Project Title: An Assessment of the Hydrologic Vulnerability of the Missouri River Basin to Climate Variability at Interannual to Decadal Timescales

Program Element: Sectors Applications and Research Program (SARP)

Principal Investigators

Dr. Vikram M. Mehta
Lead PI; Executive Director,
The Center for Research on the Changing Earth System,
Columbia, Maryland 21044;
Vikram@crces.org;
Phone: 410-992-5300 ext. 14

Dr. Norman Rosenberg
PI; Senior Scientist
The Center for Research on the Changing Earth System,
Columbia, Maryland 21044;
normjrosenb@crces.org;
Phone; 410-992-5300 ext. 13

Consultant

Dr. Robert Hearne
Assistant Professor
Department of Agribusiness and Applied Economics
North Dakota State University
Fargo, North Dakota 58105
rhearne@ndsuext.nodak.edu
Phone: 701-231-6494

Advisory Committee

Prof. Donald A. Wilhite
Director,
National Drought Mitigation Center,
Univ. of Nebraska
Lincoln, Nebraska 68583
dwilhite2@unl.edu
Phone: 410-992-5300 ext. 14

Dr. Steve McIntosh
Surface Water Section Chief
Water Resources Program
Missouri Department of Natural Resources
Jefferson City, Missouri 65102
steve.mcintosh@dnr.mo.gov
Phone: 573-751-7823

Prof. Eric F. Wood
Dept. of Civil and Environmental Engineering
Princeton University
Princeton, New Jersey 08544
efwood@princeton.edu
Phone: 609-258-4675

Institutional Representative

Ms. Janet L. Wood
Chief Administrative Officer
The Center for Research on the Changing Earth System
10211 Wincopin Circle, Suite 240
Columbia, Maryland 21044
wood@crces.org
Phone: 410-992-5300 ext. 13

Requested funds: Year 1 $100,000; Year 2 $100,000; Year 3 $100,000

Last revision on: 3 July 2005

Summary

We propose to undertake a systematic, multidisciplinary assessment of the varying hydrologic and agricultural vulnerabilities of the Missouri River Basin (MRB) due to climate variability at the interannual to decadal timescales. Impacts of this variability on water resources, production of food, feed and industrial crops, the irrigation enterprise and their economic consequences in the MRB will be identified and quantified. The proposed research will be conducted via analyses of hydro-meteorological data sets, the Hydrologic Unit Model of the United States (HUMUS), the Erosion Productivity Impacts Calculator (EPIC), and analyses of economic impacts. The proposed research will be guided by a consultant and an Advisory Committee of experts on MRB climate, hydrology, agriculture, and resource economics.

In the proposed project, we will quantify statistics and patterns of hydro-meteorological variability in the MRB associated with interannual to decadal, global-scale climate phenomena such as El Niño-La Niña events and their variability. Then, based on elicitations of indicators of societal impacts of the interannual to decadal climate phenomena in the MRB from the Advisory Committee and other experts, we will conduct experiments with HUMUS to model hydrological impacts; with EPIC to model crop yield and water use, and estimate impacts on supply of and demand for irrigation water; and will estimate impacts on MRB agriculture and economy. In addition to publication of results from the proposed research in peer-reviewed papers, reports, and web sites, we will also provide briefings to state, regional (e.g., the Missouri River Basin Association), and federal water resource and agriculture policy-makers and managers; and to NOAA program managers, and NOAA climate, hydrological, and agricultural services scientists. Although the scope of the proposed project is limited to one set of models, we will prepare input data sets and design experiments with them in such a way that other researchers will be able to access and use the data sets easily in the conduct of parallel experiments with other models, if interested.

Thus, the proposed research is consistent with the FY2006 SARP goals and at least one of the priority research areas. Also, the proposed research will address a new area of research that is necessary, but not currently covered by the NOAA/OGP/RISA program.

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1. Results from Prior Research

1.1 Climate Variability Research

Two recently completed research efforts, funded by the NASA-Ocean Physics Program and the NOAA-Office of Global Programs-Climate Change Data and Detection Program, are relevant to the interannual to decadal climate variability aspect of this proposal.

Several studies have found that interannual El Niño-Southern Oscillation (ENSO) variability, its relationship with other climate phenomena such as the Asian-Australian Monsoons, and its predictability vary at decadal-multidecadal timescales. A recent study with the ECHO-2 global coupled model suggested that long-persistent temperature and salinity anomalies can emerge in the equatorial central Pacific Ocean at the eastern edge of the western Pacific Warm Pool (WPWP), modulate the sea-surface temperature (SST) and vertical temperature gradient in the emergence region, and modulate interannual El Niño (EN) characteristics. Therefore, we (Mehta and Fayos, 2005a) analyzed decadal-multidecadal variations in interannual EN events and their evolutions with respect to decadal-multidecadal variations in the WPWP SSTs in the HadISST, Kaplan, and Reynolds SST data sets from January 1870 to December 2000; SSTs and upper-ocean temperatures from the Joint Environmental Data Analysis (JEDA) data set from January 1955 to December 2000; and SSTs, upper-ocean temperatures, and surface wind stress from the Simple Ocean Data Analysis (SODA) data set from January 1955 to December 2000 to see if a similar EN modulation exists in these observational data sets. We also analyzed (Mehta and Fayos, 2005b) atmospheric climate anomalies associated with decadal-multidecadal variations in EN events in model-assimilated reanalyses of atmospheric observations produced by the National Centers for Environmental Prediction (NCEP)-the National Center for Atmospheric Research (NCAR) (1950-2001) and the European Center for Medium-range Weather Forecasts (ECMWF; ERA40) (1958-2001).

