A Framework of Hydroclimate Modeling and Decision Support Tools for Sustainalbe Water Resources Planning in a Changing Climate

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ABSTRACT

Climate variability and change continue to threaten the sustainability of water resources around the world. Increasing temperature is likely to modify the timing, form, and intensity of precipitation events, which will alter regional and hydrologic cycles. Since drought, water shortages, and subsequent water conflicts may become an increasing threat in many international watersheds, sustainable water resources planning is critical to cope with climate change. In this study, the authors propose a framework of sustainable water resources planning based on coupled hydroclimate modeling and decision support tools to promote collaborative efforts against abrupt future climate change. A participatory modeling approach based on a stakeholder-driven decision support system will provide useful insights for water planners to pursue sustainable water resources under uncertain future climate. Additionally, the framework suggested by this study will facilitate multidisciplinary responses to future climate variability in the context of socioeconomic implications and policy decisions in human dimensions

INTRODUCTION

Recent climate models continue to reveal a wide variety of environmental and socio-economic interests that are vulnerable to water shortages (IPCC2007). In fact, the U.S. Department of Commerce's National Climatic Data Center has recorded 13 drought years in the United States from 1980 to 2007 that have exceeded $1.0 billion in damages/costs (Lott and Ross 2006). The total cost for the droughts and associated heat waves has been estimated at nearly $157 billion. Although a rough estimate, this represents an annual average of at least $5.6 billion dollars in direct drought losses.

Given current climate change projections, this trend in losses is likely to continue or increase. Increasing temperatures are likely to modify the timing, form, and intensity of precipitation events, which will alter regional and local hydrologic cycles. As a result, drought, water shortages, and subsequent conflicts may become an increasing threat in several regions of the United States, especially in the western and southwest areas (Figure 1). To maintain reliable and sustainable water resources and stable economies in the face of uncertain climatic and hydrologic conditions, it is imperative that systems be in place to assess the overall impacts of climatic changes on both the potential water management options and beyond.

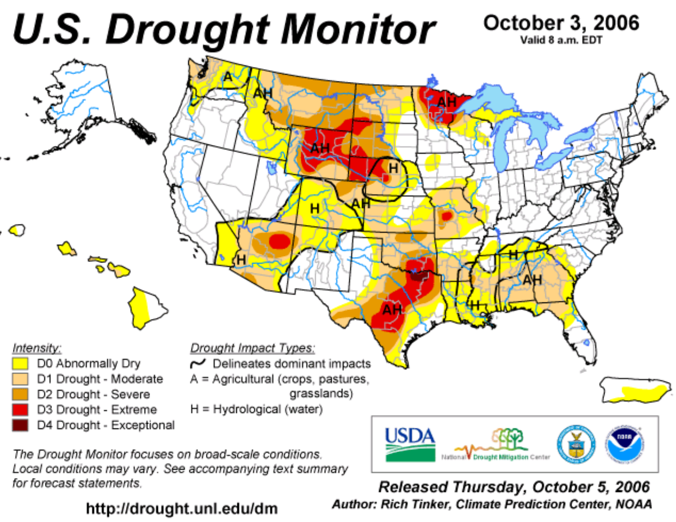

Figure 1: The weekly US Drought Monitor map depicting drought occurrence and severity across the United States. Drought occurrence is expected to increase in many areas of the United States under climate change scenarios.

However, developing such systematic plans during periods of large climate variability is one of the most significant challenges facing water scientists today. Therefore, in this paper, we propose a framework to develop decision support tools for sustainable water resources planning in a changing climate and challenges embedded in (1) climate scenario selection processes to hydrologic models, (2) integration into system dynamic models, and (3) stakeholder-driven decision support.

CLIMATE SCENARIOS AND REGIONAL HYDROLOGY

The Global Circulation Models (GCMs) are the primary tool for understanding of past climate variations and for predicting future climate conditions associated with various boundary conditions and environmental forcing, including the initial conditions between the atmosphere and sea surface, the amount of solar energy, the concentration of anthropogenic gases and particles in the atmosphere. Although such GCMs are promising in their ability to predict future climate conditions for the next few decades, there are not yet fully understood (IPCC 2007).

