Potential Impacts of Climate Change on Minnesota's Water Resources: An Economic Analysis

This study was conducted on behalf of the
Legislative-Citizens Commission on Minnesota Resources

by

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Introduction and Background

This report contains the economic component of a larger research project directed by the University of Minnesota, Natural Resources Research Institute. According to the 2007 LCCMR project Workplan, the overall purpose is "to quantify climate, hydrologic, and ecological variability and trends, along with economic impacts of environmental fluctuation on water resources, and to identify indicators of future climate change effects on aquatic systems. This report presents economic conceptualizations of climate change as a policy challenge and empirical findings on "economic impacts of environmental fluctuation on water resources."

The Scientific Context for Climate Change Impacts on Minnesota Resources

According to USEPA Office of Water 2008"Climate change will have numerous and diverse impacts, including impacts on human health, natural systems, and the built environment. Many of the consequences of climate change relate to water resources, including:

- warming air and water;
- change in the location and amount of rain and snow;
- increased storm intensity;
- sea level rise; and
- changes in ocean characteristics."

"Impacts should be expected to vary regionally, but in general, climate change could result in increased demands on our infrastructure systems, both in terms of O&M costs and the need for capital expenditures. The suite of expected impacts can be grouped according to the type of change a system may face and fall roughly into the following categories:

- more water (through increased precipitation and storm intensity) and sea level rise;
- less water, with increased frequency and duration of drought;
- temperature change; and
- damage from more intense storms." USEPA Office of Water (2008), page 51.

The MPCA climate change website states: "Minnesota is already experiencing impacts from climate change, and will continue to experience impacts to our ecosystems, natural resources, and infrastructure." The MPCA website quotes the US Global Change report which highlights Key Impacts in the Midwest:

- During the summer, public health and quality of life, especially in cities, will be negatively affected by increasing heat waves, reduced air quality, and increasing insect and waterborne diseases. In the winter, warming will have mixed impacts.
- The likely increase in precipitation in winter and spring, more heavy downpours, and greater evaporation in summer would lead to more periods of both floods and water deficits.

- While the longer growing season provides the potential for increased crop yields, increases in heat waves, floods, droughts, insects, and weeds will present increasing challenges to managing crops, livestock, and forests.
- Native species are very likely to face increasing threats from rapidly changing climate conditions, pests, diseases, and invasive species moving in from warmer regions.

Specific Findings on Climate Change Impacts on Minnesota's Water Resources

Climatologist Mark Seeley presented and discussed major trends in Minnesota's climate at the Climate Adaptation Summit, December 3, 2009. Those highlighted here are most relevant for this report given their potential socio-economic significance. Again the focus is on implications for water resources.

1. Changing character and quality of precipitation: there is an increasing proportion of annual precipitation coming in summer thunderstorms and these have more spatial variability than other precipitation events,
2. Warmer winter minimum temperatures,
3. Higher summer heat indices due to higher humidity and higher ambient air temperature,
4. Increase in the number of freeze/thaw days

Dedaser-Celik & Stefan (2009) analyzed trends in streamflow in Minnesota since 1946 using gauges from five different river basins across the state. The trends observed matched many predicted by other climate change literature such as increased high flow due to increased runoff. While extreme flood events have not increased, flows over a wide range of recurrence intervals have either increased over time or remained the same. These researchers did determine that rivers located in areas with higher rates of precipitation showed increases in streamflow.

Selected findings from the five basins are:

<u>Flow Duration Curves</u>. The Minnesota River Basin has experienced the largest stream flow changes in the last 20 years compared to the other four basins. High, medium, and low flows have increased significantly from the 1946-1965 to the 1986-2005 period (on average Q50 increased by about 200%). The increases in medium to low flows were larger than the increases in high flows. Considerable changes in flows were also observed in the Upper Mississippi River Basin and the Red River of the North Basin (on average Q50 increased by about 80%).

<u>High and Low Flow Ranking</u>. Both annual peak flows and 7-day average low flows were higher in the 1986-2005 period in the Minnesota River Basin, Red River of the North Basin, and Upper Mississippi River Basin. Increases in observed 7-day average low flows were more significant than increases in observed annual peak flows.

<u>Flood Frequency Analyses</u>. Separate flood frequency analyses were conducted on the stream flow data from the 36 stream gauging stations for the (1946-1965) and the (1986-2005) periods to identify changes in the 1-, 2-, 5-, 10- and 25-yr floods. The results were most consistent for the Red River of the North Basin. In this basin, magnitudes of the 2- to 25-yr floods increased at all six stream gauging stations (average increases were from about 30 to 60%) and the magnitude of the 1-yr flood decreased (average of 20%).

The river basins which showed the largest increases in stream flows (Minnesota River Basin and

Red River of the North Basins) drain regions (climate divisions) where significant increases in precipitation have been observed. Agricultural drainage and changes in crop patterns are other potential causes that need to be considered."

Ice Duration Analysis

Virginia Card (2010) provided findings from the dataset on dates of ice formation and ice thawing on 40 lakes from 1970 to 2008. The average number of days of ice duration lost or gained over this period was also calculated. It was found that lake ice duration in the Minnesota sample is significantly decreasing at a mean rate of 3.3 days per decade from the time period of 1970 to 2008.

Fish Habitat Changes and Fish Abundance Shifts

Two separate Minnesota studies have examined the impacts of climate change on freshwater fisheries. In the first study, Schneider, Newman, Card, Weisber, and Pereira (2005) examined the impacts on changing ice-out conditions in Minnesota on walleye spawning timing. The researchers found that for every one day decrease in the presence of lake ice there was a .5 to 1 day decrease to the day that a walleye lays its eggs. These authors postulated that this may have an impact on the well-being of the fishery if there is a mistiming in the availability of prey with a change in spawning timing.

In the second study, Schneider, Newman, Weisberg, and Pereira (2009) examined the current trends in fish communities in response to changing climate in Minnesota. Several temperature variables were compared with the abundance of species in 35 different lakes. These researchers discovered that the majority of fish species were expanding their range northward except smallmouth bass. In addition, these researchers discovered that increases in average summer temperature were correlated with increases in largemouth bass and sunfish abundance. Moreover, increasing air temperature was correlated with a decrease in the abundance of whitefish and trout.

Water Quality

The project team includes researchers focusing on trends in water quality in Minnesota lakes. Axler et al. (2009) provided online resources to access a voluminous database that they developed for water quality parameters from over 630 MN lakes. Lakes selected had more than 15 years of data for at least one water quality measure involving 1.9 million records. Major findings from their analysis of the data include: (pages 12-16)

"In the context of the climate change issue that spawned the present study, the most important result derived from the exploratory trend analyses has been that for lakes with significant time trends during the summer, more than 90% showed surface water warming as compared to cooling."

"*Warmer growing season air temperatures have generally been predicted to decrease the depth of the thermocline (i.e. creating a shallower epilimnion) in most lakes as a consequence of increased warming of the epilimnion and increased thermal stability. Although only 16% of lakes with >5 years of data had significant trends in thermocline depth, 85% of those that did,* *exhibited decreasing (i.e. shallower) thermocline depths."*

"The salt content of surface waters and chloride concentration has increased over time in more than a third of the lakes with >5 years of data, 50% of those with >8 years, and 90% with >18 years of data. This is consistent with increased summer surface warming but also with potential increased exposure to winter de-icing salts and/or increased stormwater runoff from either urban or agricultural areas."

"Perhaps the most surprising result found in this study was that there was internal consistency within the group of trophic status indicators (secchi depth clarity, chlorophyll-a, total phosphorus and total Kjeldahl nitrogen) that suggests a strong overall improvement in water quality."

There are countervailing trends at play here, such as reduced industrial discharges and nutrient reductions from some non-point sources, while increasing population and intensity of development in many lakesheds heightens impacts. A myriad of watershed impacts must be juxtaposed with effects of climate change. It is extremely difficult to isolate the impact of climate change separately.

Despite these mixed results on trends in Minnesota water quality, it is extremely important to consider potential impacts of climate change given the importance of the resources at stake. The current impaired waters list in Minnesota includes over 1,000 lakes and 400 rivers. Indeed preliminary efforts to improve these conditions, i.e. point and non-point pollution reduction efforts that have existed for decades, should be part of the positive changes evidenced by these project findings. A related, major concern for the future of Minnesota waters is the threat of invasive species. Climate change can be a contributing factor to a worse future for Minnesota's surface waters, such as impeding improvements from ongoing efforts.

Conceptual Framework for Inferring Economic Impacts

Potential economic impacts of climate change must be understood within the conceptual framework about what people value. Environmental economics identifies two major conceptual components of value: use values and passive-use value. The theory and practice has developed toward the conventional wisdom that only recognizing use values in evaluating environmental effects would lead to substantial underestimation of value to the public.

It is also worthwhile to relate conceptual components of value to the benefits estimation techniques available to measure them. Benefits estimation must be grounded in measurement of market and non-market Values. Market values ideally measure willingness-to-pay (WTP) based on derivation of the market demand curve. Actual expenditures are a lower-bound estimate of WTP in that consumer surplus would be missed. Non-market values are not directly revealed in market transactions. Purchases of items, such as bird-watching equipment, can indicate people's values for these activities. Existence values are most often measured through direct statements rather than being revealed through market choices.

In terms of water resources, some of the major **market values** that could be impacted are:

- recreational fishing,
- commercial fishing,

- commercial transportation on waterways,
- agricultural irrigation,
- infrastructure damages from flooding (drinking water, wastewater, and stormwater facilities, roads, bridges, culverts, and other structures),
- flood damages to crops, forests and other lands with commercial yields
- hydroelectric power generation,
- water-borne diseases
- insurance costs

In terms of water resources, some of the major **non-market values** that could be impacted are:

- water quality
- fish habitat
- preservation of "natural" distribution of cold-water species such as lake trout and cisco
- preservation of native aquatic plants
- preservation of "natural" levels of surface waters

Reducing the risk to water resources from climate change also generates a risk-aversion premium defined as option value. It is analogous to the motives for profit-generating insurance premiums being willingly paid to insurance companies. An important distinction is that option value accumulates to all individuals that are averse to these risks. So benefit accumulates simultaneously to all of these individuals due to policies that reduce these risks. This collective benefit fits the definition of a public good

Option value applies more widely to climate change impacts than just to water resources. In fact it addresses a fundamental aspect of the potential economic loss from climate change. Statisticians characterize distributions with measures of Central Tendency and Dispersion. Much of the concern about climate change impacts has focused on increases in measures of Central Tendency such as higher average temperatures of higher mean precipitation. But from a socio-economic perspective the potential damages linked to increasing dispersion, such as more extreme temperatures or precipitation patterns may be just as damaging to social and economic well-being. The concept of option value is fundamental to understanding the economic impacts of climate change.

Sustainability and the Precautionary Principle are crucial concepts to consider in understanding the economic aspects of climate change. The value of water resources and the ecological services provided are so large as to indicate that it would be economically efficient to incur substantial costs to avoid these losses. As the USEPA document "National Water Program Strategy: Response to Climate Change" suggests, large costs to reduce other bad actions that compromise drinking water or surface water quality may be warranted to offset the degradation that could be anticipated from climate change. For example, it may be economically efficient to invest in land-use changes and/or wastewater treatment that reduce nutrients so that climate change does not put us over the threshold toward lower water quality.

If an economic standard is met indicating that the benefits of protecting water quality against degradation from climate change are worth the costs, the next decision criterion would be to achieve these benefits at minimum cost. In order to protect these water resources, the costs of countervailing measures would need to be compared to the costs of reducing greenhouse gas emissions as root causes of these problems.

The evidence on climate change impacts suggests that irreversible damages could occur. Good policy formulation can provide flexibility to alter future pollution abatement investments. Human/social decisions should be more reversible than many environmental impacts; damages to ecosystems, loss of native species, etc. There are severe risks from disrupting energy flows in an ecosystem so that outcomes from the processes related to the First and Second Laws of Thermodynamics degrade ecological goods and services. Most importantly, climate change poses the risk of loss of human life. These risks are seen by this analyst as being much greater and more difficult to monetize than expenditures on pollution control devices.

Concepts of intergenerational equity are central to applying sustainability to the issue of climate change. One view of intergenerational equity relates closely to the Anishinaabe ethic of "The Seventh Generation." Similar environmental ethics can be found in various indigenous cultures around the world and generally imply that actions today must be in the interest of those seven generations into the future. Current generations of indigenous peoples face unusual threats from climate change. Traditional practices that depend on natural process and ecosystem services may disappear with disruption from climate change. The most vulnerable groups across many societies are likely to suffer the greatest losses from climate change. For indigenous people in regions around the planet attempting to live in traditional ways, climate change may put those ways of life in jeopardy.

Survey of the Literature on Economic Impacts of Climate Change

The Stern Review (2006) made extensive arguments as to why it would be economically efficient and equitable to take immediate action to reduce GHG emissions. One of his equity positions was that the long-term consequences of climate change make discounting unfair to future generations, being future impacts would be severely diminished in relative importance compared to current impacts. Stern estimates losses in terms of global gross domestic product (GDP). He also estimates the percentage of global GDP that would be needed to fend off the worst of future impacts. More detail on the Stern Review is provided in the annotated bibliography presented in Appendix D.

The methods and conclusions of the Stern Review have been subjects of substantial disagreement in the economics literature. Stern served a constructive purpose in stimulating enlightening discussion. Heal (2008) summarizes the economics literature on climate change as follows: "I suggest that the recent debate has clarified many important issues, and that we are now in a position to identify those conditions that are sufficient to make a case for strong action on climate change. However, more work is needed before we can have a fully satisfactory account of the relevant economics. In particular, we need to better understand how climate change affects natural capital - the natural environment and the ecosystems comprising it - and how this in turn affects human welfare."

Implications of climate change for the insurance industry were the subject of a great deal of analysis in the late 1990's. In an article on global change, Berz (1999) speculates that "changing probability distributions of many processes in the atmosphere" will result in "serious consequences for all types of property insurance." "In areas of high insurance density the loss potential of individual catastrophes can reach a level at which the national and international insurance industries will run into serious capacity problems." Three insurance industry experts, Mills, et al. (2001) estimate a 15-fold increase over the period 1970 -2000 in insured losses from catastrophic weather events (defined as exceeding $1 billion of damages.)

The focus of the workplan on water resources within the state leads to emphasis on the three categories of environmental impacts below. The major mechanisms for economic impacts to occur are included.

1. Lake and stream levels: flood damages, especially to infrastructure
2. Water temperatures: shorter ice duration, changes in fish populations, habitat, winter and summer kills
3. Water quality: multiple values of clean water

There is a great deal of evidence that water quality is extremely important to Minnesota, The value of water quality is manifested in recreational and tourism activities, property values for lakeshore, investments in policies to protect water, and other ways in which citizens demonstrate WTP and the role of water in the MN quality of life. The evidence of historical trends on water quality in MN lakes yields mixed results, with general trends toward improving water quality measures. It is difficult to isolate potentially negative impacts of climate change on lake water quality from the backdrop of other complex processes that are having a net positive effect.