The results of our analyses of the five oceanographic data sets (Mehta and Fayos, 2005a) show that interannual EN events in Northern Hemisphere winter and their evolutions were significantly different during the analysis period in all five data sets in warmer-than-average and less-warm-than-average phases of decadal-multidecadal variations of WPWP SST, classified as type I and type II EN events, respectively. In the 1955 to 2000 period, type I EN events were weaker, initiated at the surface in the equatorial central Pacific Ocean, and confined largely to the equatorial Pacific region whereas type II EN events were less frequent but stronger, initiated at the surface near the South American coast, meridionally extending along the coasts of the Americas to midlatitudes, and extending to at least 200 m depth. In the 1870 to 1954 period, also in the HadISST and Reynolds SSTs, type I EN events were weaker and confined largely to the equatorial Pacific region, whereas type II events were much less frequent but stronger and meridionally broader. Differences in upper-ocean heat content, Ekman mass and heat transports, and zonally-averaged shallow tropical circulation in the Pacific Ocean between these two types of EN events were also significant. The results of these analyses of five observational data sets are thus consistent with the ECHO-2 global coupled model results, suggesting that decadal-multidecadal variability of the WPWP may be modulating interannual EN events in nature also.

The results of our analyses of the two atmospheric reanalysis data sets (NCEP-NCAR and ECMWF ERA40) in the Northern Hemisphere winter show (Mehta and Fayos, 2005b) that the impacts of type I and type II EN events on the atmosphere were quite different during the 1950s to 2001 analysis period. In addition to the local (the tropical Pacific) impacts on the Walker Circulation (WC) and atmospheric water vapor transport, the distant impacts were most pronounced in the North Pacific-North America sector. In type I EN events, the WC weakened and the eastward migration of rainfall to the central equatorial Pacific was fed by anomalous water vapor transport from the western tropical Pacific. The Aleutian Low was deeper by 2-3 mb, resulting in stronger westerly winds across the U.S., especially in the upper troposphere. In type II EN events, these local and distant impacts were approximately twice as strong as in type I events. Thus, it seems that the apparent modulation of interannual EN events by decadal-multidecadal variability of the WPWP SST results in significantly different EN impacts on the atmosphere, especially in the North Pacific-North America sector.

1.2 Societal Impacts Research

Three recently completed research efforts are relevant to the societal impacts focus of this proposal. These include publication of a special issue of the journal Climatic Change entitled "Climate Change impacts for the Conterminous USA: An Integrated Assessment" (Rosenberg and Edmonds, eds. 2005). This issue is a compilation of nine papers describing modeling studies of how a set of climate change scenarios for the USA involving three global climate models at two levels of global mean temperature change (a surrogate for time), and with and without CO_2-fertilization, might impact on the production of major crops in the USA, on the hydrologic cycle, on water demand for irrigation, water supply to meet this demand and on land use change. All 18 Major Water Resource Regions of the U.S.A. were studied; agricultural analyses were done for 204 sites (a representative farm in each 4-digit basin) and water resources for 2101 locations (8-digit basins). Results, in terms of dryland and irrigated crop production of major grains and forages, were integrated in an agricultural and land use model to calculate implications for producers and consumers and for the U.S. economy as a whole. This effort (funded by NSF's 'Methods and Models in Integrated Assessment' program) follows in the path of the well-known, DOE-funded "MINK Study" (Rosenberg, ed., 1993).I In that study a surrogate climate change, recurrence of the 'dirty-thirties', is imposed on the Missouri-Iowa-Nebraska-Kansas region in the central U.S.A and impacts on agriculture, water resources, forestry, the energy economy and regional and national economies are assesses.

In a contribution to the so-called "National Assessment" (OSTP, 2000) the EPIC and HUMUS models (proposed for use in this study, as well) were applied to scenarios for the conterminous U.S.A. derived from the HadCM2 global climate model. Two future periods were considered –2030 and 2095. HUMUS modeling results (Rosenberg, et al., 2003) show that water yields, used as a measure of water supply for irrigation, increase at first in the western region of the country and decrease in the central and southeast regions. By 2095, however, water yield increases are typical throughout the country, relatively more in the west than the east. But the seasonal patterns of runoff also change, so that flows are generally greater in late winter and spring, raising problems of water storage for the irrigation season.

In the companion National Assessment paper (Izaurralde et al., 2003), the EPIC model simulates increase in dryland corn yields for the Great Lakes, Corn Belt and Northeast regions. Simulated irrigated corn yields increase almost everywhere. Soybean yields generally decrease under the HadCM2 scenarios in most regions and wheat yields trend upwards. Overall national corn production is projected to decline in the earlier period because of losses in the Northern Plains region. National wheat production is projected to increase in both periods. A proxy indicator was developed to provide a sense of where in the country and when, water would be available to satisfy changes in the irrigation requirement for corn and alfalfa production as influenced by the HadCM2 scenarios and the transpiration-suppressing effects of CO_2-fertilization.

Another study, funded by NASA and NOAA-Office of Global Programs, reported on a study of simulated impacts of ENSO on U.S. water resources. HUMUS was used to simulate impacts on water resources in the conterminous U.S.A. of four types of ENSO events or states—Neutral, EN, La Niña and Strong EN (defined by their five month running mean of spatially averaged SST anomalies over the equatorial eastern Pacific). La Niña events increased water yields over much of the U.S. Water yields increased across the southern U.S. in EN events while declining in much of the rest of the country. Under strong EN conditions, however, regional water yields were much higher than under the Neutral ENSO state, especially along the West Coast. Therefore, we conclude that impacts of strong EN events are not merely an amplification of EN impacts; patterns of water resource response are strikingly different in the two types of EN events. Reported in Thompson et al. (2003), this paper was awarded the American Water

Resources Association's Boggess Prize as Best Paper of 2003). Such different impacts of two types of EN events on the U.S. water resources are consistent with significantly different climate impacts of two types of EN events mentioned in section 1.1.

Statement of Work: (15 pages max., excluding figures)

2. Identification of the Problem

In the latter half of the twentieth century the extent of land under irrigation doubled to cover 17% of the world's total farmlands. Currently, irrigated lands produce a third of the world's food supply. In the U.S., 18% of the total cropland (20 million hectares) is irrigated and irrigation accounts for the largest consumptive use of freshwater (Thomson et al., 2005a). Of the 18 Major Water Resource Regions (MWRRs; Figure 1) of the U.S., freshwater withdrawals for irrigation are greatest in California, the Pacific Northwest and the Missouri River Basin (MRB).

