UNCERTAINTY OF HYDROLOGIC EVENTS UNDER SOUTH DAKOTA'S CHANGING CONDITIONS: A RESEARCH AGENDA

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ABSTRACT

The widespread flooding across South Dakota (SD) in 2011 has spurred a new look at the institutional, regulatory, and mathematical models used to manage the Upper Missouri River Basin as it affects all aspects of life in SD. A SD EPSCoR planning grant was awarded to a group of local, national and international researchers. The team developed a strategy to create a research infrastructure with the goal of the development of conceptual and mathematical models to understand and describe the uncertainty of hydrological events (HE) across SD. There were two main tasks: planning for study of uncertainty of HE in Upper Missouri Basin and developing concepts for communicating uncertainty of HE for wider use outside the professional community. The plan brings together a variety of disciplines, and outlines the development of an artificial intelligence approach to analyze the interaction of HE, engineering installations and social systems in the SD setting.

The object of study is taken to be the system hydrological researcher – mathematical modeler – stakeholder, and the process considered was the interaction of knowledge with uncertainty in application to HE (Figure 1). Uncertainty in HE must be defined using concepts broader than hydrology (such as statistical learning) and linked to the concerns of all SD social, cultural and economic sectors.

Considering this system of interacting participants allows focusing on the principal stages in tackling uncertainty, from developing the research task and obtaining the hydrological results to communication between researcher and stakeholder. Mathematical models are the universal the language in scientific research and should also be adapted to bring the results to stakeholders. Three mathematical approaches to modeling HE and impacts on SD were considered: distributed system interactions, statistical learning and cellular automata.

Specific concepts of uncertainty for modeling watersheds and describing the time-space variability of water cycle and budget for regional hydrologic study were developed (remotely sensed data use, scale and influence of drainage and irrigation on GW regime and hydrology of wetlands and lakes in the Missouri River valley and Prairie Pothole areas). Additional necessary concepts concern risk assessment and HE interaction with the sociology and economy (types and scales of regionalization of the physical and human environment), and the design of interactive simulation models (cartographic presentation and simplified educational modeling) of the HE in the natural landscapes and industrial/changed conditions of the state of SD.

SD's economy and the wellbeing of its citizens depends greatly on natural conditions and events and SD will benefit from a program working for improved evaluation and visualization of the risk associated with HE and improved reliability of information pertaining to irrigation and drainage, water management, and crop insurance. The first results obtained in dealing with uncertainty for HE via the planned research infrastructure need to be expanded to fully include socio-economic research.

The state of the science: an introduction

South Dakota has experienced hydrologic extremes over the past decade that demonstrate the susceptibility of the state's water resources to climate fluctuations. Drought conditions threatened agricultural productivity and lowered reservoir levels from 2002 to 2008, whereas deep snowpack and record flows in the Missouri River caused extensive and prolonged flooding in 2011. The year 2012 severe drought took over the most part of the state of SD. This extreme variability in water supply creates uncertainty for land managers and industries that rely upon water. The Governor's Office of Economic Development (2012) touts water availability as an attraction to industries seeking to locate in South Dakota, but how reliable is it? How can extreme hydrological events (HE) that affect South Dakota's economy be better forecasted?

To better deal with the mid- and long-term risk of HE such as drought and flooding, the uncertainty of those HE in South Dakota has to be studied, described and widely understood. Formal descriptions based on mathematical models of uncertainty will provide better risk assessment and help preparing for the impacts of HE. This has been thwarted by the exceptional complexity of HE and absence of suitable tools for identifying interactions between HE and objects and practices designed by humans. Dams wrought a major alteration of land use in the Missouri River Valley, but as river courses change, the limitations in their design are increasingly evident, as is the need for research on dam operations' effect on economy and environment. With the increased numbers of drainage and irrigation projects, it has been stressed that the hydrological effects of those practices cannot continue to be handled on a case to case basis as the cumulative effect on hydrology at both sub-watershed and watershed scale has to be considered (Christiansen, et al., 2011; Cook, et al., 2011; McVicar et al., 2011; Wang and Hejazi, 2011).