If climate change has a negative impact on thousands of lakes within the state, the loss of economic value would be substantial. These assets (natural capital) would me much less valuable to MN than they otherwise could be. For a thousand lakes that might be degraded from climate change, the loss could be in the tens of billions of dollars. Time will tell what kinds of relative changes will result in light of other positive and negative processes impacting water quality, but the evidence in the literature indicates climate change is likely to have a negative net effect.

Potential Economic Effects of Changes in Minnesota's Water Resources

Research efforts on the implications of climate change for MN are in the early stages. Hence it is appropriate that economic analyses focus on advancing conceptual understanding. Economic analysis depends on underlying science describing the environmental effects to be valued. Evidence is emerging, and this overall project advances the science, but limited data make empirical evidence somewhat preliminary. The statistically meaningful trends in climate patterns on temperatures and precipitation do imply changes in water resources in MN: some resource changes are currently identifiable, others will take longer to reveal. Empirical economic analyses are reported here that match the strongest findings thus far.

Empirical economic analyses were performed on two impacts to MN water resources: 1) magnitudes and types of infrastructure damages due to weather-related events, particularly floods and 2) the trend toward shorter ice duration on MN lakes. This is likely to affect recreational fishing which is extremely important to MN.

The longest yearly record for weather-related damages in MN comes from figures reported in a NOAA study (2002) that re-examines damage figures from 1925-2000. Figures are provided state-by-state from 1955 to 2000. From 1955-2000 occasional weather events caused damages (in constant 1995 dollars) in the tens of millions of dollars. Damages in the hundreds of millions of dollars also occurred over this time period. By far the two years with the highest damages were 1997 and 1993. The floods of 1993 caused damages in excess of $1 billion in constant 1995 dollars.

The MN Department of Public Safety's Division of Homeland Security & Emergency Management provided summarized damage information over the past two decades. The damage figures for the 1990s are contained in a report "A Decade of Minnesota Disasters: A Historical Look at Minnesota Disasters in the 1990s." According to the report, these damages are increasing and during the 1990s there were 14 presidential declarations of major disasters. Most of the damages were the result of flooding, ice storms, snow removal, straight-line winds, tornadoes, and heavy rain. From the disasters of the 1990s, Minnesota taxpayers spent $827 million and the cost to insurance companies was more than $2 billion.

Analysis conducted by Virginia Card as part of the larger project found that ice duration is getting shorter in the state. The trend analysis indicated that ice-duration has on average been getting shorter by a third of a day in a typical year, or 3.3 days over the course of a decade. A direct socio-economic impact of shorter ice duration will be the switch of recreational days for ice-related activities to open-water activities. The change in environmental conditions will cause positive and negative effects on opportunities for recreation. Patterns of gains and losses will impact different groups and different communities differently. Certainly activities dependent on ice and snow are likely to suffer based on climate evidence. Indirect socio-economic effects are also likely to occur from shorter ice duration as one aspect of changing conditions in the aquatic ecosystem. There is an important linkage between ice-on/ice-off periods, limnological conditions/water quality, fish habitat and species distribution/abundance.

Creel survey data includes variables on the time respondents spent fishing, catch rates and other aspects of the fishing experience Shorter ice duration can reasonably be expected to diminish the benefits the public enjoys from ice fishing. Since some MN lakes, most notably Upper Red Lake, see higher use in winter months, the onset of climate change through decreasing lake ice will likely have a net negative impact on recreational benefits from use of these lakes.

Seasonal patterns of use were examined for other large walleye lakes in the state. These generate a very large portion of the overall fishing activity in the state. In contrast to Upper Red Lake, other large walleye lakes (and statewide data for smaller lakes) show that summer effort significantly exceeds effort in the winter. A higher amount of angler effort in the open-water season is likely to lead to a net positive impact from the onset of climate change.

An additional empirical question investigates whether changes already occurring in species distribution and abundance are leading to changing patterns of fishing effort. The results from the multiple regressions did not show significant results for a change in yield per unit of effort in response to change in species abundance over certain regions of the state over time. Nor did they indicate increasing effort thus far in areas where yields might be expected to increase in the future as certain species become more abundant. As mentioned in the literature, certain species, such as trout, have a higher WTP than walleye and panfish. Therefore, a change in these species abundances could have a significant impact on the WTP by anglers. For example, fewer trout (which are predicted to decline from climate change) would be detrimental to recreational benefits. The net impact from these changes in species abundance and the economic consequences cannot be estimated given current limitations of available data.

Further Conclusions

The relative emphases of the economic analyses and the empirical estimation are dependent upon the findings of the other environmental components of this research effort. To a certain extent, the findings on environmental impacts at this juncture are predicated on available data that are constrained in both temporal and spatial scale. So while evidence is mounting that Minnesota's water resources are vulnerable to the effects described in the workplan (higher surface water levels/streamflow, increased sedimentation, degraded water quality, infrastructure implications) some of the more extreme impacts anticipated at the global or regional scale are difficult to detect statistically at the smaller statewide scale. This is due in part to lack of small spatial scale data over the length of time needed to detect statistically meaningful trends.

MN should adopt a two-pronged approach to risk management to the degree that MN can inventory watersheds for the combination of two groups of characteristics. A convergence of two characteristics that cause greatest vulnerability to damages from flash floods should be inventoried. Watersheds most vulnerable to damages have: transportation infrastructure 1) geomorphology conducive to flash floods and 2) human and natural environments that put highly valued assets and human life in harm's way.

The economics literature on risk-aversion should inform decisions on climate change. The potential damages from climate change are the types of risks that people typically wish to guard against. Most citizens place a value on risk reduction and are willing to pay for the insurance value this yields. Public policy that provides this is a public good to all those who have risk-averse preferences. It is a collective value derived from the sort of individual value many people place on private insurance. Fundamental aspects of climate change involve risks and this conceptual economic approach is enlightening.

SECTION I.
INTRODUCTION AND BACKGROUND

A. Purpose of the Study and the Overall Research Project

This report contains the economic component of a larger research project directed by the University of Minnesota, Natural Resources Research Institute. According to the project 2007 LCCMR Workplan, the overall purpose is "to quantify climate, hydrologic, and ecological variability and trends, along with economic impacts of environmental fluctuation on water resources, and to identify indicators of future climate change effects on aquatic systems. This report presents economic conceptualizations of climate change as a policy challenge and empirical findings on "economic impacts of environmental fluctuation on water resources."

Further background on the overall project is provided in the following excerpts from the "Project Summary and Results." "Minnesota's climate has become increasingly warmer, wetter, and variable, resulting in unquantified economic and ecological impacts. More recent changes in precipitation patterns combined with urban expansion and wetland losses have resulted in an increase in the frequency and intensity of flooding in parts of Minnesota with extensive and costly damage to the State's infrastructure and ecosytems. We are examining historic climate records and developing a database of key climatic measures and their variability in a current LCCMR project "Impacts on Minnesota's aquatic resources from climate change". To assess the consequences of past climate trends on aquatic resources we are analyzing hydrologic, water quality, and fish community responses. We propose to expand that study to develop prediction for future climate specific to Minnesota, and then quantify the potential economic impact of climate-induced changes in precipitation and hydrology on the water resource infrastructure, including storm sewers, bridges, water treatment facilities, and shoreline development."

The economic asessment (Result 1 of the Workplan) is described as follows: "Economic assessment of potential impacts on water resource infrastructure. Description: Recent changes in precipitation patterns, combined with urbanization, wetland loss, and increased tile drainage have resulted in higher riverine base flows in Minnesota, compared to historic averages. These changes are associated with increased flood frequency and intensity. The economic impact of such floods has been substantial. We will use data from our current LCCMR project, along with the outcome of Result 2 to quantify the economic cost of flooding and degraded water quality and assess infrastructure changes needed to meet future climate projections (Result 2). Outcome: An economic analysis of floods and the cost of water quality protection and infrastructure needs under changing climatic conditions. The analysis will include estimates of flood damages to physical and natural assets, including costs due to increased sedimentation of surface waters using market valuation techniques. Damages to water quality will also be estimated using benefits transfer based on evidence from the literature on the public values of water quality. Costs to mitigate damages from flooding and reduced water quality will also be quantified using engineering costs and market values."

The relative emphases of the economic analyses and the empirical estimation are dependent upon the findings of the other environmental components of this research effort. To a certain extent, the findings on environmental impacts at this juncture are predicated on available data that are constrained in both temporal and spatial scale. So while evidence is mounting that Minnesota's water resources are vulnerable to the effects described in the workplan (higher surface water levels/streamflow, increased sedimentation, degraded water quality, infrastructure implications) some of the more extreme impacts anticipated at the global or regional scale are difficult to detect statistically at the smaller statewide scale. This is due in part to lack of small spatial scale data over the length of time needed to detect statistically meaningful trends.

For example, one specific finding is that increased streamflows and flooding appear to be occurring but the data make this difficult to detect at the level of watersheds or tributaries and at the extremes of 100 or 500 year floods. Consequently, the economic analysis focuses on increased frequency of "moderate" floods consistent with the hydrological evidence, even though damage estimates seem to indicate that more severe floods are increasing in frequency.

The recent history on water quality trends presents "a mixed bag" of results that are environmental outcomes from a complex set of variables and processes that are impacting the quality of Minnesota's surface waters. Again the analytical frameworks and available data make it difficult to disaggregate current and future impacts of climate change from other positive and negative impacts on water quality. The historical record shows the net effect on water quality of these simultaneously occurring impacts. So it is extremely difficult to isolate the impact of climate change separately. Water quality changes and other potential impacts of climate change on Minnesota's water resources that may occur - according to national and international evidence - are discussed at a conceptual level in order to include these risks in the discussion without devoting scarce resources to empirical analysis prematurely.

The empirical analysis in this report does indicate worsening trends in infrastructure damage based on multiple data sets through time. On the other hand, the work of researchers on other components of the project found impacts that were more significant than anticipated in the initial workplan, such as shorter lake ice duration and changing range and abundance of certain species of fish. So the economic analyses reported here have been adjusted (less attention in some areas, more in others) to reflect the evidence of climate change impacts that has emerged from this project. Greater resources, time and effort within the economic analysis have been placed on those impacts on water resources that can be demonstrated from the available data rather than impacts that may or may not be occurring but cannot be discerned from available data.

B. Limits to the Scope of the Study Relative to Global Climate Change

Efforts to enhance understanding of climate change and its potential impacts within Minnesota benefit immensely from research that has been and is being undertaken at other levels within a variety of institutional settings – academia, research institutes, state, national and international entities, etc. Global climate change is seen by many as one of the most important and complex challenges humankind has ever confronted. Any economic analysis of climate change impacts needs to consider this broad context of potential global impacts as all could alter the economic setting within which we participate in the global economy as part of our daily lives. The foundation for understanding and addressing economic impacts as part of a sustainable future requires that no major climate change impacts be excluded from the discussion. Still, it is beyond the scope of this research with a Minnesota focus to thoroughly address the broader global economic issues. Section II alludes to the broad literature on global climate change and likely impacts in relation to Minnesota's place in regional, continental and global changes.

This overall project is bringing to bear evidence on the question of impacts Minnesota is experiencing or is likely to experience among the global impacts that are being documented in the international research literature. So it is important to cite some of the main sources on these global impacts such as the Intergovernmental Panel on Climate Change (IPCC), the United States Environmental Protection Agency (USEPA), the National Oceanic and Atmospheric Adminstration (NOAA), the National Science Foundation (NSF). Findings from these and other sources are highlighted in Section II.

The previous sub-section provides details on the scope of the broader study and the economic component within the workplan. While the literature covers myriad impacts of climate change, the workplan serves to establish the focus on water resources. The title of the project reflects this well: "Minnesota's Water Resources: Impacts of Climate Change." The economic discussion below refers to the broad array of impacts of global climate change that are discussed in the literature. Impacts that do not involve water resources are discussed on a conceptual level only within the economic context of sustainability. A major strategy that is offered applies to both water impacts and other potential consequences: wise investment should be pursued in "insurance policies" to manage societal risk from potential climate change impacts at an "acceptable" level.

The report is outlined as follows: II. The Scientific Context for Climate Change Impacts on Minnesota Resources, III. Specific Findings on Climate Change Impacts on Minnesota's Water Resources, IV. Conceptual Framework for Inferring Economic Impacts, V. Survey of the Literature on Economic Impacts of Climate Change, VI. Potential Economic Effects of Changes in Minnesota's Water Resources, and VII. Summary and Conclusions.

SECTION II.
THE SCIENTIFIC CONTEXT FOR CLIMATE CHANGE IMPACTS ON MINNESOTA RESOURCES

A. Categories of Impacts Globally

Conducting economic analysis of potential impacts of climate change requires familiarity with the scientific evidence on the types of environmental changes that could result from climate change. The team assembled for this project has multi-disciplinary expertise. The findings from other team members set the foundation for the effects on water resources that provide the core of this study. Before highlighting the specific findings from the project later in this section, an overview of the literature on impacts is needed to provide a broad context for the types of socio-economic influences that could occur.

One of the most widely cited sources is the Intergovernmental Panel on Climate Change (IPCC). The IPCC does not conduct research per se, but rather serves as a clearinghouse for documents and evidence from an international network of research efforts. For the purposes of this study, primary reliance on sources will be placed on various agencies of the United States government. The US Environmental Protection Agency (USEPA), National Oceanic and Atmospheric Administration (NOAA) and the US Department of Transportation (USDOT) provide a wealth of documentation on climate change and potential impacts on the environment and infrastructure. One excellent source of information on climate change is the Office of Global Change, which emphasizes climate change as a topic. Descriptions of impacts from this source as well as the USEPA Office of Water provide background with a focus on water resources. In the interest of the length and flow of the body of this report, descriptions from other key sources are detailed in Appendix A.

According to USEPA Office of Water 2008*"Climate change will have numerous and diverse impacts, including impacts on human health, natural systems, and the built environment. Many of the consequences of climate change relate to water resources, including:*
• warming air and water;
• change in the location and amount of rain and snow;
• increased storm intensity;
• sea level rise; and
• changes in ocean characteristics."