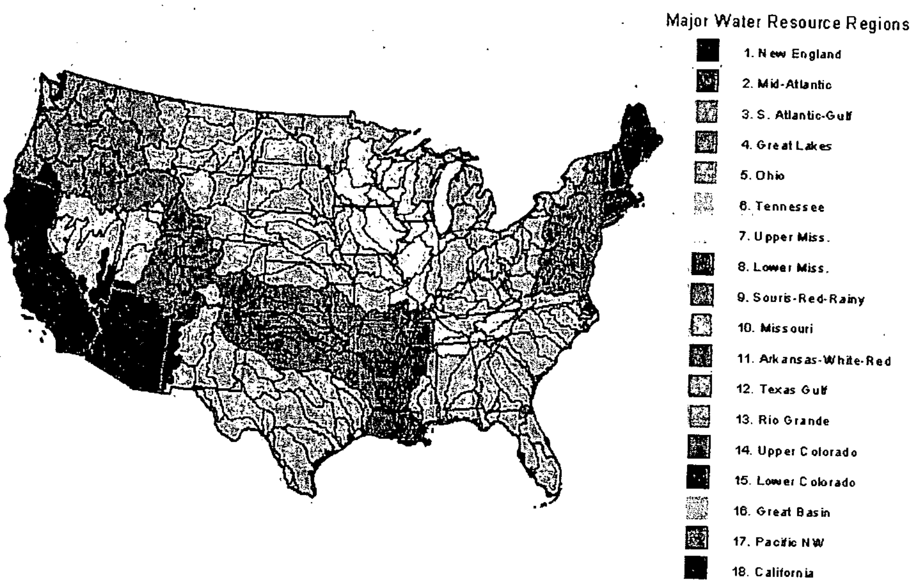

Figure 1: Hydrologic Unit Areas ("4-digit") defined by the US Geological Survey.

Gleick (1990) estimated the annual-average vulnerability of U.S. water resources to climate change by reference to five indicators; these are measures of *storage*, *demand*, *dependence on hydroelectricity*, *groundwater vulnerability*, and *streamflow variability*. Of the 18 MWRRs of the conterminous U.S. examined by Gleick (1990), only one—the Great Basin—is vulnerable according to all indicators. California and the MRB are vulnerable on four indicators; only their *storage* capacity is deemed adequate. The vulnerability of the MRB fluctuates, of course, with precipitation variability forced by large-scale climate variability, especially at interannual to decadal timescales which, as mentioned above, already explains 60-70% of the total variance of annual-average precipitation. For example, during a major, multiyear drought such as that in the late 1980s, inflows in the MRB were insufficient to fully support reservoir-based recreation and Missouri River navigation. Conversely, too much water in the MRB reservoir system during above-average precipitation years results in higher water releases from the reservoirs, threatening the viability of farming and homesites in the MRB floodplain (the Missouri River Basin Association; http://www.mrba-missouri-river.com/interest.htm). Moreover, the interannual to decadal timescale precipitation and associated temperature variability can distort the annual hydrologic cycle in the MRB, which might result in different hydrologic vulnerabilities in different seasons during any given year.

The MRB covers more than 500,000 square miles and a part of or all of 10 states (Montana, Wyoming, Colorado, North Dakota, South Dakota, Minnesota, Iowa, Nebraska, Kansas, and Missouri), numerous Native American tribal reservations, and parts of the Canadian provinces of Alberta and Saskatchewan.

People living in the MRB depend on the Missouri River for drinking water, irrigation and industrial needs, hydro-electricity, recreation, navigation, and fish and wildlife habitat. The MRB contains some of the country's most sparsely-populated agrarian counties as well as large metropolitan areas such as Omaha and Kansas City on the Missouri River and Denver at the foothills of the Rocky Mountains. Grain crops for food and feed provide much of the MRB region's agricultural income. In 2002, the combined value of all crops produced in those states where irrigation is consequential--primarily Montana, North and South Dakota, Nebraska and Kansas—was about $ 10.6 billion (USDA/NASS, 2002) (http://www.nass.usda.gov/census/census02/volume1/us/st99_2_001_001.pdf). The market value of livestock products sold in that year was $ 16.8 billion.. In all but North Dakota, livestock products exceed the value of crops sold. About 117 million acres are in cropland in the aforementioned states. Of that total about 12 million acres are irrigated. The distribution of irrigated acreage among the states is quite variable; in Nebraska 33% of the land is irrigated; in Montana 11%; in Kansas, 9% and in South and North Dakota about 2% and slightly less than 1%, respectively. These facts (taken into account, indicate that the proposed analysis of the consequences of climate variability impacts on hydrology of the MRB must consider production of all crops used for food and animal feed (grains, alfalfa, pasture grasses) and that impacts on the sustainability and profitability of the irrigation enterprise in the MRB region is critical.

Analyses (Cayan et al., 1998) of century-long precipitation time series over the MRB found that interannual El Niño-Southern Oscillation (ENSO) variability explains less than 20% and decadal (>7 years) timescale variability explains approximately 40-50% of the total variance. The interannual to decadal precipitation variability is thus responsible for 60-70% of the total precipitation variance in the MRB. Snow accumulation and stream discharge variations in the MRB generally agree with the interannual and decadal precipitation variability estimates. These results are consistent with runoff and streamflow analyses by Guetter and Georgakakos (1993) and Lins (1997). These precipitation, snow accumulation, and stream discharge estimates are also reflected in the percentage area of the MRB under severe to extreme drought conditions. As shown in Figure 2, the fraction of the MRB experiencing severe to extreme drought has ranged from 20% to 60% or more at interannual to decadal timescales in the 20th century.