For water resources management perspectives, global warming is typically described by the effect of stable CO_2 levels, such as doubled atmospheric CO_2 concentrations. Many scenarios with a combination of CO_2 levels and other environmental factors (e.g., sea surface temperature, clouds) are considered and employed in a hydrology model to project future hydrometeorological conditions with environmental forcing, such as precipitation and temperature associated with various greenhouse gas scenarios. The sustainability of water resources related to climate change is then evaluated as a function of water resources availability induced by climate change.

Two different approaches are most common for indicating the impacts of climate change on the adequacy of water supplies. The application of the coupled climate-hydrologic models to evaluate potential effects of climate change is one approach. Basically, this approach combines the hydrologic models with the output from GCMs and carbon dioxide scenarios in GCMs to simulate runoffs for large-scale simulation (Lettenmaier et al. 1999). For watershed scale simulation, additional downscale methods, such as regression (Enke and Spekat 1997), clustering (Gutierrez et al. 2004), and relatively simple method (Ryu et al. 2009) are utilized to incorporate global climate information into local meteorological and hydrological applications. Alternatively, the climate adjustments in runoff are also widely used. The idea is to reflect the differences in climate change that characterize the control and analog periods into natural streamflow so that flow reconstructions, consequently, are induced by climate change (Frederick 1993). For instance, streamflow can be generated as an input of adjusted precipitation and temperature, such as 20% and 2°C increase, respectively, induced by future climate change.

Although this process is straightforward in the coupled climate-hydrology modeling setting, the uncertainty inherent in estimating greenhouse gases (e.g. carbon dioxide, CO_2) is still criticized. For example, the Intergovernmental Panel on Climate Change (IPCC) provides several different future climate scenarios, such as IS92a, predicts CO_2 emission under average development and growth projection without considering any adaptive policies for emission mitigation. But, recent emissions have shown the CO_2 level is below the levels predicted by IS92a (Bou-Zeid and El-Fadel 2002). Also, the role of CO_2 in the global hydrologic cycle is contentious. Thus, global warming is typically described by the effect of stable CO_2 levels, such as doubled atmospheric CO_2 concentrations. To evaluate the sustainability of water resources associated with climate change, hydrologists typically incorporate future hydro-climatic conditions into local hydrologic models by perturbing environmental forcing, such as precipitation and temperature. One approach is commonly used in hydrologic community, such that the output from GCMs and carbon dioxide scenarios in GCMs are routed into the hydrologic models to simulate climate-driven streamflows at the watershed scale and/or larger scales (Lettenmaier et al. 1999). But, the role of CO_2 in hydrologic runoff processes remains uncertain.

In the hydrologic modeling block, CO_2 plays a key role of facilitating a plant's photosynthesis affecting evapotranspiration (ET) in the water cycle although how CO_2 directly impacts ET through plant's stomata on the leaf or stem surfaces is still controversial. Stonfelt et al. (2000) indicate that three environmental variables, including radiation, water, and CO_2 contribute to photosynthesis and thus directly regulate plant productivity. Therefore, if CO_2 concentration acts as a limiting factor, greater plant growth results in reduced water availability in soil and decreased surface runoff (Stonefelt et al. 2000). Kimball et al. (1999), however, pointed out that there are counteracting reasons why the increasing CO_2 concentration might either increase or decrease ET under open field condition and they emphasized that the explanatory energy balance model on the Earth's surface is needed to further evaluate the effects of elevated CO_2 on plant canopy energy balance and ET. More recently, however, hydrologists demonstrated that generally the effects of elevated CO_2 on ET resulted in reducing streamflow and water resources (Fontaine et al. 2001; Jha et al. 2006). Further research opportunities to identify the role of CO_2 in the global water cycle, therefore, are an urgent need to predict future water availability associated with long-term climate scenarios.

SUSTAINABLE WATER RESOURCES MANAGEMENT –DECISION SUPPORT SYSTEM (SWRM-DSS)

Sustainable water management has received considerable attention because population increase, climate change, infrequent water conflicts and land use change continue to threaten water system reliability, water quality, and financial security. A variety of techniques can be incorporated into a general long-term planning process used to evaluate sustainable water resources management. Most of today's planning tools are typically implemented with computer models because accounting for numerous decision variables, constraints, and socio-economic factors is an extremely difficult task in the hand-written analytic framework. A computer model (e.g. simulation model) is able to answer many research questions toward sustainable water resources management so that it would be a very useful tool. These questions may include 1) the model is capable of incorporating drought indicators as a function of future climate conditions thereby trigging proactive drought responses, 2) the model is able to provide useful insights into questions and the concerns embedded in system constraints (e.g. water conflict), 3) the model provides the opportunity for a high level of involvement by all stakeholders, such as water managers and the general public.