*"1. <u>Increases in Water Pollution Problems</u>**:** Warmer air temperatures will result in warmer water. Warmer waters will:*
• hold less dissolved oxygen making instances of low oxygen levels and "hypoxia" (i.e., when dissolved oxygen declines to the point where aquatic species can no longer survive) more likely; and
• foster harmful algal blooms and change the toxicity of some pollutants.
The number of waters recognized as "impaired" is likely to increase, even if pollution levels are stable.
*2. <u>More Extreme Water-Related Events</u>**:** Heavier precipitation in tropical and inland storms will increase the risks of flooding, expand floodplains, increase the variability*

of streamflows (i.e., higher high flows and lower low flows), increase the velocity of water during high flow periods and increase erosion. These changes will have adverse effects on water quality and aquatic system health. For example, increases in intense rainfall result in more nutrients, pathogens, and toxins being washed into waterbodies.
*3. Changes to the Availability of Drinking Water Supplies**:** In some parts of the country, droughts, changing patterns of precipitation and snowmelt, and increased water loss due to evaporation as a result of warmer air temperatures will result in changes to the availability of water for drinking. In other areas, sea level rise and salt water intrusion will have the same effect. Warmer air temperatures may also result in increased demands on drinking water supplies and the water needs for agriculture, industry, and energy production are likely to increase.*
*4. Waterbody Boundary Movement and Displacement**:** Rising sea levels will move ocean and estuarine shorelines by inundating lowlands, displacing wetlands, and altering the tidal range in rivers and bays. Changing water flow to lakes and streams, increased evaporation, and changed precipitation in some areas, will affect the size of wetlands and lakes, including the Great Lakes.*
*5. Changing Aquatic Biology**:** As waters become warmer, the aquatic life they now support will be replaced by other species better adapted to the warmer water (i.e., cold water fish will be replaced by warm water fish). This process, however, will occur at an uneven pace disrupting aquatic system health and allowing nonindigenous and/or invasive species to become established. In the long-term (i.e., 50 years), warmer water and changing flows may result in significant deterioration of aquatic ecosystem health in some areas.*
6. Collective Impacts on Coastal Areas: Most areas of the United States will see several of the water-related effects of climate change, but coastal areas are likely to see multiple impacts of climate change. These impacts include sea level rise, increased damage from floods and storms, changes in drinking water supplies, and increasing temperature and acidification of the oceans." USEPA Office of Water (2008), pages i-iii of Executive Summary.

"Impacts should be expected to vary regionally, but in general, climate change could result in increased demands on our infrastructure systems, both in terms of O&M costs and the need for capital expenditures. The suite of expected impacts can be grouped according to the type of change a system may face and fall roughly into the following categories:
• more water (through increased precipitation and storm intensity) and sea level rise;
• less water, with increased frequency and duration of drought;
• temperature change; and
• damage from more intense storms." USEPA Office of Water (2008), page 51.

"The impacts of climate change present ongoing challenges for the Agency's emergency response program. The possibility of more frequent and severe storms and flooding due to climate changes, along with the continued threat of terrorist attacks on our water and wastewater infrastructure, calls for a coordinated approach. To address this

challenge, EPA has developed an agency-wide approach that identifies roles and responsibilities for Regions and Headquarters. The EPA approach incorporates an Incident Command System (ICS) that provides a set of core concepts, terminologies, and technologies common to all federal agencies." USEPA Office of Water (2008), page 53.

The US Global Change Research Program reports impacts by sectors. Details are quoted in Appendix A. Sectors listed are: Water Resources, Energy Supply and Use, Transportation, Agriculture, Ecosystems, Human Health, and Society. Given the focus of this project, greater detail is paid to statements on the website about water resources.

Water Resources *"Climate change has already altered, and will continue to alter, the water cycle, affecting where, when, and how much water is available for all uses."* page 41

"Floods and droughts are likely to become more common and more intense as regional and seasonal precipitation patterns change, and rainfall becomes more concentrated into heavy events (with longer, hotter dry periods in between)." Page 44

"Precipitation and runoff are likely to increase in the Northeast and Midwest in winter and spring, and decrease in the West, especially the Southwest, in spring and summer." . . .

"In areas where snowpack dominates, the timing of runoff will continue to shift to earlier in the spring and flows will be lower in late summer." Page 45

"Surface water quality and groundwater quantity will be affected by a changing climate." Page 46

"Climate change will place additional burdens on already stressed water systems." Page 47

"The past century is no longer a reasonable guide to the future for water management." Page 49

As a transition from the water sector to the other sectors, the US Global Change Program report discusses how water impacts will be interconnected to effects in other sectors. Highlights of the section Water-Related Impacts by Sector are:

"Human Health - Heavy downpours increase incidence of waterborne disease and floods, resulting in potential hazards to human life and health.

Energy Supply and Use - Hydropower production is reduced due to low flows in some regions. Power generation is reduced in fossil fuel and nuclear plants due to increased water temperatures and reduced cooling water availability.

Transportation - Floods and droughts disrupt transportation. Heavy downpours affect harbor infrastructure and inland waterways. Declining Great Lakes levels reduce freight capacity.

Agriculture and Forests - Intense precipitation can delay spring planting and damage crops. Earlier spring snowmelt leads to increased number of forest fires.

Ecosystems - Coldwater fish threatened by rising water temperatures.
Some warmwater fish will expand ranges."

Excerpts from other sections of the US Global Change Program report on potential climate change impacts on Energy Supply and Use, Transportation, Agriculture, Ecosystems, Human Health, and Society are provided in Appendix A.

Foreshadowing the economic discussion below is the following statement from the National Climatic Data Center (NCDC.) *"The National Climatic Data Center (NCDC) is the "Nation's Scorekeeper" in terms of addressing severe weather events in their historical perspective. As part of its responsibility of "monitoring and assessing the climate," NCDC* *tracks and evaluates climate events in the U.S. and globally that have great economic and societal impacts. NCDC is frequently called upon to provide summaries of global and US temperature and precipitation trends, extremes, and comparisons in their historical perspective."*

The report goes on to describe weather events that have had the greatest economic impact since 1980. *"The U.S. has sustained 96 weather-related disasters over the past 30 years in which overall damages/costs reached or exceeded $1 billion. The total normalized losses for the 96 events exceed $700 billion."*

Specific Sources on Climate Change and Freshwater Fisheries

Warming climate has the potential to impact the water temperature of freshwater lakes containing fish; Chu, Mandrak, and Minns (2005) showed how different species of freshwater fish were impacted from global climate change in Canada. A number of different variables were indicated to have a potential effect on freshwater fish populations. These researchers chose a select group of species (brook trout, walleye, and smallmouth bass) and attempted to model the effects on each population from the interaction of several variables. Variables of influence were selected by a correlation matrix. The model combined these variables to predict the occurrence of a species by region. For example, dew point, growing degree days, precipitation, and average hourly wind speed were included for determining the presence of walleye. This source indicated that cool water species will be threatened by warming water temperatures. These researchers further determined that previously existing warm-water species may expand their range northward, which may cause disruptions in previously existing population dynamics. For example, walleye and smallmouth bass may extend their range northward and prey upon previously undisturbed species.

These impacts that may occur are primarily due to changes in water temperature and changes in the levels of nutrients that may be present in the water bodies (Ficke, Myrick, & Hansen, 2007; Lettenmaier, Major, Poff, & Running, 2008). Changes in water temperature have been predicted to occur due to interactions between the changing air temperature and the surface water temperature (Lettenmaier et al., 2008). Changing the surface water temperature was predicted to cause a change in the amount of dissolved oxygen (DO) that is present in a water body (DeStasio, Hill, Kleinhans, Nibbelink, & Magnuson, 1996). Changing the amount of DO and its effects on fish populations was illustrated by Ficke, Myrick, and Hansen (2007) who illustrated that variables such as oxygen content and temperature have an effect on the well-being of fish populations. Stefan, Fang and Eaton (2001) reached similar findings for North American lakes.

B. Categories of Impacts in Minnesota

Discussions of potential impacts in Minnesota are provided by the MPCA, the MN DNR and the MN Sea Grant Office. Noteworthy assessments of climate change impacts in our region have also been provided for Wisconsin by the Wisconsin Initiative on Climate Change Impacts (WICCI.)

The MPCA climate change website states: *"Minnesota is already experiencing impacts from climate change, and will continue to experience impacts to our ecosystems, natural resources, and infrastructure."* The MPCA website quotes the US Global Change report which highlights Key Impacts in the Midwest:

- *During the summer, public health and quality of life, especially in cities, will be negatively affected by increasing heat waves, reduced air quality, and increasing insect and waterborne diseases. In the winter, warming will have mixed impacts.*
- *The likely increase in precipitation in winter and spring, more heavy downpours, and greater evaporation in summer would lead to more periods of both floods and water deficits.*
- *While the longer growing season provides the potential for increased crop yields, increases in heat waves, floods, droughts, insects, and weeds will present increasing challenges to managing crops, livestock, and forests.*
- *Native species are very likely to face increasing threats from rapidly changing climate conditions, pests, diseases, and invasive species moving in from warmer regions.*

The MN DNR has constructed an informative webpage on climate change strategies. In discussing the importance of climate change the DNR webpage states: *Climate change poses great challenges to natural resource management. It is impacting the health and productivity of lands and waters and the animals and plants that depend on them, and will exacerbate other threats from habitat loss and invasive species. It threatens the services natural lands provide—from clean water and forest products to outdoor recreation."*

"<u>*Increasing need to adapt to climate change*</u>***:*** *Minnesota ecosystems will be in transition over the next 50 to 100 years. Managers must find new ways to sustain the health, diversity, and productivity of ecosystems in the face of climate change.*

<u>*Warming waters*</u>***:*** *Climate change is expected to cause major changes in lakes and streams. Warming waters could shrink the number of trout streams and lake trout and cisco lakes, push walleye and northern pike populations northward, and expand the distribution of bass and panfish populations.*

<u>*Drying wetlands*</u>***:*** *Wetlands are projected to become drier, altering plant communities and degrading waterfowl and other wildlife habitat.*

<u>*Shifting forests*</u>***:*** *The range of major northern tree species such as black and white spruce and balsam fir is projected to shift northeastward out of the state if warming trends continue over the next 100 years. Forests may become savannas, and hardwood forests may persist mainly on north-facing slopes in some areas.*

<u>*Recreation and tourism*</u>***:*** *Recreation will be affected by changed winter weather, loss of habitat, and shifts in fisheries and wildlife populations."*

The Wisconsin Initiative on Climate Change Impacts (WICCI) is composed of a number of working groups on climate change. Their work is reported on a website. (For URL address, see Reference section at the end of this report.) The section on stormwater on the WICCI website is very relevant for economic analysis. The recommendation on adopting a risk/consequence approach to infrastructure planning in general and stormwater investment, in particular, is similar to the precautionary principle and the risk-aversion concepts discussed later in this report. The quote below is very relevant for this LCCMR project:

Stormwater *"Wisconsin's climate is changing. Wisconsin's cities and towns must also change how they manage their water resources if they are to adapt to the increases in rainfall and groundwater elevation we are already seeing. The Stormwater Working Group has brought together Wisconsin water resource managers to find ways to reduce risk to our communities and improve our stormwater management infrastructure."*

To highlight "Vulnerabilities" the website states:
Local and state government and private sector developers make significant investments in long-lived infrastructure that controls or is affected by stormwater runoff from large rainfalls. Likewise, municipal waste water treatment plant operators make substantial long-term investments in their system capacity that anticipates development, but not increased stormwater inflow and groundwater infiltration. This infrastructure is designed using standards based on rainfall data from the latter half of the 20th century. By having assumed "stationarity" of climate in the design of our infrastructure, we are now vulnerable to the following impacts from more intense rainfall events and elevated groundwater:

- *Conveyance systems filled beyond capacity cause flooded homes and urban streets;*
- *Roadways and bridges are washed-out or become impassable;*
- *Groundwater flooding of property and cropland increases;*
- *Rural residential wellheads are contaminated by flood waters and high groundwater;*
- *Impoundments and stormwater detention ponds fail more frequently;*
- *Raingardens and other biofiltration BMPs fail due to saturated soil conditions;*
- *Increased erosion of slopes by intense rainfall events leads to high sediment and phosphorus loading to surface waters;*
- *Runoff of manure from fields, and accompanying fish kills, are more frequent;*
- *Storm water inflow and groundwater infiltration to sanitary sewers, results in untreated municipal wastewater flowing into to lakes and streams.*

In summary, our previous investment in public safety and environmental protection risks being overwhelmed by precipitation impacts that are beyond those anticipated by past infrastructure designers and water resource managers."

This mindset is applied in the section on Adaptation Strategies.
"*There is a growing consensus that scientific knowledge about the potential increase in magnitude and frequency of large rainfalls is sufficient to warrant immediate changes in the methods used to design and manage storm water-related infrastructure." . . .*
"Use a risk/consequence approach to evaluating and modifying existing infrastructure to accommodate observed and predicted changes in climate."

The section on Adaptation Science is insightful, especially in applying the concepts of option value defined in Section IV of this report. *"Now imagine being a city planner or hydrologic engineer responsible for designing and implementing new storm water structures that are meant to last for the next fifty years. If you design these structures based on the weather from the last fifty years, they might lack sufficient capacity to handle rain storms of increasing intensity and frequency, perhaps leading to flooded streets and homes. On the other hand, if you plan for the worst-case scenario even though there is a small probability of it happening, you may over-design the system at a significant cost to the taxpayer if those extreme events do not materialize."*

It is noteworthy that this same challenge of weighing risks of being wrong can be applied to the trade-offs of risks in reducing greenhouse gas (GHG) emissions. Current investments in GHG reductions initiates an "insurance policy" for future decades to reduce the severity of future impacts, but there is a parallel risk in learning through time that these expenditures on emission reductions were less necessary than anticipated. The trade-offs in risks have been described as "Doing too little, too late, or doing too much, too soon." These concepts are covered in Section IV below.

The WICCI Stormwater Group offers Adaptation Science as a type of risk assessment and management. *"This conundrum represents the world of adaptation science. At a fundamental level, there are only two parts to adaptation science; calculating the probability of a future event, and creating contingency plans for those events most likely to materialize. Adaptation should focus on the greatest vulnerabilities. In short, where are the greatest risks if climate changes occur? Identifying these vulnerable locations or situations, and then creating a range of contingency plans, is the focus of many WICCI Working Groups."*

The WICCI report also provides helpful content on Milwaukee and the special risks and vulnerabilities of urban areas. Particularly relevant for this project is the section on coastal communities on Lake Superior and Lake Michigan. Numerous impacts that could result from coastal flooding and coastal erosion are highlighted. Further detail is provided in Appendix A.

The US Global Change Research Program predicts likely impacts on Lake Superior: *"Significant reductions in Great Lakes water levels, which are projected under higher emissions scenarios, lead to impacts on shipping, infrastructure, beaches, and ecosystems. . . .*
Higher temperatures will mean more evaporation and hence a likely reduction in Great Lakes water levels. Reduced lake ice increases evaporation in winter, contributing to the decline. This will affect shipping, ecosystems, recreation, infrastructure, and dredging requirements. Costs will include lost recreation and tourism dollars and increased repair and maintenance costs." pages 117 -122.

The MN Sea Grant Program also discusses likely impacts on Lake Superior. Categories of impacts are:

- *"Lake Superior's surface water temperature in summer has warmed twice as much as the air above it since 1980. Lake Superior's ice cover is diminishing.*
- *Wind speeds over Lake Superior are increasing.*

- *Lake Superior's summer stratification season is longer.*
- *Lake Superior's summer stratification season is longer."*

Another potential impact to water resources in MN is on fish and fisheries. The WICCI website emphasizes the vulnerabilities of coldwater fish and fisheries.
"Coldwater fish, such as Wisconsin's native brook trout, are very sensitive to changes in water temperature and other environmental conditions and may be important ecological indicators for climate change. In addition, native coldwater fish are an integral part of Wisconsin's natural legacy, brook trout in net and coldwater fisheries are a core part of our culture and identity. Anglers make a significant contribution to the local and state economies in pursuit of their passion. In the face of changing climate conditions it is important to assess the potential impacts to coldwater fish and fisheries and implement adaptive management plans to ameliorate climate change impacts on Wisconsin's coldwater streams and inland lakes and their fisheries."

