonen (2003) analyzed the potential effects of climate change on groundwater levels in Lansing, Michigan by using GCMs, hydrological, and groundwater flow models. The GCMs developed by the Canadian Climate Centre and the Hadley Centre were used. Depending on the GCMs used, different results were generated: predicted groundwater levels would decline under the Canadian GCM, but increase under the Hadley GCM in the Saginaw aquifer in the Lansing area. Chen et al. (2004) studied the relationships between climate variability and groundwater levels in an upper carbonate aquifer in Manitoba, Canada, and concluded that groundwater levels would decline as a result of decreased net recharge caused by increased temperature predicted from GCMs. Brouyère et al. (2004) simulated the direct impacts of climate change on groundwater levels and reserves in the Geer Basin, Belgium by using an integrated hydrological model (MOHISE). Holman (2006) addressed the direct and indirect impacts of climate change together with socio-economic changes on groundwater recharge. Scibek and Allen (2006) incorporated climate and groundwater models to evaluate the impacts of climate change on groundwater recharge and levels in an unconfined aquifer near Grand Forks in south central British Columbia, Canada. More recharge to this unconfined aquifer was found from spring to summer based on future climate projections. Hsu et al. (2007) analyzed the effects of climate variability on groundwater in the Pingtung Plain in Taiwan. The groundwater model, MODFLOW SURFACT, was used to characterize the groundwater flow system, and a linear regression model was established for future precipitation predictions based on the historical data. Their regression results showed that groundwater levels would decrease (decreased groundwater availability) so that conflicts of water supply and demand would be aggravated. Tapoglou et al. (2014) simulated the variations of groundwater levels in the area of Agia in Crete, Greece using neural network under three climate change scenarios representing small, medium, and severe changes in precipitation and temperature. Their studies predicted negative effects such as increased possibility of drought under the scenario of high precipitation decreases only (reduction by over 10%), but neutral to positive effects under the other two scenarios.

Climate Change Impacts on Surface and Ground Water Interactions

Surface water and groundwater are inextricably linked; understanding of their interactions is essential for developing effective conjunctive water resources management strategies, especially for adaptation to future climate change (Sophocleous, 2002; Allen et al., 2004; Woldeamlak et al., 2007). Some researchers have conducted studies related to surface-water and groundwater interactions under climate change. For example, Eckhardt and Ulbrich (2003) investigated the impacts of climate change on streamflow and groundwater recharge using a conceptual eco-hydrologic model based on a revised SWAT. Their results indicated that streamflows and groundwater recharge would be reduced by over 50% in summer. Scibek et al. (2007) simulated the impacts of future climate change on groundwater-surface water interactions and groundwater levels in the unconfined Grand Forks aquifer in British Columbia, Canada using a three-dimensional transient groundwater flow model. Under future climate scenarios, differences of aquifer water levels would vary from less than 0.5 m away from floodplain to over 0.5 m near the river. More studies can be found in Hatch et al. (2006); Ferguson and Maxwell (2010); McCallum et al. (2013); Taylor et al. (2013).

Interannual Climate Variability

Interannual variability of climate such as temperature and precipitation is vital to assess the climate change impacts and develop corresponding adaptation strategies effectively (Andersson et al., 2011; Fatichi et al., 2012). The variability between years can result in direct or indirect effects on hydrological, ecological, and biogeochemical processes (Fatichi et al., 2012). In general, the standard deviation is applied to measure interannual variability of temperature, and the coefficient of variation expressed as a ratio of standard deviation and the mean is used to measure the variability of precipitation (Räisänen, 2002; Coppola and Giorgi, 2010). Since the research by Rind et al. (1989), many studies have been reported to examine the interannual variability of temperature and precipitation. Recently, (Räisänen, 2002) conducted a comprehensive investigation of CO_2-induced interannual variability of temperature and precipitation using