The scales of climate and land use changes require enormous amounts of research mainly in the engineering field, however, in this particular proposal we are targeting the core area of needed research: the concepts of uncertainty to describe the natural events and the models to reflect and adapt to the new and constantly changing environment. In the environment, the water cycle is the dynamic component and in the same time the most involved one in the all the climate change and human activities processes (Khan, 2012; Wehner, et al., 2011). The focus is on the uncertainty of our knowledge and on communicating that knowledge with the use of mathematical models. The outcome of research in this direction will have direct and defining effects on engineering application development, all levels of education, and on developing method to reach out to state and local governments and communities.

Uncertainty has been under consideration in environmental disciplines for some time, in regional climate and precipitation predictions (Hawkins and Sutton, 2009; Hawkins and Sutton, 2010), for flood study (Wurbs et al., 2001), for flood inundation modeling (Gilroy, and McCuen, 2011; Wilson and Atkinson, 2010), and also for flood disaster assessment (Du, et al., 2006; Qin, 2011; Rao, et al., 2011). It was shown the need to consider uncertainty of climate study in connection to social and decision sciences (Pidgeon and Fischhoff, 2011).

The most attention in resource uncertainty quantification literature has been paid to groundwater as a major source of fresh water (Fenech, et al., 2003; Harou, et al., 2010; Truong, 2011). The leading role of research in this direction has focused on the states of California (Nelson, 2012) and Kansas (Sophocleous, 2011). Groundwater is the natural resource with the most discussions about sustainable use (Gleeson, et al., 2011; Kanivetsky and Shmagin, 2005, 2006; Peterson, et al., 2011; Ruhl, et al., 2002; Zhou, 2009). Satellite Gravity Recovery and Climate Experiment (GRACE) measurements supposedly allows monitoring of groundwater recharge and depletion on regional level (Kjaersgaard, et al., 2011; Krakauer, et al., 2011; Kuss, et al., 2012; Nelson, 2012; Niu, et al., 2007), bringing a new hope for sustainable use of groundwater.

The countries of the European Union are working and have completed research in connection of HE and climate change on economy. The research completed for irrigation could be taken as an exemplar for state of South Dakota (Schaldach, et. al, 2012).

In the US, each state bears responsibilities to provide information and specification about risk and danger from the effects of natural events including HE for businesses and the population. Every state must develop their own unique plan to deal with extreme HE. For example, the state of Iowa has developed informational and research infrastructure as Iowa Flood Center to deal with floods (http://iowafloodcenter.org/).

Given the developed regional, sub-regional and site specific information and specification, we propose for the state of South Dakota to create a research infrastructure integrating of the intellectual potential dispersed in the state's academic institutions:

* to bring and apply new developments from federal agencies and from international bodies, adopting these methods to natural and socio-economic conditions and industries specific for the state;

* to trace the effect of HE in the history of socio-economic relations and changes and present the scale of those changes;

* to develop new media to visualize HE and their associated dangers and then bring those developments to communities, K12 education and USDA extension to explain the effect of HE and the concept of risk of dealing with them.

The approach for uncertainty and risk assessment for HE

The object of study is the system: hydrological researcher – mathematical modeler – stakeholder. The process considered is interaction of knowledge – uncertainty in application to HE (Figure 1). Uncertainty in HE must be defined using concepts broader than hydrology (such as machine learning) and linked to the concerns of all SD cultural and economic sectors. The significance of the uncertainty concept will be shown by tracing the influence of HE on all the sides of life in SD. The plan brings together a variety of disciplines, and allows for the development of an artificial intelligence approach to analyze the interaction of HE, engineering installations and socio-economic systems in a SD setting. The definition of the uncertainty for HE is consideration in an article in this Proceedings (Shmagin, …). The main points are:

* An uncertainty analysis is needed for extreme HE, because conventional modeling approaches failed to adequately forecast the hydrologic extreme of the 2011 Missouri River flood.

* We seek to understand and describe the uncertainty of hydrological events from the artificial intelligence standpoint.

*A significant part of the group of models supported will be simplified simulation models specially developed for community use. Such simplified models may serve for wide outreach, targeted decision making in communities, state and local government, agriculture, manufacturing and consulting industries, and also for education at all levels and application by environmental researchers whose work is based on (or connected with) the better understanding of the HE.