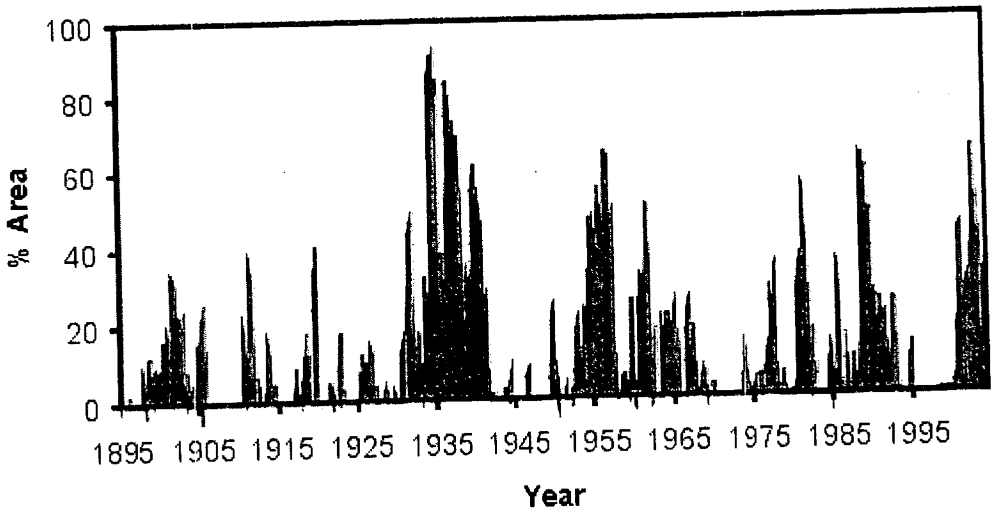

Figure 2: **Percent area of the Missouri River Basin experiencing severe to extreme drought between January 1895 and March 2004. Based on data provided by the National Climatic Data Center, NOAA; Copyright 2004 National Drought Mitigation Center.**

Accordingly, we propose to undertake a systematic, multidisciplinary assessment of the varying hydrologic vulnerability of the MRB at interannual to decadal timescales, its impacts on water resources, especially irrigation and agriculture, and its economic consequences in the MRB. Climate variability induces variability in both the supply of and demand for water. In this first step toward development of this methodology, our analysis will be limited on the demand side to changing requirement for irrigation water although, of course, demand for industrial, municipal, navigational and recreational purposes also vary with climate. On the supply side we will confine our analysis to streamflow as the source of water for irrigation. Groundwater resources used for irrigation in the MRB are also sensitive to climatic variaibility and change. There is evidence, for example, that the High Plains (Ogallala) aquifer that underlies much of the Missouri and Arkansas-White-Red basins is responsive to relatively short-term climate fluctuations (McGuire and Sharpe, 1997). However, the groundwater resource will not be specifically addressed in this first methodological study.

A multidisciplinary Advisory Committee, composed of decision-makers and academic experts specializing in various aspects of the MRB hydrologic variability and its economic impacts, will provide guidance to the proposed project. The proposed research will draw upon and stimulate ongoing climate variability research in CRCES funded by the NASA-Ocean Physics Program and the NOAA-Climate Change Data and Detection Program.

3. Scientific Objectives

The proposed research will be conducted to achieve the following scientific objectives:

O1. To identify impacts of global-scale interannual to decadal timescale climate variability, especially ENSO and its decadal variability, on the hydro-meteorology of the MRB;

O2. To identify hydrologic responses to this hydro-meteorological variability;

O3. To identify impacts of this hydro-meteorology on yields of dryland and irrigated crops in the MRB;

O4. To evaluate impacts of the above on demand for and supply of water for irrigation; and

O5. To calculate the first-order economic effects and identify further societal impacts on the MRB region.

4. Proposed Methodology

4.1 Role of the Advisory Committee and the Consultant

As a first step in initiating the proposed research, a small, multidisciplinary Advisory Committee has been recruited to advise the investigators from the proposal-writing stage, particularly about the information elicitation and dissemination of results (described below under *Tasks*). The Committee consists of Professor Don Wilhite (National Drought Mitigation Center, University of Nebraska, Lincoln), Dr. Steve McIntosh (Water Resources Program, Missouri Department of Natural Resources), and Professor Eric Wood (Princeton University). Committee members will identify others in the MRB region and elsewhere for the elicitation described in Task 2 and will themselves participate in this Task.

Dr. Robert Hearne (Department of Agribusiness and Applied Economics, North Dakota State University) has been recruited as a consultant and has been involved in the proposed research from the proposal-writing stage. Dr. Hearne will guide the research team in the economic impacts component of the proposed research. The Advisory Committee members and Dr. Hearne will be co-authors of appropriate papers and reports. Letters of support from the Advisory Committee members and Dr. Hearne are attached to this proposal.

4.2 Research Tasks

The research will consist of five Tasks:

4.2.1 Task 1: Diagnoses of Hydro-meteorological Variability

While previous studies (e.g., Cayan et al. (1998) and others cited earlier) provide a large-scale, time-average picture of rainfall, snow pack, and streamflow variability in the MRB and neighboring regions, detailed, quantitative analyses of relationships between MRB hydrometeorology and indicators of global-scale, interannual to decadal climate phenomena such as ENSO and its decadal variability are necessary to estimate societal impacts of these phenomena on the MRB, especially on water resources and agriculture. Quantification of such relationships would also be very useful for predicting hydrological and agricultural impacts of these global-scale climate phenomena in the MRB region, as shown, for example, experimentally for the eastern U.S. by Wood et al. (2002). High resolution (in space and time) hydro- meteorological data sets for the MRB and indices of ENSO and its decadal variability are required for this purpose.

We propose to use a model-derived data set (Maurer et al., 2002) of land surface states and fluxes for this purpose. This very high resolution (1°/8 in space, 3 hours in time) and long time span (1950-2000) data set has observed precipitation, surface air temperature, and surface winds used to force the Variable Infiltration Capacity (VIC) model; and surface runoff, baseflow, soil moisture, snow water equivalent, and surface heat fluxes. As Maurer et al. (2002) have shown, the average annual cycle of runoff in the MRB and its interannual variability over a 10-year period are reproduced reasonably accurately by the VIC model. Monthly values of these data are available from http://www.hydro.washington.edu.