The WIICI document advocates for maintaining the value of fisheries as a public good. It provides an example of an economic approach to maximizing net benefits given constrained resources. The Coldwater Fish Group considers a triage approach described as follows*:*
"A triage approach to the management of coldwater streams may involve classifying streams based on their potential to withstand climate change impacts. Our best, most resilient coldwater streams may be protected from habitat degradation. We may cease to allocate scarce resources to our marginal and least resilient coldwater streams. For those coldwater streams in between, we may allocate habitat restoration money or stocking quotas to those streams most likely to realize benefits in the face of changing climate." Other strategies noted are to establish *"refugia" from high water temperatures and to focus on best land-management practices in the watersheds of coldwater streams to enhance "biological integrity" and "resiliency to climate change impacts."* The underlying concepts for these precautionary approaches are discussed further in Section IV on non-market values and risk aversion premiums. Additional content from the WICCI Stormwater Working Group is provided in Appendix A.

Consistent with the approaches advocated by the WICCI Working Groups, MN should identify settings with the greatest vulnerability to catastrophic failure such as loss of life and property if structures fail. Most of the MN topography does not cause as great of danger of flash flooding as in more mountainous areas. The severe flood in southeastern MN in 2007 demonstrates that the topography of that part of the state makes it more vulnerable to severe flash floods. Elsewhere, overland flooding is more likely to occur rather than the deep rush of water with floods in hills and valleys. The tragedy of loss of life in the June 2010 disaster at the Albert Pike Recreation Area in Arkansas is an example of the type of worst-case scenario from flash flooding. MN should adopt a two-pronged approach to risk management to the degree that MN can inventory watersheds for combination of two groups of characteristics. A convergence of two characteristics that cause greatest vulnerability to damages from flash floods should be inventoried: 1) geomorphology conducive to flash floods and 2) human and natural environments that put highly valued assets and human life in harm's way.

Findings from the component of the project on streamflow reported in Section IIIC below indicate that the Minnesota River Basin and the Red River of the North have larger increases in sreamflow than the other three basins in the state. Even though extreme precipitation events are likely to be randomly located across the state, it would be a wise investment to protect against such disasters in the most vulnerable locations. This would be a sound application of the Precautionary Principle and risk aversion discussed further below in Section IV.

SECTION III.
SPECIFIC FINDINGS ON CLIMATE CHANGE IMPACTS ON MINNESOTA'S WATER RESOURCES

A. Evidence of Climate Change in Minnesota

Climatologist Mark Seeley presented at the Climate Adaptation Summit, December 3, 2009. Major trends in Minnesota's climate were discussed. Those highlighted here are most relevant for this report given their potential socio-economic significance. Again the focus is on implications for water resources.

1. Changing character and quality of precipitation: there is an increasing proportion of annual precipitation coming in summer thunderstorms and these have more spatial variability than other precipitation events,
2. Warmer winter minimum temperatures,
3. Higher summer heat indices due to higher humidity and higher ambient air temperature,
4. Increase in the number of freeze/thaw days

The overall research project included climatic analyses as a foundation for understanding potential impacts on Minnesota's water resources. This component of the research project was conducted by Richard Skaggs and Kenneth Blumenfeld. Findings are summarized in an earlier project report: LCCMR 2005 *Impacts on Minnesota's aquatic resources from climate change, Phase I - W-12*, Result 2: Historic Climate Data. The analysis of climatic regimes or episodes concludes: "Dry summers are likely to be normal or warm, and cool summers most frequently normal for precipitation. Also, warm, wet summers are quite rare. Warm summers tend to be dry or normal, and wet summers tend to have normal, or even cool temperatures. These patterns were consistent throughout the state, for summers, aquatic growing seasons, and for water years. During winter periods, no clear relationships emerged, but also, the differences in the total quantity of water between 'wet' and 'dry' winters was much smaller than for summers." Page 8

The MN Sea Grant findings on changes in climate in the region are as follows:
"*Although the details of regional climate predictions are still crude and model-dependent, it seems likely that around Lake Superior people should expect:*

- *More frequent and intense storms.*
- *Increased climate variability and extremes.*
- *Warmer annual temperatures.*
- *Drier summers (reduction in soil moisture).*
- *Warmer nights. (Minimum or 'overnight low' temperatures have been rising faster than the maximum temperature.)*
- *Warmer winters. (Winter temperatures have been rising about twice as fast as annual average temperatures.)*
- *Similar winter precipitation. (But more will fall as rain.)*
- *Lower water levels in Lake Superior. (Even for scenarios that forecast increases in precipitation, most climate models predict lower water levels for Lake Superior because of increased evaporation.)*

- *Changes in the species composition of both terrestrial and aquatic ecosystems.*
- *Longer growing seasons."*

B. Potential Environmental Changes in Minnesota

Some studies at the national or international level reduce the spatial scale down to the state level. Research for the National Weather Service has categorized weather-related damages by state. A study by Pielke, et al. (NOAA, 2002) estimates the monetized damage estimates from National Weather Service records for each state. This information is aggregated from separate datasets. Information from local regions was added to statewide data in some cases. Damage information spans from 1925 to 2000. Despite some data limitations that are explicitly noted, the document contains useful information. For example, flooding in Minnesota cost over $900 million in 1993 and $700 million in 1997. The annual damage figures for MN from 1955 to 2000 are reported in Section VI. Current and constant dollar estimates are provided.

Research by Lettenmaier, et al. (2008) examines the current relationship between climate change and water. This study projects the near term impacts of global climate change on water resources in the United States for the next 25 to 50 years. Major aspects included are streamflow, evaporation, drought, precipitation, runoff and water quality. Minor focus areas include land use and ground water impacts. In the analysis of streamflow, trends from 393 stations in the US were plotted on maps with statistically significant increases reported in the central portion of the United States, including source stations in Minnesota. Evaporation rates are examined and where net decreases occur plausible explanations are offered, such as being due to increased cloud cover.

Droughts are anticipated to occur more frequently in the West and Southwest. A wetter climate overall is found to occur based on data from 1915 to 2003. Droughts are not projected to affect the central portion of the United States. Regional analysis is conducted for the central portion of the US, which includes Minnesota. Two separate studies have indicated an overall increase in precipitation in this region.

In relation to increased precipitation, runoff rates are explored using USGS statistics on runoff trends from 1901 to 1970. Projection these trends into the future, suggests an overall increase in runoff in the central US. Within this region, there is likely to be an increase in runoff in the Upper Mississippi basin.

Water quality is also examined. Variables such as eutrophication from increased nutrient loads and increased temperature are explored. Nutrient loading may occur from increased runoff and more highly variable heavy precipitation events. Decreased consistent precipitation could cause eutrophication, especially in rivers, from the increased levels of nutrients without adequate consistent flows. Also, nutrients create the conditions for algal growth. The existence of algae will lower the amount of dissolved oxygen due to consumption when photosynthesis is not occurring. The reported past changes in water quality have not been attributed to climate change. Land use is also discussed as a major determinant of water quality. A MN study is cited referring to high rates of chloride and phosphorous in urban and agricultural area waters respectively. These differing land use practices can impact runoff rates.

Further detail on this study can be found in the Annotated Bibliography in Appendix D. Apppendix A and Section VI provide additional content from state agencies, including the MPCA, MNDNR, MN Department of Health (DOH), MN Department of Transportation (DOT) and the MN Department of Public Safety.

One of the themes that emerges in the literature applying economic analysis to climate change impacts is that infrastructure investment should establish a larger margin of safety for the future in roads, bridges, culverts, drinking water facilities, and wastewater and stormwater facilities as a precaution against more extreme weather patterns. It is informative to consult the manuals used by MNDOT for road, culvert and bridge design. The MNDOT Drainage Manual http://www.dot.state.mn.us/bridge/hydraulics/drainagemanual/ includes sections (see 3.2.1 and 4.2.3) with recommended design frequencies.

For bridges, typical design is for 50-year floods, with recommendations to check 100-year flow levels and to check scour for 100-year and 500-year flows or the minimum flow level that would cause overtopping. For roadside channels the recommended design is for a 100-year flood frequency. Culverts less than 48 inches have 50-year flood design and those greater than 48 inches require risk assessment and computation of the 500-year flood or floods that are more frequent that would be sufficient to cause overtopping. The required risk assessment utilizes hydrographs for anticipating rainfall and runoff for the particular watershed and location of the infrastructure. But climate change indicates that these hydrographs should be adjusted or a buffer built in for higher rainfall amounts and more frequent heavy rain events.

It is also useful to consult the State Aid Manual to Counties and Cities for projects using State or Federal funds. One topic is the design and construction of storm sewers for moving water off of roads. The manual includes tables which set the maximum fraction of a road surface (driving lane) that can have water over it during a severe rain event. This manual also has a section on "Sizing and Over-sizing." This section has a "Maximum Allowable Spread Table" for state aid storm sewer design.

MNDOT officials regard the current design protocols as building in a margin of safety that should be sufficient to handle the increases in flows and more frequent flood events anticipated in the literature (personal correspondence, Frank Pafko, MNDOT Chief Environmental Officer and Director of Environmental Services.) It would be a mammoth undertaking requiring enormous investment to prepare most transportation infrastructure for 500-year floods. So a margin of safety is built in except perhaps for extreme events that are randomly distributed and impossible to anticipate.

C. Evidence of Environmental Changes in Minnesota: Project Findings

Water Levels in Lakes and Streams

Two reports have emerged on water resources as part of this LCCMR project. Dedaser-Celik and Stefan (2007, 2008) produces two main findings of particular importance for economic analysis. First, water levels were rising in some Minnesota lakes (Dedaser-Celik & Stefan, 2007). Second, precipitation in Minnesota had a trend that is increasing in intensity and amount (Dedaser-Celik & Stefan, 2008). These findings were similar to those predicted in the literature indicating that climate change may cause precipitation and runoff rates to increase in northern latitudes. However, these implications were contradicted by the study below.

Dedaser-Celik & Stefan (2009) analyzed trends in streamflow in Minnesota since 1946 using gauges from five different river basins across the state. The trends observed matched many predicted by other climate change literature such as increased high flow due to increased runoff. While extreme flood events have not increased, flows over a wide range of recurrence intervals have either increased over time or remained the same. These researchers did determine that rivers located in areas with higher rates of precipitation showed increases in streamflow.

Selected findings from the five basins are excerpted below from the project summary: "Stream Flow Studies: *Stream Flow Response to Climate in Minnesota."*
Data from 36 gauging stations located in five river basins of Minnesota (Minnesota River, Rainy River, Red River of the North, Lake Superior, and Upper Mississippi River Basins) were used for the 1946-2005 period.

Flow Duration Curves. To detect any changes that have occurred over time, data from the (1986-2005) and the (1946-1965) period of record were analyzed separately. Flow duration curves were prepared for all gauging stations, low flows (Q90, Q95), medium flows (Q50), and high flows (Q5, Q10) in the two time periods were examined.

The Minnesota River Basin has experienced the largest stream flow changes in the last 20 years compared to the other four basins. High, medium, and low flows have increased significantly from the 1946-1965 to the 1986-2005 period (on average Q50 increased by about 200%). The increases in medium to low flows were larger than the increases in high flows. Considerable changes in flows were also observed in the Upper Mississippi River Basin and the Red River of the North Basin (on average Q50 increased by about 80%). Streams in the Rainy River Basin and tributaries to Lake Superior showed little or no change in stream flow distribution (about 10 to 30% on average) between the 1946-1965 and 1986-2005 periods.

High and Low Flow Ranking. Both annual peak flows and 7-day average low flows were higher in the 1986-2005 period in the Minnesota River Basin, Red River of the North Basin, and Upper Mississippi River Basin. Increases in observed 7-day average low flows were more significant than increases in observed annual peak flows. For example, in the Minnesota River Basin and Red River of the North Basin, all stations showed more than the expected number of peak annual and 7-day average low flows in the last 20 years.

Flood Frequency Analyses. Separate flood frequency analyses were conducted on the stream flow data from the 36 stream gauging stations for the (1946-1965) and the (1986-2005) periods to identify changes in the 1-, 2-, 5-, 10- and 25-yr floods. The results were most consistent for the Red River of the North Basin. In this basin, magnitudes of the 2- to 25-yr floods increased at all six stream gauging stations (average increases were from about 30 to 60%) and the magnitude of the 1-yr flood decreased (average of 20%). Results obtained for the Minnesota River, Rainy River, Lake Superior, and Upper Mississippi River Basins were not conclusive because the changes observed at individual stations in each river basin were not consistent; both increases and decreases were observed. Average changes in the 1- to 25-yr floods were between 21 and 320% in the Minnesota River Basin, -7% and -20% in the Rainy River Basin, -11% and 26% in *the Lake Superior Basin, and -8 and 23% in the Upper Mississippi River Basin.*

There are many potential causes for changes in stream flows. Precipitation is one. The river basins which showed the largest increases in stream flows (Minnesota River Basin and Red River of the North Basins) drain regions (climate divisions) where significant increases in precipitation have been observed. River basins which showed little or no change in stream flow (Rainy River and Lake Superior Basin) drain climate divisions where changes in precipitation were not significant. Agricultural drainage and changes in crop patterns are other potential causes that need to be considered."

Ice Duration Analysis

Virginia Card (2010) provided findings from the dataset on dates of ice formation and ice thawing on 40 lakes from 1970 to 2008. These dates were used to calculate the days of ice duration each year. The average number of days of ice duration lost or gained over this period was also calculated. It was found that lake ice duration in the Minnesota sample is significantly decreasing at a mean rate of 3.3 days per decade from the time period of 1970 to 2008. As is explained further in Section VIB, these values were also uses in a one sample t-test to test the null hypothesis that there is no change in the amount of ice duration. The mean rate of 3.3 fewer days of ice duration per decade is significantly greater than zero at the 1% level of significance.

Fish Habitat Changes and Fish Abundance Shifts

Two separate Minnesota studies have examined the impacts of climate change on freshwater fisheries. In the first study, Schneider, Newman, Card, Weisber, and Pereira (2005) examined the impacts on changing ice-out conditions in Minnesota on walleye spawning timing. These researchers found that there is a significant relationship between the change in ice-out and the change in the time that walleye lay eggs. This piece of literature combined ice-out data from lakes around the state with data concerning egg-take from walleye populations. The researchers found that for every one day decrease in the presence of lake ice there was a .5 to 1 day decrease to the day that a walleye lays its eggs. These authors postulated that this may have an impact on the well-being of the fishery if there is a mistiming in the availability of prey with a change in spawning timing. It is not clear if this change in timing was also correlated with a change in spawning duration.

In the second study, Schneider, Newman, Weisberg, and Pereira (2009) examined the current trends in fish communities in response to changing climate in Minnesota. Several temperature variables were compared with the abundance of species in 35 different lakes. Some of these variables included summer temperature, average annual temperature and temperature extremes. The methods of this study utilized catch per unit effort (CPUE) from gillnet and trapnet surveys. These researchers discovered that the majority of fish species were expanding their range northward except smallmouth bass. In addition, these researchers discovered that increases in average summer temperature were correlated with increases in largemouth bass and sunfish abundance. Moreover, increasing air temperature was correlated with a decrease in the abundance of whitefish and trout. Fang, et al, (2004) projected fish habitat changes using a scenario of doubling C)2 emissions.