The use of math models to analyze, describe and communicate the variability, risk and uncertainty of HE in changing climate and market conditions of South Dakota:

* to monitor the changes in SD;

* to create models of time spatial variability;

* the math models of variability have to be explained with system models (in the artificial intelligence approach);

* the system models will determine the design of simplified simulation models;

* simplified simulation models developed as Environmental Economic academic course by A. A. Voinov will be applied for research tasks of regional hydrology and extreme HE;

* simulation model may be used on web based maps of regionalization of Missouri watershed, SD and key or typical areas inside of SD.

The design of research infrastructure

Considering this system of interacting participants (researcher – mathematical modeler – stakeholder) allows focusing on principal stages from developing the research task by researcher and obtaining the hydrological results to the stage of communication between researcher and stakeholder (Figure 1). The general design of proposed research infrastructure with participants, used databases and other elements is shown in Table 1.

Mathematical models are the universal tool and the language in scientific research and they have to be used to bring the results to stakeholders. Three mathematical approaches to modeling HE and impacts on SD were considered: distributed system interactions, statistical learning and cellular automata. Statistical models that do not explicitly consider uncertainty won't work for hydrological modeling or for explanation of the results to the wider that civil engineers public, as was shown in 2011. The development of conceptual and mathematical models to understand and describe the uncertainty of HE has to be completed from the artificial intelligence standpoint.

The mathematics in use will be about distributed system interactions, statistical learning and cellular automata. The statistical learning with use of Vapnik–Chervonenkis dimension (Vapnik and Chervonenkis, 1971; Blumer, et al., 1989) will provide the uncertainty evaluation, and other named mathematical methods will help to understand and apply the results of statistical findings. Multiple models will help to generate results in the form of educational oriented and simplified simulation modeling for the stakeholders. The climate and land use change, as market-driven agriculture practices have very significant impact on hydrology. The model's development will consider the changing climate, the market conditions and hydrological respond to those changes for the state of SD.

The proposed research direction is about bringing the new modeling concept and approach for the study of regional variability and changes in hydrology including streamflows, wetlands, potholes, groundwater levels. Verification of the developed models will be done using: 1- USGS observations of river discharge and groundwater, 2- data about soil moisture and groundwater levels from NASA-GISS; all NASA and COOP stations with empirical soil moisture observations, and 3- geological and hydrogeological maps and groundwater levels observations from the state of SD Geological Survey at USD. Special attention will be given to the use of remote sensing that reflects the conditions on the ground using the satellite imagery. Two spatial scales of hydrological processes will be studied: the state of SD and surrounding areas (neighboring parts of Missouri watershed), and several subregions within the state. The dynamics of water cycling and HE occurrence will be modeled with consideration of the forward and feedback connections to the socio-economic process dynamics in SD. Initially annual and monthly data will be used, and more detailed time steps are in consideration. A variety of simulation models will be created to bring the results to education, state and local governments, consulting companies and project developers.

The data bases for socio-economic research exist and will be identified as one goal for complex research in South Dakota.

The proposed research infrastructure is relevant to NSF strategic goals: transform the frontiers, innovate for society, and perform as a model organization (Empowering the Nation …, 2011). Our response to the first goal in the NSF framework is the shift from traditional probabilistic model to a number of mathematic models like distributed and interactive system modeling, cellular automata and statistical learning.

The new approach of using the complex of models will be placed and tested for the changing climate, land use and market conditions of state of South Dakota, and also the life style changes in the state (recreational and conservational). Significant part in the complex of models will be specially developed for community use simplified simulation models and they may serve for the wide outreach, targeted at decision making in communities, state and local government, agriculture and other manufactures and consulting industries, and also for the education of all levels and application by environmental researchers whose objects based on (or connected with) the better understanding of the HE (the second strategic goal of NSF).

The new infrastructure creation to succeed has to be organized and placed in dynamic research environment of model and software users and developers with multi-disciplinary researchers of hydrology, hydrogeology, geology, rural sociology, economy and ecology for the state; this direction will not only perform as organization as scientific Center (the third strategic direction in NSF strategy) but will also be completed mainly by graduate students all working in STEM area.