We will use various (see, for example, Trenberth (1997) for definitions) Niño3 sea-surface temperature (SST) indices, the Southern Osicllation Index, and an index of the Indo-Pacific Warm Pool variability for the same period as the hydrometeorological data. In order to assess the importance of interannual to decadal variability in the MRB hydrometeorology, we will estimate total and fractional (in the interannual to decadal band) variances of the hydrometeorological variables following Cayan et al. (1998). To analyze impacts of EN and LN events on the MRB hydrometeorology, the hydrometeorological data, especially precipitation, temperature, runoff, and soil moisture will be composited and correlated with respect to EN and LN events, and with respect to stratified EN and LN events according to the Mehta and Fayos (2005a, 2005b) method. The data will be composited both at the peak time of EN and LN events, and also as monthly composites around the peak time to see the evolution of hydrometeorological fields. We will also estimate probability density functions (PDFs) of the hydrometeorological variables averaged in various parts of the MRB during EN and LN events to see if properties of the PDFs are significantly different for the various events.

4.2.2 Task 2: Elicitation of Societal Impacts Indicators

Associating climate variability and change with societal impacts is not a simple matter. Although the first order effects of major changes-droughts, floods, hailstorms- on, say, crop yields and river flows are obvious, the signals of interannual to decadal variability may, for a number of reasons, be much more subtle. For example, even if periodic or quasi-periodic phenomena such as EN events were to manifest themselves in precisely the same ways in predictable patterns, antecedent conditions such as soil moisture status, and concentrations of pathogenic organisms and their vectors, weed seed, and insects, would result in different effects and impacts. Similarly, prior precipitation history will determine how the effects of any particular climatic event are manifested in streamflow.

Additionally, there is evidence in nature of the more than one coincidence of periodic or quasi-periodic climate phenomena such as decadal climate variability and interannual EN events (Power et al., 1998; Arblaster et al., 2002; Mehta and Fayos, 2005a, 2005b) such that EN events, for example, will not have the same impacts in the same places each time because of the slowly-varying background climate. Further, societies and technologies change with time as do their sensitivities to periodic or quasi-periodic climate events.

How then to tease out the indicators that we seek in the proposed study? As a first step, we will engage our Advisory Committee and other collaborators in an exercise to identify most-likely second-order indicators of ENSO and other climate variability effects (such as population changes, state and regional domestic products, employment statistics, mental health statistics and others) and to organize these indicators into a preliminary "white paper" for distribution among a small (say, 10-15 member) group of MRB experts. These will include persons with specialized knowledge of the various sectors of first-order interest (agriculture, water resources, irrigation), government and private-sector decision makers, extension personnel, sociologists, economists, perhaps also media persons, to review the list, to elaborate on particular items with which they identify, to offer suggestions of ways to establish links between climate events and their impacts, and to offer suggestions of additional indicators. This elicitation will be organized as a continuous, on-line activity through the auspices and facilities of the Virtual Center for Decadal Climate Variability (http://www.DecVar.org), developed and maintained by CRCES, and funded by the NASA-Ocean Physics Program. Tasks 1 and 2 can proceed simultaneously.

Thus, a continuous elicitation process will be set in motion almost from the beginning of the proposed project. At first, the list of indicators will be general; as Task 1 proceeds and relevant climate signals are identified, the search for impacts directly attributable to them will become more specific. The outcome of this exercise will provide guidance for Tasks 4 and 5.

4.2.3 Task 3a: Hydrologic Modeling

The Hydrologic Unit Model of the United States (HUMUS; Srinivasan et al., 1993) is a Geographic Information System (GIS)-based model used to provide input to the Soil and Water Tool (SWAT), at the sub-basin scale. HUMUS works on a daily time step. Weather data can be drawn from historic records for retrospective studies or, where these are inadequate, weather data generators can be used to synthesize the necessary inputs.

SWAT/HUMUS has been validated with observed data at scales ranging from the MWRR (Arnold et al., 1999) to a small stream catchment (Arnold and Allen, 1996). Gerbert et al. (1987) estimated average annual natural streamflow from observations at nearly 6000 gauging stations in the U.S. over 1951 to 1980. Arnold et al. (1999) found that HUMUS agreed reasonably well with Gerbert et al. (hereafter, USGS-estimated) streamflow with regression slopes of 0.86 at the state level and 1.01 at the level of STATSCO soil association regions. In a contribution to the study "Climate Change Impacts on the U.S: The Potential Consequences of Climate Variability and Change" (otherwise known as the 'National Assessment, OSTP, 2000), Rosenberg et al. (2003) found that HUMUS overestimates runoff in the Great Plains and Mississippi Delta as an artifact of applying irrigation to all land within each irrigated sub-basin. They also found that HUMUS underestimates streamflow in mountainous regions, probably because of the lack of observations from high altitude locations. Thomson et al. (2005a,b) also validated HUMUS in a study of hydrologic sensitivity of the entire conterminous U.S.A. to a series of climate change scenarios.

We will further validate HUMUS to meet the needs of the proposed study by reconstructing streamflow at a selected set of USGS gauging stations within the MRB. These stations will be from the set used by Frederick (1993) to establish how the hydrology of the "MINK" (Missouri-Iowa-Nebraska-Kansas) region would respond to a return of the climate of the 'dirty thirties'. The stations in question are those at which observed streamflows appear to have been unaffected by human impacts since early in the 20th century. In this study stations will be chosen to represent the western Dakotas, eastern Dakotas, North and South Platte, Niobrara-Platte-Loup, Middle Missouri, Kansas, and Lower Missouri (4-digit basins 1005-1011).

As HUMUS cannot simulate streamflows at the site of a single gauging station, water yields will be simulated for the entire 8-digit basin in which the selected gauges are located and trends in both measures of streamflow will be compared. If agreement in trends is satisfactory, all further HUMUS simulations will be made at the scale of the 8-digit basin.

Normally HUMUS is driven by historic daily maximum and minimum temperature and precipitation data from the nearest NOAA cooperative climatological station or stations. These are processed into a time series of monthly means that 'seed' a weather generator (e.g., Richardson and Nicks, 1990), the output of which is a daily data set of maximum and minimum temperature, precipitation, runs of wet and dry days, solar radiation, windspeed and direction, and relative humidity. The same procedure will be used in this validation effort and in subsequent HUMUS runs.