In summary, changes in water temperature and variables impacting the amount of DO in a water body are the main factors that may potentially impact fish populations from the onset of climate change. The evidence indicates that Minnesota is not currently seeing some of the predicted impacts found in the broader climate change literature. These potential impacts remain tangential to the research project at hand. However, the well-being of these populations influences the economic benefits from fishing. For example, studies discussed below indicate that catch rate had a significant impact on willingness to pay (Stevens, 1966). If fish populations are negatively impacted from climate change there may also be an economic impact.

Water Quality

The project team includes researchers focusing on trends in water quality in Minnesota lakes. Axler et al. (2009) provided online resources to access a voluminous database that they developed for water quality parameters from over 630 MN lakes. Lakes selected had more than 15 years of data for at least one water quality measure involving 1.9 million records. Major findings from their analysis of the data include: (pages 12-16)

- *"In the context of the climate change issue that spawned the present study, the most important result derived from the exploratory trend analyses has been that for lakes with significant time trends during the summer, more than 90% showed surface water warming as compared to cooling. This result was found for over 26% of those lakes with at least 5 years of data (247 of the 551 lakes examined) and almost 2/3 of the 60 lakes with 18 years or more data. For the 37 lakes that showed statistically significant warming over their period of record, the mean trend was 0.080 + oC/yr. This would project to an average increase of 0.8 oC (1.4 oF) in 10 years, and 3.3 oC (5.9 oF) by 2050."*

- *"Warmer growing season air temperatures have generally been predicted to decrease the depth of the thermocline (i.e. creating a shallower epilimnion) in most lakes as a consequence of increased warming of the epilimnion and increased thermal stability. Although only 16% of lakes with >5 years of data had significant trends in thermocline depth, 85% of those that did, exhibited decreasing (i.e. shallower) thermocline depths... Thermocline stability only showed statistically significant trends in 10-18% of lakes depending on the length of data record, but almost all trends were positive. Together, these data are consistent with surface warming. Trends in hypolimnetic water showed the opposite effect with about 20% of the lakes having at least 5 years of temperature profile data having statistically significant trends and more than 75% of those being negative (cooling)."*

- *"The salt content of surface waters and chloride concentration has increased over time in more than a third of the lakes with >5 years of data, 50% of those with >8 years, and 90% with >18 years of data. This is consistent with increased summer surface warming but also with potential increased exposure to winter de-icing salts and/or increased stormwater runoff from either urban or agricultural areas. Increased loading to the whole lake such as would occur from runoff inputs are suggested for the deeper lakes where trends were found, since the entire water column, not just the epilimnion exhibited increases."*

- *"Perhaps the most surprising result found in this study was that there was internal* *consistency within the group of trophic status indicators (secchi depth clarity, chlorophyll-a, total phosphorus and total Kjeldahl nitrogen) that suggests a strong overall improvement in water quality. These trends were found for a large number of lakes- ~40% of the lakes in the secchi data set had statistically significant trends, and of these >80% were increasing (i.e. clearer water)."*

Overall, these analyses suggested an overall "improvement" in the water quality of the great majority of lakes that showed trends over the past 20 years in the sense of increased clarity and decreased chlorophyll and nutrients. A much smaller fraction of the lakes in the data set exhibited trends in thermal and related characteristics, and of those, the great majority were consistent with the predictions of potential climate warming effects for lakes in the Upper Midwest. However, it is extremely important to note that the current set of lakes is not distributed randomly across the state because the preponderance of lakes with longer data sets are located in the central and Minneapolis-St-Paul metropolitan areas of the state.

There are countervailing trends at play here, such as reduced industrial discharges and nutrient reductions from some non-point sources, while increasing intensity of development in many lakesheds are likely to heighten non-point source impacts. These watershed impacts must be juxtaposed with the potential effects of climate change and so it is extremely difficult to isolate the impact of climate change separately.

Despite these "mixed" results on trends in Minnesota lake water quality, it is extremely important to consider potential impacts of climate change given the importance of the resources at stake. The current impaired waters list in Minnesota includes over 1,000 lakes and 400 rivers. Indeed, efforts to improve these conditions, i.e. the ongoing point and non-point pollution reduction efforts , should be part of the positive changes evidenced by these project findings. Equally important however, is the potential for increased sediment and nutrient loading from increased stormwater runoff due to projected increases in the frequency of intense storms, and for decreased cold water fish habitat due to warming, more stable thermal stratification, and decreased oxygen in stratified lakes. A related, major concern for the future of Minnesota waters is the threat of invasive species, which is also projected to increase in concert with projected changes in Minnesota's climate. Therefore, climate change can be a contributing factor to a worse future for Minnesota's surface waters, by impeding the improvements being made from ongoing mitigation and restoration efforts.

Given the tremendous importance of lakes and streams to Minnesotans, including economically, the discussion below conceptualizes water quality efforts as an insurance policy. Efforts to promote lake ecological integrity and resilience can establish a cushion for the negative impacts climate change could cause. Best practices can set a margin of safety against the worst-case scenario that climate change could bring to the state's lakes and streams. A more extensive discussion of potential economic impacts of changes in water quality is found below in Sections IV and VI.

SECTION IV.
CONCEPTUAL FRAMEWORK FOR INFERRING ECONOMIC IMPACTS

The foundation for economic analysis of potential impacts of climate change is in the conceptual framework for economic valuation. There is a rich literature that establishes the analytical basis for components of value that society places on environmental goods and services. The field of environmental economics expanded immensely in response to the needs for enhanced understanding of the economic implications of the environmental policies of the 1970s. The literature and tools of economic analysis of water resources grew in tandem with and in response to the policy processes that led to the Clean Water Act. Without repeating some of the excellent surveys of the literature available, it is worthwhile for the purposes of this study to recount some of the development of concepts regarding the economic value of water resources. The conceptual framework that emerged serves as a foundation for understanding the potential economic impacts of climate change on Minnesota's water resources. Excellent explanations of these concepts and summaries of the empirical evidence can be found in Tietenberg and Lewis (2009) and Boardman, et al. (2006).

Seminal work in the economics of water quality was conducted by Desvousges, Smith, and McGivney (1983) in a study for the EPA on the economics of cleaning up the Monongohela River in Pennsylvania. The empirical analysis emphasized use values for recreation but an insightful conceptual framework was constructed for understanding the various components of economic value of clean water. This study enhanced the understanding of non-use values of environmental quality, particularly water quality. Figure IV.1 below is adapted from the Desvousges, et al. (1983) report. Potential water quality benefits were broken into two main categories: Current user benefits and Intrinsic Benefits. The latter term was chosen to infer that water generates inherent value to society separate from the extractive, commercial, recreational or aesthetic values that we place on water. The potential use of water (an insurance premium against the risk of losing the option to use) that never materializes as actual use was included as an intrinsic benefit along with existence value. This second component of intrinsic benefits comes from motives towards stewardship or to bequeathe an environmental good or service totally unrelated to current "use" of water.

Through time the literature offered alternative sets of terminology such as "use" and "non-use" value and "use" and "passive use" value. Regardless of the pros and cons among these sets of terminology for grouping major components of value, the underlying components of value continued to be use value, option value, and existence value. Further development of these concepts was shown in a closely related figure from an important survey of the literature by Mitchell and Carson (1989). Slight variation from the Desvousges, et al. conceptual framework is shown in Figure IV.2.

Potential Water Quality Benefits	Current User Benefits	Direct Use	In Lake or Stream	Recreation - fishing, swimming, boating, rafting, etc.
				Commercial - fishing, navigation
			Withdrawal	Municipal - drinking water, waste disposal
				Agricultural - irrigation
				Industrial/Commercial - cooling, process treatment, waste disposal, steam generation
		Indirect Use	Near Lake or Stream	Recreational - hiking, picnicking, birdwatching, photography, etc.
				Relaxation - viewing
				Aesthetic - enhancement of adjoining site amenities
	Intrinsic Benefits	Potential Use	Option	Near-term potential use
				Long-term potential use
		No Use	Existence	Stewardship - maintaining a good environment for everyone to enjoy (including future family use-bequest)
				Vicarious consumption - enjoyment from the knowledge that others are using the resource.

Figure IV.1. A Spectrum of Water Quality Benefits
Source: Adapted from Desvousges, Smith and McGivney (1983)

Benefit Class	Benefit Category	Benefit Subcategory (examples)
Use	In-Stream	Recreational (water skiing, fishing, swimming, boating)
		Commercial (fishing, navigation)
	Withdrawal	Municipal (drinking water, waste disposal)
		Agriculture (irrigation)
		Industrial/Commercial (process treatment, waste disposal
	Aesthetic	Enhanced near-water recreation (hiking, picnicking, photography)
		Enhanced routine viewing (commuting, office/home views)
	Ecosystem	Enhanced recreation support (duck hunting)
		Enhanced general ecosystem support (food chain)
Existence	Vicarious Consumption	Significant others (relatives, close friends)
		Diffuse others (general public)
	Stewardship	Inherent (preserving remote wetlands)
		Bequest (family, future generations)

Figure IV.2. A Typology of Possible Benefits from an Improvement in Freshwater Quality

Source: Mitchell and Carson (1989), adapted from Figure 3-1.

Another categorization that has emerged in the literature is between market and non-market values. This analytical distinction has a practical reward in that it focuses attention among empirical analysts to operationalize these value components in techniques for measuring environmental benefits. From an empirical perspective, a key issue is whether observable market data directly reveal people's values or whether indirect measures of related behavior or statements of preferences are needed to comprehensively infer total economic value. A noteworthy advancement in the literature is the multitude of studies that recognized that empirical estimates of environmental benefits would be grossly understated for many environmental goods and services if only use values were included. The Desvousges et al. study was a catalyst in this process. So to was a study by Fisher and Raucher (1984) that surveyed the literature on water quality benefits and showed evidence that empirical estimates of intrinsic benefits of water are too substantial to ignore. Conventional methods of benefits estimation needed to go beyond use values and this was reflected in empirical practices supported by the EPA and within the field of environmental and natural resource economics.

The sub-sections below further develop the concepts of market and non-market values and apply them to the potential impacts of climate change.

A. Market Values

Complete estimation of total economic value is most straightforward when use value is the only component of value and market data exist to measure the market demand curve. Measuring the market demand curve captures entire willingness to pay (WTP) for a good or service. Net benefits to consumers can be found by subtracting consumers' expenditures from WTP to find consumers' surplus, which measures the net gain to consumers. Market estimates based solely on what consumers actually pay exclude consumers' surplus and are an underestimate of WTP.

Referring to the benefits taxonomies in Figures IV.1 and 2, use values such as commercial shipping on waterways can be measured via market transactions. This is also true for recreation where monetary transactions occur in the market, such as a guided fishing activity. Market data are often available for unguided activities as well, but some uses, such as boat access via a public access, may be more difficult to capture through market transactions. Still as recreational uses, economists would look to market transactions in purchasing gas, equipment, etc. as revealing the values of those activities. Similarly, in some settings there is a market for irrigation water so that market demand could be estimated but in others markets are absent or incomplete so market data would not capture the entire WTP.

Even though public drinking water and waste disposal is often provided through the public sector, again expenditures on these activities would be looked to as evidence of the value of these services. Public pricing schemes could make WTP for these services more difficult to discern, but use values should be possible to determine.

Climate change impacts found in the literature and highlighted above in Sections II and III indicate a multitude of market values that could be impacted by climate change. In terms of water resources, some of the major market values that could be impacted are:

- recreational fishing,
- commercial fishing,
- commercial transportation on waterways,
- agricultural irrigation,
- infrastructure damages from flooding (drinking water, wastewater, and stormwater facilities, roads, bridges, culverts, and other structures),
- flood damages to crops, forests and other lands with commercial yields
- hydroelectric power generation,
- water-borne diseases
- insurance costs

B. Non-Market Values

In addition to option values and existence values discussed earlier in this section, another value that tends not to be revealed through market transactions is quasi-option value. Quasi-option value represents the value of forthcoming information yielded by avoiding an irreversible outcome. If an irreversible choice is made that precludes learning about trade-offs through forthcoming information than the value of this information is destroyed. It is distinct from option value in that it is not a risk-aversion premium, per se. Preserving forthcoming information has a quasi-option value and is often referred to in settings where policies will enable endogenous learning. Avoiding potentially irreversible consequences of climate change should generate substantial quasi-option values.

The Basic Conceptual Framework for Option Value of Avoiding Damages From Climate Change

In the extensive literature on option value, the concept is consistently defined as the difference between option price and expected consumer surplus, where option price is the maximum willingness-to-pay to maintain the option of future consumption. The concept is used to explain why people willingly purchase insurance and pay a premium that exceeds the expected loss. Hence option value is referred to as a risk-aversion premium. The conceptual framework for the application of option value to protecting against climate change impacts is adapted from the model in Freeman (1985).

Equivalent surplus, ES, is defined as the willingness-to-pay to avoid certain damages to water resources from climate change. But given climate change poses a risk of impacts greater than 0 but less than 100% certain, efforts to reduce the impacts of climate change must be seen as lowering these probabilities. Similarly climate change can be conceptualized as increasing risks by increasing the dispersion of likely future states of the world. Even if the expected values for qualities and quantities of Minnesota water resources are assumed to remain unchanged, the widening of the extreme outcomes increases the riskiness of the world in the future. Given society is made up of individuals who typically are risk averse, increased risk due to climate change causes a loss in well-being.

The theoretical discussion of option value in the economics literature associates risk-averse preferences with characteristics of the typical individual's utility function. Specifically the utility function is assumed to be concave downward, i.e. exhibiting diminishing marginal utility of income. Departures from these and other theoretical assumptions lead to different conclusions about the sign and importance of option value. Boardman, et al. (2006) provides an informative overview of this debate.

Indeed the debate in the theoretical literature on option value has also played out in the economic analysis of climate change. The Stern Review (2006) provides seminal analysis of potential global economic impacts of climate change. It has been a catalyst for further scholarship on this topic. Stern relies heavily on option value as a component of the economic value of reducing the threat from climate change. Others have concurred with this conclusion while still others vehemently disagree. A key point of disagreement with the conclusion that option value should be counted as a positive benefit of reducing the threat of climate change is the view that individuals are also averse to the risk of losing income by spending on climate change mitigation that may turn out to be unnecessary. But this argument misses the point that the trade-off in risks uses income as the unit of account. Money is the common denominator for balancing the risks of "doing too much too soon, or too little too late." The income equivalent to reduce environmental risk is already in the form of this monetary expenditure. The count money again as a risk of unneeded expenditure would be double counting. The WTP of risk-averse individuals exceeds expected loss because they see the risk of environmental damage as warranting the risk of spending money, even if unnecessarily.