Creation of research infrastructure will be connected to NSF strategic areas of research. Described approach to establish research infrastructure will be completely in connections to the requirements of STEM K12 education. The sustainability of water resources is an important issue nationwide, supported by several programs at the National Science Foundation. In addition to core programs in Hydrology (Directorate for Geociences) and Environmental Engineering and Sustainability (Directorate for Engineering), NSF has recently announced a cross-cutting program in Water Sustainability and Climate (NSF 11-551) and Sustainability Research Networks (NSF 11-574), NSF 11-531; Inactive Cross-Cutting Programs: Climate Change Education (CCE): Climate Change Education Partnership (CCEP) Program, Phase I (CCEP-I): NSF 10-542.

The main obstacle to deliver presented vision is the absence in tradition of the state of SD to study and considered the hydrology and it part of extreme HE, as a special problem. The topic of study the HE has to be brought to attention of public. There are no any other institution, group, cooperative or corporation to study the regional changes in natural and market conditions for the state of SD and they influence on socio-economic, culture and life style in the state. It has to be demonstrated that only all the intellectual forces united in higher education capable to focused on problem, to formulate the research tacks and then deliver the tools and solutions.

Bringing science to SD's daily operations as a state at whole and for numbers of industries and communities inside will provide the research tasks and data for the students of graduate schools in state and also the opportunities for opening new graduate programs.

The entire economy of state of South Dakota will benefit from the creation of this direction as state research infrastructure; the results of better understanding the uncertainty of HE allow better evaluate the risk of flooding and drought, and provide more sure consulting for irrigation and drainage, water management, and crop insurance, wildlife, conservation, recreation and tourism management. The most relevant economic priority of South Dakota to benefit will be the IT as workforce for new directions of development.

The activities proposed

The solely mathematical part of proposed research direction will not require research infrastructure and may be done in the form of publications. To incorporate scientific approach the expansion from pure mathematical task to new full size research infrastructure will be done by applying the new models to real and changing natural and socio-economic systems including in consideration existing on federal and state levels databases and thematic maps reflecting observations and conditions of the state of SD and neighboring parts of Missouri River watershed.

The goal of creating the Research Infrastructure is to develop and bring theoretical science on extreme HE, and then extend the study in the changes in market's conditions, and development of applications and tools for education and outreach. The Research Infrastructure has to support *"Research, Educational and Outreach Program (REOP) in statewide academia to understand and describe the uncertainty of hydrological events and they decisive influence on socio-economics in the changing conditions of the state of South Dakota*".

Covering unique spectrum of participants the success will begin from the shift from traditional probabilistic model to a spectrum of mathematic models like system modeling and statistical learning as parts of artificial intelligence development to represent the uncertainty of HE. The direction to succeed has to be organized and placed in dynamic research environment of model and software users and developers working with multi-disciplinarian researchers of hydrology, hydrogeology, geology, sociology, economy and ecology for the state. Mainly students, graduate with undergrad participation, all working in STEM area, will complete this study.

The proposed research infrastructure in support of the REOP reflects the unique and new approach with complex of models to be placed and tested for the changing climate and market conditions of state of SD, combined with specially developed for community use simulation models will serve for the wide outreach for decision making in communities, state and local government, agriculture and other manufactures and consulting industries and also for the education of all levels and environmental researchers whose objects based on (or connected with) the better understanding of the hydrological events.

Structure of the Program is seen as activities directed by special board in sectors: Hydrology and Climate Change in state of SD; Artificial Intelligence Math Models to Analyze the Changes; Droughts and Floods Affect on Socio-Economic Changes in the State; Food Security and Economy in Changing Climate; Education of Changes for Everybody. This structure of research is the best for the integration of intellectual potential in all in state high education institution in their academic units (Departments, Centers) willing to participate. The operation of the program will be similar to other statewide programs.

The initial list of topics to begin with of proposed infrastructure:

*Uncertainty for watershed modeling and describing the space-time spatial variability of regional water cycles and budgets.

*Risk assessment in the economy.

*The implication to use the remote sensing data for hydrology, including soil moisture, crop/plant water use and monitoring.

*Scale and influence of drainage and irrigation on groundwater regime and hydrology (wetlands, lakes, land use) in Missouri River Valley and the pothole areas.

*Concept and design of artificial intelligence simulation models and simplified simulation model in interactive format.

*Regionalization and cartographic presentation of the natural geophysical and human socio-economic environment.

*Presentation of regional and site specific educational interactive modeling of the hydrological events in the changing conditions in the state of South Dakota.