With agreement established, HUMUS will then be applied to simulate flows in the 8-digit basins using weather data generated as above but 'seeded' under scenarios of climate variability of the kinds identified in Task 1 (Figure 3). Specifically, average differences and standard deviations of precipitation and temperature, and sequences of dry and wet days for the interannual to decadal climate variability phenomena estimated in Task 1 will be used to "seed" the weather generator.

The output of this Task will be:

- A validation of HUMUS-derived natural streamflows by comparison with records at the select stations.
- A HUMUS-derived reconstruction of natural streamflows for most of the 20th century in 8-digit basins served by the select gauging stations
- Sensitivity studies of climate variability effects on natural streamflow

4.2.4 Task 3b: Crop Yield and Water Use Modeling

The Erosion Productivity Impacts Calculator (EPIC; Williams, 1995) is a biophysical process-based model that simulates production of a wide range of crops, evapotranspiration, and irrigation water requirement as well as runoff, erosion and nutrient cycling. EPIC works at the scale of a single hectare or uniform farm field. We consider this unit to be a 'representative farm' as described by Easterling et al. (1992). Data on daily weather, soil physical and chemical properties, and crop management (e.g., fertilization, cultivars, tillage) are needed to run EPIC. EPIC calculates the maximum daily increase in plant biomass allowed by the daily capture of photosynthetic radiation (0.4-0.7 micrometers) by the plant, (itself a function of the incident solar radiation and the crop leaf area index) and by the presence or absence of constraints on photosynthesis such as deficient soil moisture, temperature extremes, lack of root-zone aeration, shortage of nutrients, etc. Planting and harvesting dates in EPIC are based on accumulated heat units during the growing season and, therefore, also vary with climate. Crop yields are estimated by multiplying above-ground biomass at maturity by a crop specific 'harvest index'—the ratio of grain to total biomass. In the case of forage crops such as alfalfa the harvest index can be taken as 1.0.

EPIC has been validated in many countries and regions of the world. Specifically relevant to the proposed research are studies of potential climate change impacts on dryland and irrigated grain and forage yields for the 'MINK region' by Rosenberg, et al.(1992) and Easterling et al. (1993). Brown and Rosenberg (1996) and Thompson et al. (2005) have done similar analyses for the corn belt of the U.S. and Izaurralde et al. (1999) have examined the impacts of strong and moderate EN and LN events on crop yields in all of

North America. In all of these studies, EPIC-simulated yields have been compared with and validated against (in the U.S.) county level USDA/NASS (National Agricultural Statistical Service) data and in the Izaurralde et al. (1999) study with equivalent data from Canada and Mexico. Generally EPIC yields track NASS yields well but are higher because, for simplicity, a high level of management is assumed in the modeling—management not practiced on all or even most of the real farms that contribute to the NASS statistics. EPIC yields agree very well with those from experiment stations because the latter generally employ best management practices.

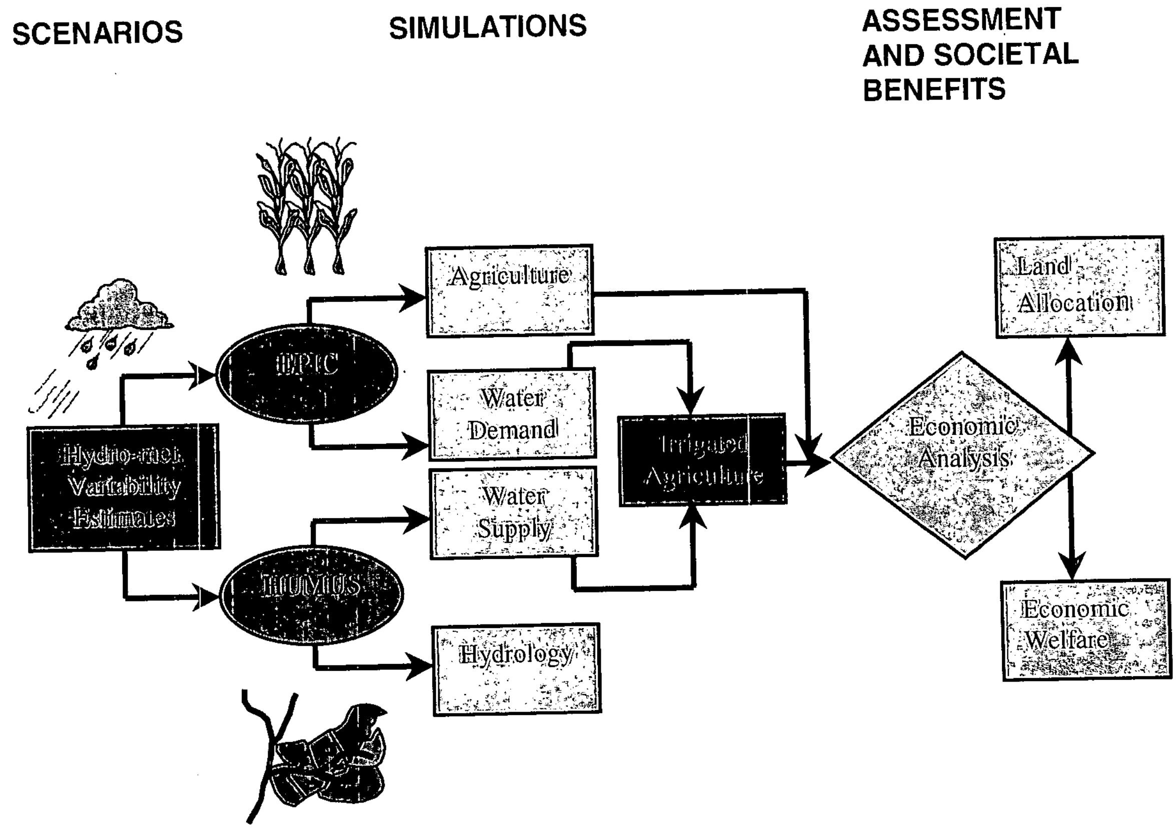

Figure 3: **From estimation of hydro-meteorological variability to assessment of societal impacts.**

In the proposed research, we will model the three dominant grain crops grown in the MRB—corn, soybean and wheat (both winter and spring, depending on location). Evapotranspiration can be calculated in EPIC by means of a number of well-known methods; we will employ the Penman-Monteith method (Monteith, 1973) in this study. Although the focus of this study is on water supply and irrigation, yields of dryland crops will also be simulated. This step is needed to establish how the extent of irrigation practiced may vary with climate variability, since farmers irrigate only when the additional yield minus expenses for irrigation increase their profit margins. In recent work, we have simulated the growth and yield of dryland and irrigated corn, wheat, soybean, alfalfa, and pasture grasses. As canola and oats are increasingly in competition for land in the more northerly sections of the MRB, these crops may also be modeled.