19 model experiments. Most of his models showed a reduced variability of temperature in winter in the extratropical Northern Hemisphere and the high-latitude Southern Ocean, and a slight increase of temperature variability over land in low latitudes and northern mid-latitudes in summer. They also pointed out an increased interannual variability of precipitation in most areas, especially in the regions with a reduced mean precipitation. Consistent conclusions were drawn in the studies by Giorgi and Bi (2005). Coppola and Giorgi (2010) evaluated climate change projections over the Italian peninsula at four IPCC emission scenarios by using the CMIP3 and PRUDENCE ensembles. Their results further demonstrated the previous findings that interannual variability of precipitation would increase in all seasons, while interannual variability of temperature would increase in summer and decrease in winter. Andersson et al. (2011) assessed possible changes of water availability and extreme hydrological events under future changing climatic conditions until 2050 in the Pungwe basin in the Southern Africa. The Rossby Centre Regional Climate Model (RCA3) was employed for future climate projections and a river basin hydrological model (HBV) was used for identification of hydrological responses to climate change. Their simulation showed a significant increase of interannual variability of rainfall by 10–50% in 2050, although the interannual variability of mean annual rainfall would be less affected. There would also be an increase of interannual variability of dry season streamflow. In assessment of interannual variability of precipitation, selecting the suitable correction methods such as scaling or bias correction methods is also crucial since it will significantly affect the associated uncertainty estimation (Johnson and Sharma, 2011). This should be paid more attention to in future climate variability and impacts assessment studies.

Conjunctive Surface-groundwater Optimization Management

Optimization models and methods are effective tools for allocating water resources and providing decision supports. A number of optimization management models have been proposed for conjunctive use of surface water and groundwater (Sethi et al., 2002; Vedula et al., 2005). These models are mainly for the purposes of cropping patterns planning and irrigation water management (Singh, 2014). Irrigation is the largest water use in the world, accounting for about 70% of global water withdrawals and about 90% global consumptive water use (Döll et al., 2012). Azaiez and Hariga (2001) presented a single-period planning model for conjunctive use of surface water and groundwater for a multi-reservoir system, with stochastic inflow to the main reservoir and irrigation water demand. de Wrachien and Fasso (2002) pointed out that conjunctively coordinated management of surface water and groundwater could achieve the maximum benefits of efficient use of total water resources. Barlow et al. (2003) developed a conjunctive management model through coupling numerical simulation with linear programming optimization model into a general framework to determine sustainable yield of the alluvial-valley stream-aquifer systems. Tradeoffs between groundwater withdrawals and streamflow depletion were analyzed. Karamouz et al. (2004) proposed a simulation-based dynamic programming optimization model for conjunctive surface water and groundwater planning and management in Iran. Management objectives of minimization of irrigation water supply shortages and pumping costs, and control of average groundwater table fluctuations were considered. Rao et al. (2004) developed a macro-level conjunctive use planning model for surface water and groundwater allocation in the deltaic regions. Syaukat and Fox (2004) presented an integrated surface water and groundwater management model to meet urban water demand in the Jakarta region, Indonesia. Khare et al. (2006) developed a linear programming model for conjunctive use management of surface water and groundwater resources in the Sapon irrigation command area in Indonesia. Net benefits from cropping activities were maximized considering water demand and availability. An increase of groundwater development was suggested to handle the surface water shortage problems. Pulido-Velázquez et al. (2006) formulated an integrated hydrologic-economic optimization model to identify the optimal water system operation and water allocation alternatives for maximizing net economic benefits.