The reasoning some authors use to conclude that climate change mitigation will not generate economic benefits in the form of option value would also be flawed when applied to the insurance industry. This reasoning would wrongly imply that individuals would quit buying homeowners insurance. In reflecting back on a year where no insurance claims needed to be filed, would a risk-averse individual attach greater risk to spending on insurance unnecessarily because no damages occurred? The repeated expenditure for insurance demonstrates that individuals benefit from the sense of security from a loss (even if it has low-probability), and weigh avoidance of that loss more heavily than the chance that they could have gotten by without purchasing insurance. The insurance industry depends on individuals having preferences in weighing risks that are manifested in WTP being more than the actuarially expected loss. That risk-aversion premium is the source of profits to the insurance industry.

Reducing the risk to water resources from climate change also generates a risk-aversion premium defined as option value. But in addition to the insurance industry analogy, option value accumulates to all individuals that are averse to these risks. So benefit accumulates simultaneously to all of these individuals due to policies that reduce these risks. This collective benefit fits the definition of a public good, explained further below.

The literature applying the concept of option value to climate change is surveyed in Section V. But for the sake of flow within the body of the report, additional material on option value is contained in the appendices. Given the complexity and technical nature of this literature, some excerpts from the literature are provided in Appendix A. The basic analytical framework is presented in Appendix B. The annotated bibliography in Appendix D highlights selected sources that apply option value to climate change mitigation.

The discussion above applies to a simple case (Case 1) where option value serves to maximize expected utility when risk is introduced to a previously riskless situation. A more realistic characterization of the risks imposed by climate change is to add greater extremes to an already risky world. The simple case presented above portrays climate change as introducing risk to the future quality and quantity of water resources. In reality, the future of Minnesota's water resources is already risky, without the added threat of climate change. So the more complex scenario modeled in Case 2 shown in Appendix B portrays climate change as widening the dispersion of likely future states of the world.

The literature on impacts notes that some environmental changes could be negative and some positive. If the negative changes outweigh the positive, there will be a socio-economic loss due to climate change. But Case 2 in Appendix B emphasizes option value by assuming that the negative and positive impacts of climate change on water resources will be of equal magnitude and equally likely. So the loss is not due to a decline in expected values. Rather it is due to the preference to reduce the risk inherent in more dispersed outcomes.

To demonstrate the conceptual point, two future states of the world are considered in Case 2. One could be a gain in the quality and quantity water resources and the other could be an equal loss. So the expected value of the resource remains unchanged but the dispersion is more extreme. Again a risk-neutral individual would sense no loss from this greater dispersion so would have no option value. But being most people are risk averse, they would attach substantial option value to insure against the dispersion between the best-case and worst-case scenarios.

Option value applies more widely to climate change impacts than just to water resources. In fact it addresses a fundamental aspect of the potential economic loss from climate change. Statisticians characterize distributions with measures of Central Tendency and Dispersion. Much of the concern about climate change impacts has focused on increases in measures of Central Tendency such as higher average temperatures of higher mean precipitation. But from a socio-economic perspective the potential damages linked to increasing dispersion, such as more extreme temperatures or precipitation patterns may be just as damaging to social and economic well-being. The concept of option value is crucial to understanding the economic impacts of climate change.

Economists generally regard option value, existence value, and quasi-option value as not being captured in market transactions. Climate change impacts found in the literature and highlighted above in Sections II and III indicate a multitude of non-market values that could be impacted by climate change. In terms of water resources, some of the major non-market values that could be impacted are:

- water quality
- fish habitat
- preservation of "natural" distribution of cold-water species such as lake trout and cisco
- preservation of native aquatic plants
- preservation of "natural" levels of surface waters

C. Sustainability

The concept of sustainability covers a wide range of concepts that share an orientation toward future well-being. As a transition from the previous section it is noteworthy that one aspect of sustainability is risk-aversion toward degradation of the quality of life of future generations. As noted above, the Stern Review emphasized option value as an important component of the benefits of controlling greenhouse gas emissions. Along similar lines, sustainability provides a rationale to take preventive action. A related approach to risk-aversion for the sake of the current or future generations is the Precautionary Principle.

The Precautionary Principle and Risk Reduction as a Public Good

Water Resources are an important category demonstrating the potential economic consequences of extreme conditions, not just a matter of changing average water temperatures or streamflows, but the potentially dire consequences of greater extremes. Drinking water, stormwater and sanity sewer systems could require enormous investments to deal with extreme conditions. The Precautionary Principle indicates that in the face of potential damages, a margin of safety is in order. Risk-aversion suggests that actions are beneficial that “play it safe” or “hedge bets.” The Precautionary Principle fortifies option value for the current generation and sustainability for the future.

The value of water resources and the ecological services provided are so large as to indicate that it would be economically efficient to incur substantial costs to avoid these losses. As the USEPA document “National Water Program Strategy: Response to Climate Change” suggests, large costs to reduce other bad actions that compromise drinking water or surface water quality may be warranted to offset the degradation that could be anticipated from climate change. For example, it may be economically efficient to invest in land-use changes and/or wastewater treatment that reduce nutrients so that climate change does not put us over the threshold toward lower water quality.

If an economic standard is met indicating that the benefits of protecting water quality against degradation from climate change are worth the costs, the next decision criterion would be to achieve these benefits at minimum cost. In order to protect these water resources, the costs of countervailing measures would need to be compared to the costs of reducing greenhouse gas emissions as root causes of these problems. The economic comparison needs to be mindful that measures that address root causes of problems often are more economically efficient than “band-aid” solutions that merely address the symptoms. A comparison of the costs of land-use changes versus greenhouse gas emissions reductions would need to consider that both choices have broader implications beyond water quality, especially the latter and on a global scale. All else equal, reducing the human causes of climate change are likely to yield larger net benefits than best practices to reduce nutrient loads to surface waters given the broader climate change impacts that could be avoided by reducing greenhouse gases.

The benefits of precautionary actions do not only accrue to one individual as with a private good. The value of precaution is a public good because it accumulates simultaneously to all individuals that are risk averse. While private goods are valued at individual WTP that is summed horizontally along the quantity axis for the good, public goods generate social benefits based on what economists call "vertical summation." This term comes from the convention of graphing WTP on the vertical axis in the market model. Benefits are aggregated for all individuals that benefit from the provision of a public good, such as reduced risks of damages from climate change.

A paper on the economic impacts of climate change by Heal and Kristrom (2002) is particularly thorough on the concept of option value and the Precautionary Principle. They extend the discussion of balancing risks in the previous section by including the aspect of irreversibility and endogenous learning. These concepts were discussed above in relation to quasi-option value. Heal and Kristrom state: "the preconditions necessary for the existence of an option value seem to be satisfied in the context of climate change. We expect to learn about the costs of climate change and about the costs of avoiding it over the next decades. And we expect that some of the decisions that we could take will have consequences that are irreversible. These are the hallmarks of decisions that give rise to option values associated with conservation . . . But although these conditions are necessary for the existence of option values they are not sufficient. . . . there is another possible real option value at work here. If substantial sunk costs must be incurred to begin the process of abating greenhouse gas emission and avoiding or minimizing climate change, if the return to this investment is the avoidance of climate change, and if we learn about the value of this over time, then there is also a real option value associated with postponing investment in greenhouse gas abatement." Page 25

Precaution against an irreversible outcome that destroys information is regarded in the literature as having quasi-option value. This argument assumes environmental damages are harder to reverse than the policies aimed to insure against them. This is referred to as asymmetric irreversibility. One view is that action should be taken to prevent potential impacts because by the time impacts are better known it may be too late. There is an opportunity for exogenous learning in waiting to see how bad damages become, but impacts may be irreversible by then. On the other hand, there could be endogenous learning enabled by taking action in that GHG abatement will teach us costs and these can be reversed later if we learn abatement is unnecessary. In fact, the EPA classifications of the kinds of pollution-control technologies, the best that might be achievable through time versus those already in place, invites an interpretation that endogenous learning can occur with these investments. Policies that generate endogenous learning are often comprised of what are commonly called "demonstration projects." Attempts to control pollution, or mitigate effects, are needed for endogenous learning to occur. But an opposing view in the literature contends that pollution control commitments may also be difficult to reverse. Heal and Kristrom advocate that policies be designed to be flexible enough to be adjusted as new information is forthcoming. They provide a conceptual framework with dollar ranges and probabilities of damages and costs of action. The Heal and Kristrom (2002) paper also contains an interesting discussion of humans' preferred temperatures and disutility from weather extremes.

Heal and Kristrom also discuss the role of the Precautionary Principle in the economics of climate change. A quote from the 1992 Rio Declaration (Article 15) is cited: "where there are threats of serious and irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation." An opposing view is that precautions should be taken against premature expenditures on pollution control. Waiting to act until more is learned about the damages will also have an information value. This is described as the “learn then act” strategy. Heal and Kristrom note that “if we follow this strategy then the risk that society faces in the future will be greater. The principle result of the Gollier et al. paper is that the balance between these two effects depends on the shape of the utility function and in particular on whether or not society shows ‘prudence’.” Page 26

The evidence on climate change impacts suggests that irreversible damages could occur. Good policy formulation can provide flexibility to alter future pollution abatement investments. Human/social decisions should be more reversible than many environmental impacts; damages to ecosystems, loss of native species, etc. Being greenhouse gases have a long residency period in the atmosphere, emissions reduction today will have a long lag period. Investment today could prevent damages for the next generation. Damages from climate change are likely to have a longer lag and be relatively less reversible than pollution control actions.

Heal and Kristrom discuss uncertainties that are both ecological and economical. A major challenge to the Stern Review is the economic uncertainties that exist about future optimal discount rates, growth rates and technological advancement. However, it should also be noted that human behaviors and adjustments to information likely provide greater reversibility and are likely to be more flexible than ecosystem constraints. Unraveling ecosystem interconnections and irreversible threshold and cascade effects are potential consequences that need to be considered. In ecosystems, constraints such as the First and Second Laws of Thermodynamics and the Law of Conservation of Matter are immutable laws, in contrast to economic laws about behaviors and incentives.

The work of Heal and Kristrom is included in this section given its focus on option values and the Precautionary Principle. Conceptual issues are raised that get to the foundation of methodological limitations in conventional economics. Other sources on the economics of climate change, surveyed in Section V below, highlight the crucial debate about the substitutability between physical and natural capital. Theoretical and practical measurement issues involving key concepts (sustainability, option value, quasi-option value, irreversibility, exogenous and endogenous learning) push the envelope of conventional methodology in terms of attaching dollar values to effects, known as monetizing.

The debate about whether option value would be positive for reducing the threat of climate change boils down to whether there is an income equivalent that expresses WTP as a risk-aversion premium. The conclusion of this analyst is that purchases of physical capital in the form of pollution control equipment - whether it be to reduce greenhouse gases or reduce nutrient loads as a safety net for water quality – can be translated more readily into income equivalents that the consequences of losing natural capital. The same is true for the potential loss of human life. <u>There are severe risks from disrupting energy flows in an ecosystem so that outcomes from the processes related to the First and Second Laws of Thermodynamics degrade ecological goods and services. These risks are seen by this analyst as being much greater and more difficult to monetize than expenditures on pollution control devices.</u>

Public Good Values of Intergenerational Equity

In a meeting document assembled by the Minnesota Department of Health (2008) entitled "Public Health Impacts of Climate Change" a perspective on sustainability was represented in the following quote from Jonas Salk: "…the most important question we must ask ourselves is, "Are we being good ancestors?"

The sustainability literature in economics adapts the intra-generational social justice concepts developed by John Rawls (1971) to inter-generational ethical decisions. In particular, sustainability applies the Rawlsian "Maximin Principle" of providing maximum well-being to the least off individuals in society to maintaining non-declining opportunity for well-being to the least well-off generation through time. The operational criterion is whether our actions today provide the resources needed to allow for a "maximum" level of well-being for the "minimum" generation.

The literature includes two major points of disagreement as to how to apply this principle: 1) issue of contention is about whether the "minimum" generation going forward is the current one or some generation in the future. Given future states of the world are unknown, the Rawlsian "Veil of Ignorance" can also be applied to yield an action rule for inter-generational equity as follows: Economic sustainability requires that the current generation provide to future generations at least as much opportunity for well-being as is currently enjoyed.

Still the argument centers on whether technological advancement in the future will enhance social well-being and whether we will pass on to future generation a planet that provides for or compromises quality of life. This leads to the second point of dispute. 2) Is the substitutability between physical capital (technology) and natural capital (the planet's ecological services and natural resources) sufficient to allow some environmental degradation without bankrupting the well-being of future generations?

Various schools of thought emerged as to the level of substitutability between physical and natural capital in determining the resource stock needed to provide opportunity for well-being to future generations. Neumayer (1999) evaluated two paradigms based on contrasting assumptions that physical capital 1. poorly or 2. strongly substitutes for natural capital. If strong substitution is possible, sustainability is achieved if the total of physical and natural capital is adequately endowed to future generations: known as weak sustainability. If substitution is poor, a certain level of natural capital must be maintained: strong sustainability. A third version that is the strictest (environmental sustainability) requires that a constant level of physical service flows from natural capital be maintained, such as a sustainable yield from a fishery or a commercial forest.

In applying principles of inter-generational equity, climate change may be the greatest environmental justice challenge the world has ever faced. From a Rawlsian perspective, it not only poses immense ethical implications for the well-being of the least well off groups currently living around the globe but also for subsequent generations of these groups and all future inhabitants of the planet.

It is informative to note that these concepts of Intergenerational Equity relate closely to the Anishinaabe ethic of "The Seventh Generation." Similar environmental ethics can be found in various indigenous cultures around the world and generally imply that actions today must be in the interest of those seven generations into the future. Current generations of indigenous peoples face unusual threats from climate change. Traditional practices that depend on natural process and ecosystem services may disappear with disruption from climate change. The most vulnerable groups across many societies are likely to suffer the greatest losses from climate change. For indigenous people in regions around the planet attempting to live in traditional ways, climate change may put those ways of life in jeopardy.

In Minnesota, this is an extremely important concern, particularly focusing on water. Inequity and environmental injustice may result from the hardship climate change causes if traditional practices related to waters in Minnesota are destroyed. The book, Sacred Water, celebrates these cultural traditions and practices and highlights environmental threats such as acid rain and mercury. It is noteworthy that Minnesota pollution control policies on both of these issues led the way for national and international progress on these issues. Given the importance of water to the native people of this region, leadership in combating these pollutants is appropriate as part of our State legacy. Issues of equity and environmental justice deserve serious attention in formulation of climate change policy.

While these equity concerns are not quantifiable in an economic sense and so are beyond the empirical scope of this study, they belong in the discussion. Minnesota has a proud tradition in leading pollution control efforts, especially in being "good neighbors" in controlling pollutants that economists refer to as interjurisdictional externalities.

D. MN's Leadership Role in Controlling Interjurisdictional Externalities

Pollutants that drift downwind or flow downstream across borders are referred to as interjurisdictional externalities. This type of externality involves many parties so is perhaps the most difficult to resolve. The global impacts of climate change will likely have uneven geographic patterns. Economists refer to damages that aren't smooth as having non-convexities. Minnesota led the way among states in controlling acid deposition even though it is an interjurisdictional externality with non-convexities of impacts. MN's share of global greenhouse gas emissions also makes it difficult to connect pollution control efforts to any improvement in the local environment. Global GHG emission will not change discernibly on the margin even if MN emissions are substantially reduced. Yet Minnesota's history with interjurisdictional externalities has been to take action by reducing the state's contributions to problem even though that amount is only fraction of continental or global problem. Inaction could result from a mindset that one state's actions would have little influence on a global solution. But the state has resisted this mechanistic approach and instead has set an example by controlling emissions in the hope that it will prompt broader reductions by others who follow suit. State strategies in leading control efforts on acid deposition and mercury have succeeded in spurring cooperative agreements which brought broader jurisdictions into the solutions.