As a first step in validating EPIC for this application, we will simulate yields of corn, soybean, spring and winter wheat, alfalfa, and pasture grasses at a representative farm in each of the 8-digit basins in which the set of 'natural flow gauging stations' are located. Results for a number of randomly selected years will be compared with the most appropriate county level NASS statistics. Agreement within +/-15-20% will be taken as indication of applicability of EPIC. If results do not agree well, diagnostic procedures will identify the causes and process-level algorithms will be adjusted based upon most recent experimental evidence. The validated or modified model will then be used to produce a retrospective yield series for each crop (dryland and irrigated) and water demand for the irrigated crops for each representative farm at least to the beginning of the 1950s, essentially when modern,, high input agriculture began in the region.. As for HUMUS experiments, average differences and standard deviations of precipitation and temperature, and sequences of dry and wet days for the interannual to decadal climate variability phenomena estimated in Task 1 will be used to "seed" the weather generator. Finally in this task, studies will be made of the sensitivity of yields and irrigation water requirements to the scenarios of climate variability developed through Task 1 (Figure 3).

4.2.5 Task 3c: Estimation of Impacts on Supply of and Demand for Irrigation Water

Climate variability induces variability in both the supply of and demand for water. We will follow the methodology employed by Thomson et al. (2005c) by integrating EPIC and HUMUS results to evaluate climate variability effects on water supply and demand. For each of the three grain crops in each of the 8-digit basins to be studied, changes in total available water simulated with HUMUS, total irrigation per unit land area applied by EPIC, area of land that can be profitably irrigated, and amount of water (if any) remaining (water yield minus irrigation) for other consumptive and non-consumptive uses will be calculated. The production of each crop in each 8-digit basin will be calculated. Where irrigated yields exceed dryland yields, the impacts of irrigation on grain production in each representative basin will be calculated by comparing production where simulated water supply limits irrigation and where the optimal production occurs if all crops are irrigated to meet their full requirement for water (Figure 3).

The input files required for application of the HUMUS and EPIC models, generated in a recently completed NSF-sponsored research project (Rosenberg and Edmonds, 2005) under its 'Methods and Models in Integrated Assessment' program, are available to us for the proposed research. Although the scope of the proposed project is limited to one set of models, we will prepare input data sets and design experiments with them in such a way that other researchers will be able to access and use the data sets easily and conduct parallel experiments with other sets of models.

4.2.6 Task 4: Estimation of Impacts on Regional Agriculture and Economy

It will not be possible in this proposed initial study to explore all--or even all the most likely--societal impacts of interannual to decadal climate variability in the MRB. We will focus the study on the regional water balance, most particularly on irrigated agriculture and how it affects farm profitability, the regional economy and, perhaps, the national economy as well.

We use one simple criterion to drive farmer or enterprise adoption of irrigation—namely, the potential for increased profit. This is a function of the increase in crop yield above that attainable from the same acreage in dryland production, minus the incremental costs of irrigation, times the price available to the producer. It is important to recognize that market forces driving adoption of irrigation in the MRB are affected by the doctrine of prior appropriation. In drought conditions, junior rights holders will not receive water. Thus, abandonment of irrigation by senior rights holders, rather than adoption, may be the more sensitive indicator of climate variability impacts.

As our objective is to identify signals of climate variability impact on the adoption and consequences of irrigation in the MRB, we must first develop a sequence of what would have happened in the past were climate variability the only factor driving these fluctuations. We must then establish how irrigation has actually affected production in the region on a year to year and place by place basis. Therefore, two parallel data sets will be created, based on model simulations and on the actual record.

Thus we will:

- Establish dryland yields of the three major grain crops in addition to alfalfa and pasture grass (actual and EPIC-simulated) throughout the MRB for the period 1950 to 2000;
- Establish irrigated yields for the same period from actual records and EPIC simulations. EPIC will also provide information on the related demand for irrigation water; and
- Establish surrogates of water availability for the same time period to meet the irrigation demand using data from the individual gauging station and HUMUS simulations of streamflow in the selected 8-digit basins.

The actual and simulated series of irrigation adoption (and abandonment) data will almost certainly differ from one another. There are many possible reasons (some explained under Task 3). But changes in relative prices among the study crops (and new crops such as canola and oats), changes in international markets, agricultural policy and agricultural technology, including genetically modified drought resistant crops, improved irrigation technologies and changing market prices over the period of the proposed study are likely the most consequential. In essence then, when the economic and other exogenous forcings have been accounted for and quantified to the extent possible, the residual signal of irrigation adoption or abandonment may become evident in the actual record and its agreement with the simulated series should improve, hopefully to a degree that allows confident conclusions to be reached about the impacts of climate variability on irrigation development in the MRB.

As a final step in this Task, the economic analysis will approach the question of how the irrigation consequences indicated by the scenarios of future climate variability may be altered by anticipated changes in agricultural policy, world markets, new crops and, possibly, by introduction of genetically modified crop cultivars.

4.2.7 Task 5: Outreach Activities

Publication as peer-reviewed papers in Journal of Hydrometeorology, Journal of the American Water Resources Association, Bulletin of the American Meteorological Society, Water Resources Research, Journal of Climate, etc.

Publication as CRCES reports

Presentations in Conferences and Workshops

Presentations on the CRCES, DecVar, and NDMC-UNL websites

Briefings to state, regional (the Missouri River Basin Association), and federal water resource and agriculture policy-makers and managers

Briefings to NOAA program managers, and climate, hydrological, and agricultural services scientists

Input data sets to be made available to hydrological and agricultural modeling groups via DecVar

4.3 Project Schedule

The following table provides a summary of the project schedule during the course of the three-year research period.