More recently, Cheng et al. (2009) advanced a linear programming model to optimize the conjunctive use of surface water and groundwater for irrigation planning in Taiwan. Yang et al. (2009) presented an integrated multi-objective planning model for conjunctive surface water and groundwater management in Taiwan by considering multiple objectives of simultaneous minimization of fixed and operating costs. The model integrated a multi-objective genetic algorithm, constrained differential dynamic programming, and groundwater simulation model named ISOQUAD into a general framework. Montazar et al. (2010) presented a non-linear programming model for irrigation water planning through optimal allocation of surface water and groundwater for maximizing the net benefits. Application of their model to an agricultural water system in Iran demonstrated the feasibility of conjunctive use and effectiveness in enhancing the total benefits. Safavi et al. (2010) proposed a simulation-optimization method for conjunctive use of surface water and groundwater on a basin-wide scale in Iran. The method incorporated an artificial neural network to simulate the variations of groundwater levels, and then used a genetic algorithm to solve the simulation-based optimization model. Chang et al. (2011) used system dynamics to examine the performance of planning alternatives of conjunctive surface water and groundwater use, and evaluated the long-term effects of these alternatives on reduction of water shortage risks. Chang et al. (2013) developed a fuzzy inference system for conjunctively managing surface water and groundwater use by incorporating expert knowledge and operational policies with the fuzzy rules. Safavi and Esmikhani (2013) presented a simulation-optimization model for conjunctive use of surface water and groundwater in the Zayandehrood river basin in Iran. Surrogate models were developed by using support vector machines to replace surface water and groundwater simulation models in the optimization management model with the objective of minimizing water shortages for satisfying irrigation demands, subject to a series of water-related constraints such as controlling cumulative water-table drawdown and maximizing irrigation system's capacity.

Systems analysis methods are highly desirable to handle water use conflicts among different parts of water management systems (Wu et al., 2015).

Conjunctive Water Management under Climate Change

The abovementioned optimization methods and models for conjunctive surface water and groundwater management didn't consider the impacts of future climate change. This lack hampered their applicability to generate effective water management strategies in future changing climatic conditions since climate change is inevitable. Recently, many researchers attempted to incorporate climate change impacts into the planning and management issues in conjunctive water use (Hoekema and Sridhar, 2013; Pingale et al., 2014). Hanson and Dettinger (2005) investigated the impacts of climate variations on conjunctive management of groundwater and surface water resources through a GCM and a RCM named RGWM. Simple statistical techniques were used to downscale the outputs such as precipitation rates from the GCM for providing the inputs for RGWM. Results from a case study of a coastal aquifer system in Southern California demonstrated that useful alternatives could be generated for guiding water planning and management practices. Wurbs et al. (2005) extended the Texas water availability modeling (WAM) system by incorporating a climate model and a watershed hydrology model to evaluate the effects of climate change on the capabilities of water supply. Their application in the Brazos River Basin in Texas showed a general decrease in the mean streamflow due to decreased precipitation and increased temperature-induced greater evapotranspiration. The significantly-varying effects of climate change on water availability were found in various regions and among various water users. Water supply shortage would increase from 4.0 m^3/s under the historical climate scenario to 8.9 m^3/s under the 2050 climate scenario. Hanson et al. (2010) used an extended MODFLOW with Farm Process (MF-FMP) to analyze conjunctive surface water and groundwater use management. Application to two representative case studies was presented, including the Pajaro Valley (micro-agricultural scale) and the Central Valley (macro-agricultural scale). Their results demonstrated the capability of MF-FMP in forecasting future water demand and constrained water supply, and evaluating the effects of potential mitigation or adaptation policies/projects on future water supply-demand patterns. Kingston and Taylor (2010) evaluated climate change impacts on river discharge and groundwater in a tropical catchment in the Upper Nile Basin in Uganda where different uncertainties were considered. Teegavarapu (2010) investigated the climate change impacts on water resources management by using fuzzy sets theory to address decision makers' preference toward climate change. Sulis et al. (2011) coupled hydrological model named CATHY and the Canadian Regional Climate Model (CRCM) for investigating the impacts of climate change on surface water and groundwater management in a catchment in Quebec, Canada. The sensitivity of the hydrological responses including aquifer recharge, soil water storage, and river discharge to future climate change was analyzed. Hanson et al. (2012) presented a supply-demand modeling framework to assess the potential effects of climate change on conjunctive surface water and groundwater resources management in the Central Valley in California. Their study linked a GCM called Geophysical Fluid Dynamics Laboratory Climate model to a mountain hydrologic watershed model (MHWM) and a Central Valley hydrologic model (CVHM) within a general framework. Their results indicated that water supply pattern would shift from surface water predominantly to groundwater for meeting agricultural irrigation needs. The secondary effects such as land subsidence caused by increased groundwater withdrawals may restrict the extent which additional groundwater pumping would be a viable option to compensate for reduced surface water availability. Also, urbanization could hinder the sustainability of conjunctive water resources use. Pingale et al. (2014) developed an integrated urban water management model to optimize water resources allocation under climate change. Multiple water sources including surface water and groundwater, as well as treated wastewater were considered. A stochastic weather generator (LARS-WG) was used to project future climate scenarios based on the Canadian GCM with various IPCC emission scenarios; a rainfall runoff model (SWMM) was employed to simulate future surface water availability; a groundwater model (MODFLOW) was used to forecast the groundwater under climate change. The applicability of the proposed model was demonstrated through its application to a real-world water supply system in India, providing optimal water resources planning strategies under various climate change scenarios.