To deal with these questions, as a simulation modeling framework, the shared vision modeling approach has been widely used because the model allows interested participants to achieve consensus by forming a shared vision of a system or process (Palmer and Keyes 1993). The shared vision approach facilitates a high level of involvement by all stakeholders so that collaborative management decisions can be made by utilizing highly interactive computer models that allow participants to visualize the impacts of their planning decisions associated with climate change. The shared vision planning approach has been applied in many real-world applications across the country, including the National Drought Study (NDS) for water supply in Boston, Massachusetts; reservoir management on the Green River in Tacoma, Washington; water supply in Norfolk, Virginia; and recreation and hydropower on the Kanawa River in West Virginia. Because of the success of the approach in many applications, this approach is a good candidate as a way to get stakeholders involved in SWM-DSS development to enhance the usefulness of the tools and increase the likelihood of the tools' adoption for uncertain future climate.

Stakeholder Involvement

Stakeholder involvement is a critical component of this approach. It will be used to gather suggestions and other feedback for the development of the tools, foster local participation and use of the product, and help evaluate the usefulness and accuracy of the tools. Interactions with those stakeholders will help the model developers and project investigators understand their perception of climate change and their needs related to climate variability so that the tools developed through this approach will be more useful and meaningful within their decision-making processes. Local stakeholder groups in a basin can include as possible participants in a series of meetings throughout the course of interactions. Those include stakeholders such as 1) local irrigation districts, 2) hydro power companies, 3) department of water resources, 4) agricultural producers, 5) aquaculture communities, and 5) other responsible federal, state, and local agencies.

Developing SWM-DSS User Interface

Stakeholder input will be critical in developing the SWM-DSS. The SWM-DSS will be used to explore system performance and reliability given various operating policies and management options associated with climate change scenarios. The model's outputs are reservoir levels, releases, and diversions, from which the predicted performance of the system with respect to such operating objectives as irrigation withdrawal, canal diversions, and instream flow requirements for ecology are typically calculated and then routed into additional modeling blocks, such as economic models as inputs to analyze how the regional economy is affected by climate change.

Model's initial condition and extensions

Several sub-tasks should be also incorporated into the system formulation and in the evaluation of its results, including:

- Releases from upstream reservoirs, if any, should be modeled as an appropriate time window (e.g. the mean weekly or monthly release) to calibrate inflow into downstream reservoirs during retrospective years.

- The system's safe yield should be defined as the quantity of water that can be taken from the reservoir system over the simulation periods (e.g., 1963-2005) of historic inflows records with failures (denoted as a failure to meet a predetermined level) in years to meet a 97% annual reliability, for instance, which can be determined as an acceptable level.

- Regulation and management scenarios from the local systems initiated by the responsible department of federal, state, and local agency should be reviewed and used where appropriate.

The SWRM-DSS model can be developed in an iterative process of focus groups, model construction, critiques, and calibration in collaboration with local stakeholders. Stakeholders expected to participate include representatives of the responsible departments, such as natural resource districts and other local water managers. Some advantages of working with stakeholders are decreased model construction time and increased feasibility of model expansion (when model modification is necessary). Additionally, the process helps ensure that the SWRM-DSS will contain a majority of the essential regional features that are needed in local decision-making processes, such as 1) information that represents the interests and perspectives of all participants and 2) insight into questions and concerns related to climate variability and change. Figure 2 shows the potential user interface of the SWRM-DSS.