SECTION V.
SURVEY OF THE LITERATURE ON ECONOMIC IMPACTS OF CLIMATE CHANGE

A. Literature on Economic Impacts at the Global Level

The Stern Review (2006) made extensive arguments as to why it would be economically efficient and equitable to take immediate action to reduce GHG emissions. One of his equity positions was that the long-term consequences of climate change make discounting unfair to future generations, being future impacts would be severely diminished in relative importance compared to current impacts. Stern estimates losses in terms of global gross domestic product (GDP). He also estimates the percentage of global GDP that would be needed to fend off the worst of future impacts. More detail on the Stern Review is provided in the annotated bibliography presented in Appendix D.

The methods and conclusions of the Stern Review have been subjects of substantial disagreement in the economics literature. Stern served a constructive purpose in stimulating enlightening discussion. Heal (2008) summarizes the economics literature on climate change as follows: "I suggest that the recent debate has clarified many important issues, and that we are now in a position to identify those conditions that are sufficient to make a case for strong action on climate change. However, more work is needed before we can have a fully satisfactory account of the relevant economics. In particular, we need to better understand how climate change affects natural capital - the natural environment and the ecosystems comprising it - and how this in turn affects human welfare." Page 1

"The emission of greenhouse gases is a massive negative external effect - the Stern Review refers to it as possibly the greatest market failure in history." Heal (2008), page 2. Heal provides a conceptual discussion of the magnitude of the discount rate, importance of potential impacts on natural capital, risk & uncertainty, equity, and the costs of action vs. inaction as a percentage of global GDP. Heal notes that analysis based on GDP excludes non-market goods and he refers to mass extinction as an important non-market value. Heal focuses on the key issue of substitutability between physical and natural capital, and the degree to which consumption goods and services can replace ecological goods and services. "We have explored the model space and the parameter space much more thoroughly, though there are still unexplored regions. I think this should change the presumption that economists hold about the need for strong action on climate change from largely negative (prior to Stern) to positive. We can see many ways for making a case for strong action now, and few for denying it." page 15 "We have really not spent enough time on the impact of climate change on our natural capital and the ways in which this may compromise the flow of essential ecosystem services." page 16 As stated at the conclusion of Section IV.C.1 above, the reducing the risk of irreversible loss of natural capital is much more valuable than reducing the risk that investments in "damage control" might be made prematurely. Compelling scientific evidence in the literature surveyed in other sections of this report indicates that natural capital is in jeopardy.

Over a decade ago, Michael Tucker (1997) provided a perspective on climate change action based on the market for insurance. "A convincing economic argument for taking action to prevent or ameliorate climate change has not developed because of both uncertainty about the degree of change and its timing. Recent costly weather-related catastrophes with consequent negative impacts on the insurance industry has made the insurance industry a potential advocate for slowing what has been identified as a causal factor in climate change: emissions of greenhouse gases. However, rising costs of claims, without a longer-term trend of such catastrophic losses, will make it difficult to present a strong case for taking costly economic action." Tucker developed a technical, industry-specific argument regarding pricing of insurance to strengthen the case for action on climate change. He concluded that "economically justified higher insurance premiums" would result from "increasing levels of climate variability as embedded in the anticipated variability of damage to insured asset." While potential climate change impacts such as sea level rise are often conceptualized as not occurring until far into the future, Tucker's perspective of weather related damages brings the consequences into the present day, even in 1997. Ongoing discussion from the perspective of the insurance industry is highlighted below. In terms of empirical evidence provided in Section VI, summary statistics on weather-related damages over time are presented. Minnesota seems to be well above the medium in terms of magnitudes of weather-related damages.

Insurance Industry Perspectives

There is a wide array of literature relating climate change to the insurance industry. Following is a statement from the website of the Insurance Information Institute. "Catastrophes appear to be growing more destructive, but insured losses are also rising because of inflation and increasing development in areas subject to natural disasters. In 2005, the year of hurricanes Katrina, Wilma and Rita, catastrophe losses totaled $64.3 billion. Hurricane Katrina caused losses of $41.1 billion, the highest on record, about twice as much as Hurricane Andrew would have cost had it occurred in 2005. Seven of the 10 most expensive hurricanes in U.S. history occurred in the 14 months from August 2004 to October 2005. If, as suggested, hurricane-related losses grow by as much 40 percent over the next 20 years, a Katrina-like storm could cause $60 billion in losses, or significantly more if it struck a densely populated metropolitan area like Miami or New York City."

The evidence from the scientific literature does not lead to consensus about trends in hurricane frequency and severity. But these damage figures are of concern to many in the insurance industry and have broader implications for society as a whole.

In their paper on the economics of climate and insurance, Valerde and Andrews (2006) state: "As a key instrument and enabler of loss mitigation and risk transfer, the U.S. insurance industry lies at the nexus of several crucial dimensions of the climate change problem, especially as it relates to the potential implications of climate change for society and the global economy. Having sustained record-breaking natural catastrophe losses, insurers and reinsurers are openly—and, indeed, justifiably — questioning the potential linkage between anthropogenic climate change and extreme weather, looking at both the likely short-term implications for the industry, as well as potential long-term impacts on financial performance and corporate sustainability." page 1 "A fundamental question that we pose here, then, is whether the risks posed by global climate change are, in some way, structurally different than what has previously come to pass, thereby presenting insurers with new — and, some would argue, unprecedented— challenges, requiring a fundamental rethinking of the mindsets and methods that are used to manage these risks. Indeed, it may be the case that traditional underwriting and risk management methods are not adequate for this task." page 3 Despite the highly developed theory and practice of actuarial science these authors are suggesting that the risks posed by climate change may present unprecedented challenges.

Implications of climate change for the insurance industry were the subject of a great deal of analysis in the late 1990's. In an article on global change, Berz (1999) speculates that "changing probability distributions of many processes in the atmosphere" will result in "serious consequences for all types of property insurance." "In areas of high insurance density the loss potential of individual catastrophes can reach a level at which the national and international insurance industries will run into serious capacity problems." (A longer excerpt from the Berz paper is included in Appendix A.) Three insurance industry experts, Mills, et al. (2001) estimate a 15-fold increase over the period 1970 -2000 in insured losses from catastrophic weather events (defined as exceeding $1 billion of damages.)

In an analysis of trends in the Canadian insurance industry, White and Etkin (1997) "At the same time that a scientific consensus has arisen that the world will most likely experience a changing climate in the near future, with more frequent extreme events of some weather hazards, the insurance industry, worldwide, has been hit with rapidly escalating costs from weather-related disasters. This conjunction of scientific belief and economic impact has raised the questions as to (1) whether more frequent extreme events have contributed to the rising insurance costs and (2) how will future climate change affect the industry? Based upon historical data, it is difficult to support the hypothesis that the recent run of disasters both world-wide and in Canada are caused by climate change; more likely other factors such as increased wealth, urbanization, and population migration to vulnerable areas are of significance. It seems likely, though, that in the future some extreme events such as convective storms (causing heavy downpours, hail and tornadoes), drought and heat waves will result in increased costs to the industry, should the climate change as anticipated."

The evidence on worsening trends in weather-related damages has continued to grow over the last decade. The World Wildlife Fund for Nature and Allianz Insurance Company issued a report (2009) on tipping points from climate change and damage potential. The report notes that "The phrase 'tipping point' captures the intuitive notion that "a small change can make a big difference." As a concept for understanding risks, the tipping point invites comparisons to the argument by Valerde and Andrews that the insurance industry may need to develop a new paradigm. Tipping points in ecosystems, ecological goods and services and in the planet's life support systems could force tipping points in many human-social institutions. Further discussion of the tipping point and "tipping elements" is provided in Appendix A.

Studies on the Economic Effects of Impacts on Fisheries

Pendleton and Mendelsohn (1998) attempted to economically model the potential impact of climate change on sportfisheries using two different models. The first was the hedonic travel cost method. This used different characteristics and amounts resources expended to reach a specific recreation destination to estimate an economic value for the area. The second method used was a random utility model (RUM), which combined income, the travel cost function and a random variable for site location. These variables were combined to form a function explaining the utility gained from the activity. The results of the analyses indicated that a decline in the catch rates of certain types of fish could have a negative economic impact on the enjoyment of the people fishing. However, this study found that some Northeastern states may see a potential increase in welfare from the onset of warming. This was dependent on the preferences of anglers. For example, although rainbow trout were predicted to decline from climate change impacts, all other trout species and panfish were predicted to increase. This study revealed that climate change could positively impact the economics of the region, depending on which climate scenario emerges. These researchers indicated that climate change impacts may not be completely negative, which is consistent with the analysis in Section VI.

B. Literature on Potential Economic Impacts in Minnesota

Much of the literature on the economics of climate change addresses impacts at a global scale. Even analyses of industry impacts, such as the insurance industry, are done at the national level. It was noted at the conclusion of Section IV.D above that it is difficult to identify Minnesota's distinct share of global impacts. It would also be difficult to quantify a cause-and-effect relationship between emissions reductions within the state and environmental improvements. The same is true with economic analyses. The findings of the Stern Review on percentages of global GDP that could be lost due to climate change damages and lower proportions of GDP that should be invested in mitigation are difficult to apply at a smaller geographic scale. It is problematic to "downscale" these data and estimates to identify the Minnesota share of global loss of GDP. Added complications result from the fact that some of the most severe economic damages, from sea level rise, for example, would not impact the region or state directly. Rather these losses could reverberate through the global economy, so Minnesota would suffer as part of the global loss.

This provides another frame of reference on the difficulty of doing economic analysis, particularly benefit-cost analysis, on Minnesota actions given the state has a small share of global emissions & impacts. The focus of this workplan is to investigate environmental impacts on water resources and to draw economic implications from these changes. The economic component that fits the focus of the workplan is applied microeconomics rather than global macroeconomics. Global GDP is an untenable basis for economic analyses within this workplan. Benefit-Cost analysis offers the greatest insights on potential economic impacts of changes to Minnesota's water resources.

The focus of the workplan on water resources within the state leads to emphasis on the three categories of environmental impacts below. The major mechanisms for economic impacts to occur are included.

1. Lake and stream levels: flood damages, especially to infrastructure
2. Water temperatures: shorter ice duration, changes in fish populations, habitat, winter and summer kills
3. Water quality: multiple values of clean water identified in Section IV.

This list of categories of impacts and potential "receptors" that could lead to economic effects serves as a foundation for the empirical analyses reported in Section VI. Section VI.A relies on findings from the "lake and stream level" component of the larger study (led by Heinz

Stefan.) Changes in streamflow are considered as a basis for changes in damages from flooding. Historical data on damages to infrastructure from flooding and other weather-related damages is presented. Section VI.B uses evidence on shorter lake ice duration and creel survey data on patterns of recreational fishing to estimate potential changes in economic benefits from fishing.

As noted above in Section IIIC, the project findings on water quality were mixed, but generally historical trends, regardless of climate change, are toward improving measures of lake water quality. The historical trend results from a complex set of factors that influence water quality. Many factors are having a positive influence. Still the literature regards climate change as likely to have a negative impact on water quality. In this context, a brief overview of the importance of water quality in Minnesota is in order.

Overview of the Importance of Water Quality in Minnesota

The economics literature contains extensive conceptual treatment and empirical analyses of the value of water quality. Section IV covers major conceptual components and notes key contributions to the analytical framework and empirical evidence from works by Desvosges et al. (1983) and Fisher and Raucher (1984). Mitchell and Carson (1989) surveyed the literature thoroughly to that date. Various methods to measure economic benefits from water quality are found in the literature. Some employ techniques that include all aspects of WTP and others are lower-bound estimates based on market expenditures that capture only use values. Estimates in the literature also vary based on the narrowness or comprehensiveness of the water quality change evaluated. Water quality definitions in federal policy regarding suitability for boating, swimming and fishing have been the focus of benefits estimation studies. These aspects provide different foundations for defining the good to be valued. Under different circumstances, annual household values range from the double digits to low four digits.

There is a great deal of evidence that water quality is extremely important to Minnesota, “The Land of 10,000 Lakes.” These lakes contribute to the ecological, economic and cultural well being of the State. A report on water by the Minnesota Department of Natural Resources (MNDNR, 1998) stated: “High-quality water is essential for a healthy state economy.” The value of water quality is manifested in recreational and tourism activities, property values for lakeshore, investments in policies to protect water, and other ways in which citizens demonstrate WTP and the role of water in the MN quality of life.

A series of studies on the economic value of water have been conducted on surface waters in northern Minnesota. Henry, Ley and Welle assessed the willingness-to-pay for a particular lake, Lake Bemidji, among the general population in the surrounding trade region. Varying the geographical scope of water quality protection from national standards to aspects of a particular lake obviously affects the magnitude of value. Also the aggregate benefits to a population are directly related to population size. The average value for Minnesota households to protect lakes from acid rain was found by Welle (1986) to be around $75 per adult per year. Such average figures sum to large aggregate values when multiplied by millions of people who receive these benefits from protecting water quality.

Over the last twenty years a handful of studies have estimated the economic benefit of water quality as evidenced by tourism or recreational expenditures. Henry and Welle (1987) found tourists in northern Minnesota most often reported enjoying a clean environment as a motive for their trip, with spending of over $600 per party per vacation (thousands of dollars in today's terms.) Over three-fourths of respondents indicated an environmental attribute of the area as the thing they liked best about the area.

Throughout the 1990s a series of studies conducted by economists (Steinnes and Raab and others) at the University of Minnesota- Duluth and the Natural Resources Research Institute generated various estimates of benefits from water quality using recreational expenditure data, revealed preference techniques (travel-cost approach and hedonic-property values) as well as surveys. Total expenses for water-related recreation statewide were estimated at nearly $900 million with almost half of that designated as net gain to consumers (or consumer surplus.) Consumer surplus per acre of fishable water varied from over $100 to $900 across regions of Minnesota. In an extension of this approach, collaboration between the Minnesota Lakes Association and the Office of Tourism yielded estimates of the economic impact and employment effects of fishable lakes. The happy average that was plugged into the formula was that the typical acre of fishable lake generated $687 of direct consumer purchases. Economic values on a per acre basis were also estimated using Input-Output Analysis.

In a CVM study for the MN Pollution Control Agency, responses from Minnesota households yielded an average annual willingness-to-pay of about $200 to reduce mercury deposition in aquatic ecosystems in the state. Many respondents would explain that it was worth it to spend this amount on pollution prevention (which is equivalent to less than a dollar a day) to protect lakes that are such an essential part of our natural heritage. Again multiplying this average benefit per household times the millions of affected households yields an aggregate value in the hundreds of millions per year.