Among all the countries, China is facing severe water shortage and water use conflict problems. Climate change and human activities such as urbanization and land use have significantly affected and will continue to affect water resources, aggravating water crisis in China (Lu et al., 2013). Although total amounts of water resources in China are huge, the amounts per capita are very limited. In China, the primary challenges are the imbalance between water supply and ever increasing water demand, uneven spatial distributions of water resources, and inter-regional water use conflicts (Cui et al., 2009; Cheng and Hu, 2012). Wang et al. (2014) suggested an increase of water shortage in Tuwei river basin in Northwest China by up to 80% in 2030 with current management practices or using water supply management strategy. Although upgrading water infrastructure or add alternative sources may temporarily alleviate water shortage problems, water demand management including improvement of water use efficiency, establishment of market-oriented water allocation patterns, effective enforcement of regulations and laws, and effective control of water is the best to improve water resources management over a long time, especially under future climate and land use changes (Arnell, 1998; Cheng and Hu, 2012). China should shift the strategies from water supply management to water demand management pollution, or both. Integrated sustainable water resources management should be based on both supply- and demand- management to meet the ever increasing water demand with the limited water supplies under future changing climatic conditions (Cheng and Hu, 2012; Wang et al., 2014).

Challenges and Perspectives in Conjunctive Water Management under Climate Change

One main challenge in conjunctive surface water and groundwater management under climate change is mismatch between large-scale global or regional climate models and small-or medium-scale hydrological processes (Arora and Boer, 2001; Merritt et al., 2006; Young et al., 2009). This can limit the effectiveness of climate models in supporting conjunctive water management. In order to transform the coarser outputs of GCMs to match the smaller scales of hydrological systems, effective downscaling techniques and methods are desirable (Hanson and Dettinger, 2005; Mileham et al., 2009).

Uncertainty is another challenging problem in climate change impact studies. A variety of uncertainties are inherently associated with GCM structure and its initial conditions, greenhouse gas emission scenarios, downscaling methods, hydrological model structures and parameters, and conjunctive water use optimization management (Serrat-Capdevila et al., 2007; Kay et al., 2009; Chen et al., 2011; Kienzle et al., 2012). Uncertainty can significantly affect the accuracies of forecasting hydrological responses to climate change and consequently the effectiveness of conjunctive water management strategies (Candela et al., 2012). Effective reflection and quantification of these uncertainties are critical for making appropriate climate-change mitigation strategies for conjunctive water management (Brekke et al., 2004). The largest source of uncertainty in climate change impacts studies is GCM structure and selection due to high sensitivity of water resources systems to future climate change projections (Dessai and Hulme, 2007; Kay et al., 2009; Prudhomme and Davies, 2009; Lespinas et al., 2014); even for the same GCM, different downscaling techniques/methods can generate different prediction results (Manning et al., 2009). Not only uncertainty associated with GCMs can result in large differences in future climatic scenarios, but also selection of different hydrological models with various modeling structures can affect hydrological responses to climate change (Jiang et al., 2007; Lespinas et al., 2014). This was demonstrated by Jiang et al. (2007) in their analysis of climate change impacts on water availability in the Dongjiang basin in South China. Six hydrological models were used in their study, leading to significant differences in forecasting future hydrological impacts of climate change. In order to avoid possible inadequateness and potential misleading of analysis of climate change on water resources management, multi-model approaches are recommended to reduce the impacts of uncertainty since a single GCM and/or downscaling method and/or hydrological model could lead to moderate to severe bias of climate change impacts results (Prudhomme and Davies, 2009; Kingston and Taylor, 2010; Chen et al., 2011; Zhang et al., 2011a; Hagemann et al., 2013). It is also desired to improve the regional climate simulations with reduced uncertainties (Piao et al., 2010). More details on regional investigations and more reliable projections of climate change scenarios are highly desirable (Viviroli et al., 2011).