Every member must be willing to work in the team and the team as a whole represent the unique ability to take on very complex and challenging scientific and practical problem of and fulfill the goal of the new research infrastructure creation that will benefit the scientific frontier, higher education the research potential in the state of SD. For everyone on the team creation of the proposed research infrastructure is the natural expansion (extension) of their research and educational priorities. There are many scientific and other connections for the majority of the team members. Diverse scientific background and interest will insure the wide spectrum of topics for consideration and input from obtained results in theory, applications, outreach and education.

The new direction of research emerged recently in cooperation of hydrologist and mathematician and in the application to Missouri River watershed; this cooperation will be extended to the multi-disciplinary team with additional research tasks in computer science, ecology and economy applications, education and outreach. Working out the scientific frontier as a team will bring to the team members new experience and deeper visions of the problems in their own disciplines. The research part, the communication and the multilevel educational part are new in their own parts and in the integration. Creation of research infrastructure will be connected to NSF strategic areas of research for the next decade. Those allow expecting that proposals writing in numerous directions of the study might be successful. All parts of the program are in the field of STEM in definition of Federal agencies that might be additional source for seeking additional funding, however the student participation in the research will be very good for the state in grow educated labor force.

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Additional Information

The draft of the article was presented for publication in the Proceedings; however with consequence of different events only the Abstract was published:

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Table 1. The elements of proposed research infrastructure (RI) for state of South Dakota (SD), including artificial intelligence (AI) tools and simplified system models (SSM).

Element in the chain	**Researcher**	**Mathematical modeler**				**Stakeholder**
		Object	Data	Models	Results	
Content	**Natural & social scientists**	**Natural & human influenced systems**	**All existing**	**Processes with forward & feedback connections; in specific time-space domains**	**Time-space structure of variability**	**Scientist, consultant, teacher, community member, planner, manager**
Knowledge	**Conceptual model**		**Empirical**	**Multi- scales & dimensions**	**Maps, AI-models & SSM**	
Uncertainty	**Defining the object, task & observations**			**Schematization**	**Games with SSM**	
Media	**Scientific discipline**	**Tools for observation**	**Networks & databases**	**Digital**	**Games & site specific maps**	
RI for SD	**In SD**	**Landscapes, industries & people of SD**	**Integrated networks & databases**	**HE influence on culture & economy of SD**	**HE influence**	**Feedbacks on developed products**

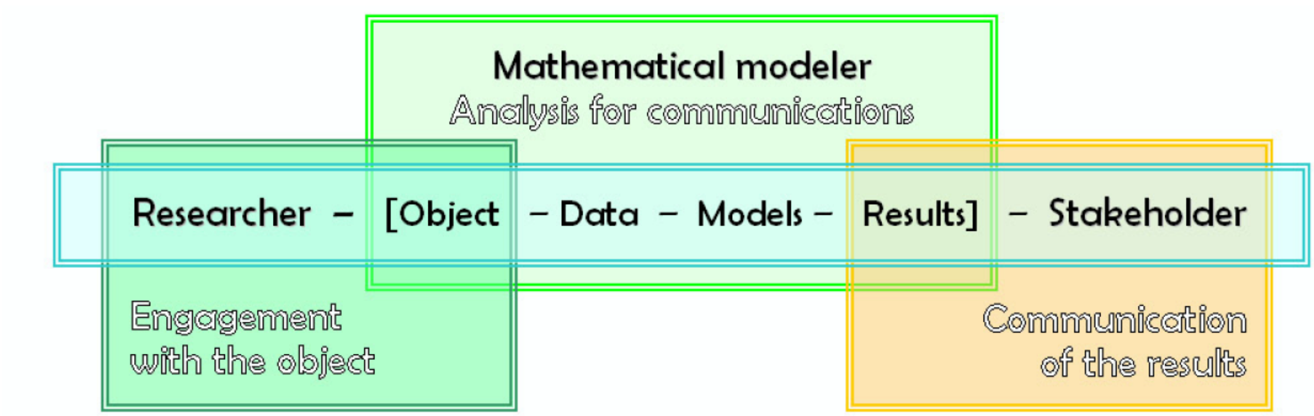

Figure 1. A system view of study and communication for understanding hydrological events.