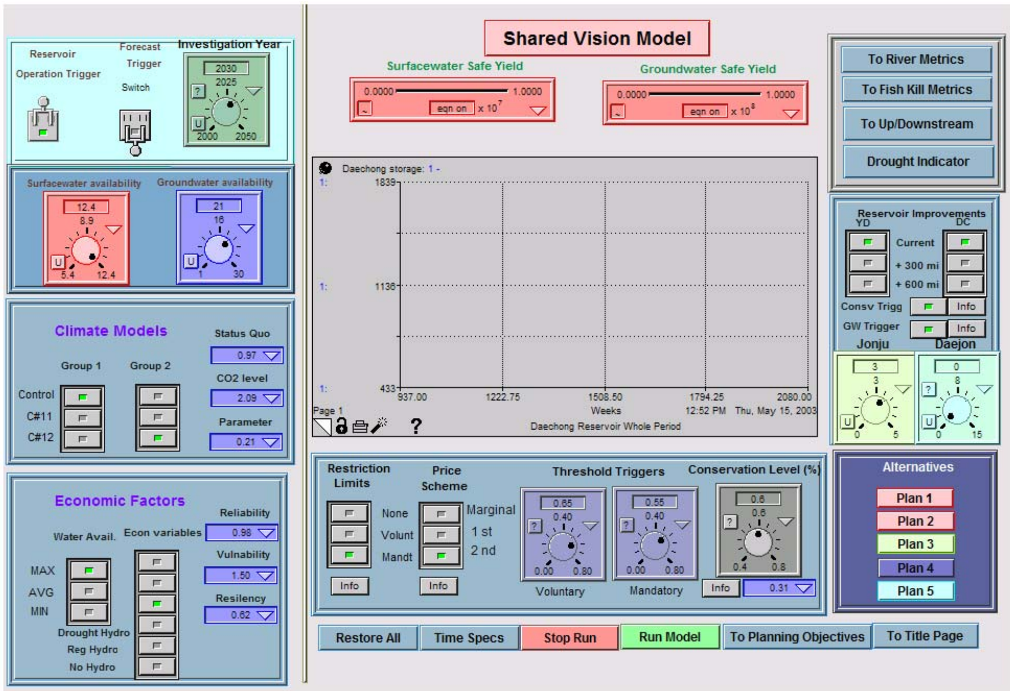

Figure 2: User Interface of the Sustainable Water Resources Management-Decision Support Tool (SWRM-DSS)

SUMMARY AND FUTURE WORK

The most important aspect of the possible climatic change and variability at first hand could be the impacts on regional water resources and hydrologic cycles. Moreover, climate-driven water availability can generate many derivative water issues, including water shortage, water conflicts, and environmental concerns, thereby confounding the social and economic impacts in the human dimension. Many scientific efforts were made to identify major contributors to global warming, which exacerbate the climate equilibrium. The concentration of CO_2 in the atmosphere, in particular, has been highlighted in the sense that a gas form from byproducts of combusting coal and fossil oil traps outgoing solar radiation (e.g. latent and sensible heat flux) that is attempting to escape from Earth increases global average temperature. A CO_2-enriched atmosphere affects the rate of ET through plant's increased photosynthesis so that plant physiological processes ultimately alter physical runoff processes. However, further understanding of this whole physical process is required since the role of increased CO_2 concentration in plant physiology and hydrology is still disputable and controversial.

Quantifying uncertainty embedded in both climate and hydrologic modeling block is also a critical research need in the climate impact study in a changing climate. For instance, systematic bias during downscaling process from climate models and regional hydrologic models and uncertainty embedded in hydrologic models is still challenging to demonstrate. Based on general principles, if the climate models does not have a high level of confidence, statistical downscaling and/or spatio-temporal adjustment will rarely produce a low level of uncertainty. To minimize uncertainty in climate models and hydrologic models during downscaling and calibration processes, model-wide uncertainty analysis is an important task and will be considered in future research.

In light of the current challenges and concerns about sustainable water resources management under uncertain future climate, community collaborative work is urgently needed. For example, Community Collaborative Rain, Hail & Snow Network (CoCoRaHS) is a grassroots volunteer network that reports observed weather data from backyards using low-cost measurement tools. CoCoRaHS provides high-quality precipitation data and encourage citizens to be actively involved in enrichment activities in water and weather resources targeted to a variety of organizations and individuals, including scientists, educators, engineers, governmental agencies, agricultural producers, and students from K-12 to college (For details, see http://www.cocorahs.org). Another example is the Weather and Society*Integrated Studies (WAS*IS). WAS*IS is also stakeholder-driven grassroots movement to integrate meteorological research and practice into social science applications, such as socio-economic evaluation induced by current and future weather conditions (http://www.sip.ucar.edu/wasis/). These kinds of grassroots movement are extremely important steps for sustainable water resources management in a changing climate.

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