Task	Year 1		Year 2		Year 3	
Diagnoses of Hydro-meteorological Variability	X	X	X	-	-	-
Elicitation of Societal Impacts Indicators	X	X	X	X	X	-
Hydrologic Modeling	X	X	X	X	X	-
Crop Yield and Water Use Modeling	-	X	X	X	X	-
Estimation of Impacts on Supply of and Demand for Irrigation Water	-	X	X	X	X	-
Estimation of Impacts on Regional Agriculture and Economy	-	X	X	X	X	-
Outreach Activities	X	X	X	X	X	X
Submission of peer-reviewed publication(s)	-	-	X	X	X	X
Presentation(s) at Workshops/Conferences	-	-	X	X	X	X
Annual report to NOAA	-	X	-	X	-	-
Final report to NOAA	-	-	-	-	-	X

5. Relevance to the Goals of the SARP Program and Program Priorities

According to the SARP Information Sheet, SARP is designed to systematically build an interdisciplinary and expressly applicable knowledge base and mechanism for the creation, dissemination, and exchange of climate-related research findings critical for understanding and addressing resource management challenges in vital social and economic sectors. Two of the three overarching goals of SARP are:

- The provision of new and/or synthesized science-based knowledge that results in the identification and reduction of vulnerability to climate variability and change in key socio-economic sectors; and

- The development of a research and operations agenda that increasingly meets the need of the Nation and NOAA through an understanding by scientists and science managers of stakeholder requirements.

Under these general goals, one of the four SARP priority research areas in FY 2006 is:

- An economic analysis of the sectoral impacts of climate variability and where the improved use of climate information affects the management of risk. Specifically, NOAA is interested in what costs and benefits climate fluctuations can impose upon a segment of society, and how costs can be reduced through the applications of climate science and technology. The results of this study will improve the ability of decision makers to understand and assess the economic implications of climate variability, and the resulting response options. Furthermore, this work will help shape requirements and priorities for efforts to address climate in each of these sectors.

The proposed research will contribute significantly towards the above two SARP goals by providing new science-based knowledge which will result in the identification of vulnerability of water resources and agriculture in the MRB to interannual to decadal climate variability; and by the development of a research agenda based on the proposed elicitation of information about socio-economic impacts in the MRB. The proposed research will address all aspects of the above SARP priority research area.

Finally, the proposed research will address a new area of research that is necessary, but not currently covered by the NOAA/OGP/RISA program.

6. Benefits to the General Public and the Scientific Community

This will be the first quantitative assessment of the vulnerability of water resources and agriculture in the MRB, including its economic cost, to interannual to decadal climate phenomena. Such an assessment will enable decision-makers in the MRB and in relevant federal government departments/agencies to estimate the financial impacts on the MRB region's citizens, businesses, and governments. In the future, if the climate variability responsible for these impacts on the MRB and the impacts themselves can be predicted in advance, then mitigating measures can be applied to reduce or eliminate the financial impacts, benefiting the general public. The proposed research will also show a use of taxpayer money for societal benefits.

The proposed research will stimulate scientific research, including multiyear to decadal predictability research, on global-scale climate phenomena affecting the MRB. The development of an assessment methodology for the MRB water resources and agriculture impacts may be adapted for use in other river basins in the U.S. and in other countries.

7. Human Resources, Budget, and Facilities

The Lead PI will have the overall responsibility for the management of the proposed project, including planning proposed activities, achieving targets, evaluating progress, and reporting to NOAA. The two PIs will jointly evaluate candidates for the Research Assistant to be recruited to run experiments with the HUMUS and EPIC models. Carolina Fayos, a Research Assistant in CRCES, is experienced in processing and analyzing observational data sets; she will be in charge of obtaining, preparing, and analyzing the precipitation, temperature, and streamflow data sets. The two PIs together will lead and assist the two Research Assistants in developing the data analysis techniques, and designing experiments with the HUMUS and EPIC models. The two PIs will interact with the Advisory Committee and will be in charge of outreach activities. Dr. Robert Hearne will guide the team in the societal impacts component of the proposed research, especially Tasks 4 and 5.

One month's salary support for Dr. Vikram Mehta, two months' salary support for Dr. Norman Rosenberg, six months' salary support for the to-be-recruited Research Assistant, and two months' salary support for Carolina Fayos are requested. In each year, Dr. Hearne will be paid a consulting fee as budgeted. The Advisory Committee will meet the research team in the CRCES office in Columbia, Maryland once every year. Members of the Committee will be paid a $1,000 honorarium and travel expenses for the annual meeting as budgeted. It is planned that at least one peer-reviewed publication for a refereed journal will be prepared every year during the course of the research -- thus the request for publication costs. Results from the proposed research will be presented in several relevant Workshops/Conferences every year – thus the request for the travel costs.

CRCES is located in a Class-A building overlooking Lake Kittamaqundi in Columbia, Maryland. CRCES's computational infrastructure consists of a cluster of Linux-Windows and Macintosh workstations, a cluster of data and web servers, a cluster of dedicated "model-running" computers, a high-speed Internet line, and a selection of printers. The workstations, dedicated model-running computers, and servers are equipped with more than 1.5 Tbytes disk space and various software packages necessary for data processing and analysis, visualization, word processing, and presentation. Current computer resources in CRCES are sufficient for running experiments with the HUMUS and EPIC models. We will augment the computational infrastructure, if necessary, from the Facilities and Administration part of the proposed budget.

Some of the required datasets for the proposed research have been acquired in the PIs' previous research. The remaining datasets will be acquired during Spring and Summer of 2006. Portions of the required software, including the HUMUS and EPIC models, are available from the PIs' previous and current projects.

Facilities of the NASA/Ocean Physics Program sponsored Virtual Center for Decadal Climate Variability (http://www.DecVar.org) will be used in the proposed project for interactions among CRCES scientists, the Consultant, the Advisory Committee members, and decision-makers and stakeholders.

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