In development of conjunctive use optimization management, uncertainty also exists in a number of modeling parameters, management objectives, operational policies, and decision makers' preferences toward climate change on water resources management (Teegavarapu, 2010). These will affect the effectiveness of future conjunctive water resources management strategies under climate change. Limited availability of long-term groundwater data and information impaired our abilities to investigate the responses of groundwater systems to climate variability and change (Taylor et al., 2013). It is thus desired for more intensive groundwater monitoring efforts and/or effective methods for dealing with the scenarios with limited or scarce data sets. Most of the previous climate change impacts studies used stochastic methods for handling the uncertainties. When the available data and information are insufficient for generating probability distributions or subjective knowledge and information such as decision makers' preferences are involved, these stochastic methods can become incapable. Methods of interval analysis and fuzzy sets theory have provided effective tools for handling the non-random uncertainties (Zhang et al., 2009a,b, 2011b,c). It will be helpful to enhance the ability to tackle multiple forms of uncertainties in evaluation of climate change impacts on future water resources management through integration of these random and non-random methods. In addition, more complex uncertainties such as interactional relationships among the uncertain parameters should be effectively reflected and quantified due to their impacts on adaptation and mitigation results.

In general, small unconnected water supply sources are more sensitive to climate change than large connected ones (Arnell, 1998). There are needs for considering the unique characteristics of small and large sources to make sure the generated management and adaptation strategies more effective to meet their specific requirements. The integrated water resources management strategies should be capable of dealing with not only local-scale but also basin-sale issues (López-Moreno et al., 2014). In addition, the activities related to enhancement of social awareness and public attitudes to water resources and their management, capacity building, community involvement should be promoted (Vargas-Amelin and Pindado, 2014).

Non-climatic factors such as land use changes and water use practices can also affect sustainability of water resources significantly under future climate change (Merritt et al., 2006; Hagemann et al., 2013). An important assumption in assessment of climate change impacts on water resources is that land use would remain unchanged in the future (Blanc et al., 2014). Whether such an assumption can hold in the future needs to be justified in specific regions and problems. In addition to climate change, changes in land use may impact the water resources through changes of infiltration, evapotranspiration, groundwater recharge, and water quality in receiving water bodies (Anderson et al., 2008; Tong et al., 2012). However, most of the previous studies either considered climate and land use changes separately, or were limited to single impact such as flow or water quality; even for the limited number of reports on their combined effects, scenarios were also very limited. In order to generate more effective climate change adaptation and mitigation strategies, the combined effects of climate and land use changes as well as other factors such as population changes on flow and water quality on a basin scale should be incorporated into the integrated water management framework (Parajuli, 2010; Tong et al., 2012; López-Moreno et al., 2014). Understanding and incorporation of these non-climatic factors into climate change scenarios will be beneficial to decision makers and planners for development of more realistic and feasible water management policies and climate-change mitigation measures (Woldeamlak et al., 2007; Tong et al., 2012). More detailed studies are desired to address the abovementioned issues in development of imperative conjunctive water management strategies under climate change.

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