Krysel, et al. (2003) conducted a hedonic-pricing study on lakes in the Headwaters region of the state. Evidence from a series of studies in Maine indicated that water quality affects lakeshore property prices in a positive way because there is significant demand for it. Krysel et al. tested whether water quality similarly affects lakeshore property prices of Minnesota lakes. The major finding of this research is that water clarity positively influences lakeshore property prices.

The implicit prices of water clarity estimated in this study were based on a sample of lakeshore property transactions that took place on 37 lakes involving 1205 residential lakeshore property sales that occurred between 1996 and 2001. Property values were found to be higher on clearer lakes because buyers of lakeshore properties prefer and will pay more for properties on these lakes, all else equal. Therefore, sustaining and/or improving lake water quality will protect and/or improve lakeshore property values. On the other hand, if water quality is degraded, lower property values will result, which in turn will increase demand and development pressures on remaining lakes with the better water quality and could ultimately lower their water quality as well.

Based on prices in 1999, the median year of this study, a one meter decline in water clarity on the typical lake would result in loss of lakeshore property value of approximately $60 per frontage foot of lakeshore: known as the implicit price. This result was comparable to estimates in Maine that found the typical lakeshore lot would lose around $6,000-$8,000 in value due to the loss of clarity. The Headwaters Region of MN would be on the high end of this range considering the typical lot sold during the study period had about 150 feet of frontage. For many lakes in both Maine and MN with thousands of lakeshore lots, this translates to property value changes in the millions of dollars. Given inflation of lakeshore values since these data were collected of about 200% or a multiple of three, the implicit price today could be around $200 per front foot for a one meter loss in clarity. For a lot of 150 front feet, this converts to a $30,000 loss per lakeshore lot. This implies a loss of $1 million for lakeshore around a small lake with about 30-40 lots of typical size. An alternative calculation could b based on the total number of frontage feet on a typical lake, rather than the Maine calculation based on lots of typical size. If a loss of clarity of one meter resulted in a $200 loss in property value per front foot, this would amount to a $10 million loss for a MN lake of typical size of roughly 50,000 front feet of lakeshore. Most of the state's largest lakes and/or lakes with irregular shorelines have over 100,000 feet of shoreline. Leech Lake has over 880,000 feet of shoreline. These rough approximations suggest some lakes would see losses in the tens of millions or even hundreds of millions of dollars if climate change reduces water clarity by a meter.

If climate change has a negative impact on thousands of lakes within the state, the loss of economic value would be substantial. These assets (natural capital) would me much less valuable to MN than they otherwise could be. For a thousand lakes that might be degraded from climate change, the loss could be in the tens of billions of dollars. Time will tell what kinds of relative changes will result in light of other positive and negative processes impacting water quality, but the evidence in the literature indicates climate change is likely to have a negative net effect. Lakeshore property values provide just one measure of economic value of MN lakes to one group of citizens, riparian property owners. This excludes the benefits of water quality to all those resident and non-resident recreational users who don't own lakeshore. These people also have non-use values of water quality as do those who don't use the lakes at all.

Further evidence of high economic value of MN water quality is found in a study for the MPCA by Welle and Hodgson (2008). This study analyzed all components of public values for restoring water quality in impaired lakes within two watersheds in the Upper Mississippi River Basin of Minnesota. WTP for restoring impaired lakes is estimated among property owners (riparian and non-riparian) within the watersheds. The watersheds are the Sauk River (also known as the Horseshoe) Chain of Lakes and the Lake Margaret-Gull Lake Chain.

The causes of the impairments differ between the two watersheds, so different management options may generate different levels of net benefits. The analysis demonstrates that the watersheds are also different in terms of how property owners in the watershed relate to the impaired lakes. Many property owners are not residents of the watersheds (67% have ZIP codes outside the watershed for Margaret) and are wealthier and older than the average residents of the area. The pattern is less severe in the Sauk Watershed as about 11% of the property owners have mailing addresses outside of the watershed and Stearns County.

The Margaret-Gull Chain has a high degree of surface water as a percentage of watershed acreage compared to Sauk, and consequently a high proportion of lakeshore owners relative to the overall population of property owners in the watershed. The Margaret-Gull Chain also has many highly-valued lake properties owned by people with high incomes and a large amount of recreational use by lake owners and visitors.

The responses were utilized in various multiple regression functions to find specific equations that yield estimates of WTP. Estimates of mean WTP per household varied somewhat between alternative versions of the functions but the average was around $200 per year among respondents in the Margaret sample and around $20 for the Sauk respondents. These stark differences are explained in the model given the contrasts in the characteristics of the watersheds and the patterns of property ownership within the watershed. While the estimated equations for the two watersheds have slightly different coefficients, the extreme differences in WTP result from huge differences in the average values for the variables (percent of property that is riparian, percent who recreate on the impaired lakes, etc.) between the watersheds.

Even the lower end of this dollar range leads to substantial economic value for the population given water quality improvements are a public good enjoyed by all who hold preferences for water quality, regardless of whether they own riparian property or recreate on these lakes. These household WTP values can be used as the basis for crude estimates of the value of avoiding loss of water quality that could result from climate change. Evidence is lacking to determine whether only a few or very many MN lakes might be negatively impacted by climate change. But being it is a global phenomenon that pertains to all MN watersheds, as opposed to excess nutrient loads in a particular lake, the percentage of lakes impacted is more likely to be higher than lower. Given the introduction of aquatic invasive species is expanding through time, if climate change tilts the scale toward invasive plants crowding out native lake vegetation, this could damage thousands of MN lakes.

As an example that yields round numbers, the median of the dollar range for restoring lakes found by Welle and Hodgson (2008) could be used: $100 per household per year. The study found that the lower value for the average respondent in the Sauk watershed resulted from them living 20-40 miles from the impaired lakes and never recreating on them. Some of these respondents expressed much higher WTP to restore lakes in adjacent watersheds that were nearer to them and that they used for recreation. If one thousand MN lakes were to suffer negative impacts from climate change, this would encompass lakes that are “favorites” to many people around the state, not to mention visitors. In that case, the WTP for the average MN household would be much higher, perhaps even above the Margaret-Gull average WTP of $200 per household per year. Using $100 per year as the value of the public good and assuming the collective benefit goes to 2 million MN households, this would yield $200 million in economic benefit per year. When accumulated over decades, even with discounting of future values, this rough approximation indicates benefits in the billions of dollars. It should be noted that these billions of dollars in economic benefits would go to all citizens, most of whom don’t own lakeshore. So the portion of multi-billion dollar benefits accruing to Minnesotans who don’t own lakeshore would need to be added to the multi-billion dollar estimate of lakeshore property values that could be lost.

Use values and non-use values of non-residents for MN water quality would need to be considered to estimate the total value of these potential impacts. MN residents could reasonably be expected to also attach value to water quality in neighboring states and provinces. While the analysis of water quality trends conducted for this project do not allow isolation of climate change effects on MN water quality, this summary of economic evidence indicates that the stakes are high.

C. Other Potential Economic Impacts in MN

It is beyond the scope of this study to conduct thorough conceptual and/or empirical analyses of potential impacts of climate change on MN resources other than water. Still a cursory discussion of other major impacts provides context for the subject. Considering these other types of impacts also broadens and deepens the understanding of potential impacts on water resources. Major categories of impacts that could have significant economic consequences are listed below. This section concludes with elaboration on the economic channels through which these impacts could be manifested.

1. Health Impacts
2. Energy Impacts
3. Forestry Impacts
4. Agricultural Impacts
5. Cold-Weather Research
6. Transportation & infrastructure not related to Water
7. Ecological Impacts
8. Potential Recreational Impacts, non-water related

1. Potential Health Impacts

The MN Department of Health (MDH) has been studying the issue of climate change in the context of its mission as a state agency. MDH staff participated in the adaptation summit held in Decemeber of 2009 and shared helpful information for the purposes of this study. A document assembled for an agency meeting (MDH, 2010) was based in part on materials from the State Environmental Health Indicators Collaborative (SEHIC, see English, et al., 2009). Section V.C from the MDH report lists SEHIC’s proposed categories of indicators for climate change. The categories below could have severe negative economic impacts leading to loss of state, national or global GDP. The GDP losses would be comprised of severe losses in specific markets. Substantial losses of non-market values could also occur. The health impacts stress - as much as any category of impacts - the potential loss of human life, which is difficult to value in dollar terms.

Environmental Indicators: Greenhouse Gas Emissions, Air Mass Stagnation Events, Ozone due to Climate Change, Maximum and Minimum Temperatures/ Heat Index, Increase in Heat Alerts/ Warnings, Pollen Counts, Wildfire Frequency, Severity, Distribution, and Duration, Droughts, and Harmful Algal Blooms;

Morbidity & Mortality Indicators: Excess Mortality due to Extreme Heat, Excess Morbidity due to Extreme Heat, Number of Injuries/ Mortality from Extreme Weather Events, Human Cases of Infectious Disease/ Positive Test Results in Sentinels and Reservoirs, Respiratory/ Allergic Disease and Mortality Related to Increased Air Pollution and Pollens;

Vulnerability Indicators: Population Vulnerability or General Social Vulnerability, Heat Vulnerability, Flood Vulnerability, and Sea Level Rise Vulnerability

2. Potential Energy Impacts

The interface between climate change and energy demand is often expressed as the change in heating and cooling degree days. Climate change evidence indicates increases in ambient temperatures so that MN is experiencing fewer heating degree days, especially in the cold months and more cooling degree days in the summer. In light of the research by Heal and Kristrom (2002) on humans' preferred temperatures mentioned above in-door climate control leads to changing energy demand. Given MN's image as a cold place, many might expect that fewer heating degree days would be a huge, positive result of climate change. But the dividing line between whether more energy is used for heating or cooling cuts through MN with the majority of the population in the metro area residing south of the line, so greater annual energy demand goes to cooling. Warmer ambient temperatures will increase energy demand. So even in MN this will be a positive feedback mechanism leading to a cycle of potentially greater GHG emissions.

Another energy feedback is associated with higher heat indices in the summer, which also project to greater demand for cooling. Higher ambient temperatures are being combined in summer with higher dew points, so that more cooling for comfort is needed to deal with higher humidity/heat indices. One energy impact that is related to water could be on hydroelectric generation. Given more extreme variations in streamflow, low flows could become insufficient for energy generation.

3. Potential Forestry Impacts

Projected changes to MN forests include changes away from the classic pine forests of northern MN to oak savanna and greater distribution of deciduous trees. A positive impact that is predicted is longer growing seasons so increased rates of growth in the commercial forests of the state. Yet there is concern about the changing composition of the forests that might shift toward less desirable tree species with less economic value. These are potentially large economic consequences. While economic impacts to forests are beyond the scope of this study, it is important to note that ecological goods and services extend beyond commercial forestry and cold have substantial market and non-market values.

4. Potential Agricultural Impacts

Potential impacts to agriculture that are water related include vulnerability of water supplies for irrigation. Drought-related low flows could lead to surface water and groundwater deficits. Just as trees could have longer growing seasons and higher rates of growth, so to could agricultural plants. Impacts to agricultural crops could become a positive impact.

5. Cold-Weather Research

Cold-weather research adds economic activity that is important to many MN communities. A major industry that utilizes the MN climate for product testing is the automotive industry. These and other products must hold up to the cold faced by millions of people within local and international markets. Evidence on climate change in MN cited above indicates that MN is experiencing warmer winters, especially higher minimum temperatures. Climate data indicates a shift toward more frequent freeze-thaw cycles. Some cold-weather research seeks out sub-freezing temperatures, while others come to MN in late winter to test product performance in freeze/thaw cycles. MN may become less suited for testing in sub-freezing conditions but more attractive for freeze/thaw testing. Given global climate change, global markets may shift away from sub-zero product performance concerns toward freeze/thaw performance as well as tolerance to extreme heat.

6. Transportation and Infrastructure Not Related to Water

Empirical analysis in Section VI.A below investigates damages to infrastructure from weather-related events. Historical trends in damages are presented, including from federally declared disasters. Many of the transportation damages come from flooding, such as washouts of roads, bridges and culverts. These damages are a focus of this study being they are water related. Transportation impacts not related to water include possible damages to road materials due to the increased freeze/thaw cycles noted above.

7. Ecological Impacts

Ecological changes that could result from climate change could have positive and negative effects on the flows of ecological goods and services. While some of the goods and services have values revealed in markets, many of these are non-market values. A major concern based on the literature should be loss of ecological integrity and resilience, with increased stress on many species that may confront conditions outside their tolerances. In particular, the literature points to circumstances which are conducive to native species being replaced by invasive species, both aquatic and terrestrial. Such changes could have severe socio-economic consequences, especially if conditions change beyond tolerances of native species.

8. Potential Recreational Impacts

Empirical analysis in Section VI.B below investigates potential climate change impacts on recreational fishing as a result of shorter ice duration. As important as water-based recreation is in MN, there could be climate impacts on recreation not related to water. Winter recreation is important to the way of life (and quality of life) of many in the state. Some choose to live in MN for the pronounced seasons or perhaps because winter is their preferred season. Winter conditions in MN will likely “soften” in the future. There will likely be a loss of recreation depending on cold and snow. But these losses may be completely or partially offset by more days for recreation that don’t depend on snow and ice.

SECTION VI
POTENTIAL ECONOMIC EFFECTS OF CHANGES IN MINNESOTA'S WATER RESOURCES

A. Potential Economic Impacts from Changes in Water Flows

Economic analysis of the potential impacts of climate change must be based on sound-reliable scientific evidence on the change that could result. This economic study is one component of a larger project designed to gather evidence of current changes that may be unfolding. Section IIIC above is critical to this report given its findings from other researchers on the project team regarding changes occurring to Minnesota's water resources. Section B below explores potential climate change impacts on recreational fishing due to shorter ice duration. The empirical evidence is summarized in that section. As a foundation for this section, the evidence on changing streamflows will be reviewed briefly.

While the literature on global changes, including US federal government research, indicates higher lake levels in the Midwest, except perhaps the Great Lakes, research on MN lake levels thus far yields mixed results. Lake levels appear to be less susceptible to immediate pulses of water from precipitation and snowmelt than are rivers and streams. In a sense it's like the vulnerabilities of rivers and streams to flash-flooding that is not an immediate concern for lakes. This is not to say that fluctuations in lake levels are not a concern in MN, but the evidence thus far points to water levels in rivers and streams warranting more attention.

Project team member Heinz Stefan and his colleagues have studied water levels in lakes, rivers and streams. The streamflow analysis was based on data from gauging stations in the five major river basins of the state. In general, this evidence is consistent with impacts predicted in the literature. Results vary between the five basins, but generally the data indicate higher median flows and higher 90th percentile flows. Methods of describing riverine flows utilize measurements of time spans, such as 1-year, 10-year, 20-year, 100-year and 500-year floods. Ten-year floods should occur every ten years so should have a one in ten chance of occurring in any given year. One-hundred year floods should have only a one-percent chance of occurring and 500-year floods should have a probability of only two tenths of one percent. The work by Stefan and associates indicates that these floods are happening more frequently than the odds predict, especially for the 10-20 yr. floods. The statistics are less meaningful for the most extreme events associated with the most severe damages: 100-year and 500-year floods. If the chances of these categories of floods are increasing beyond the corresponding frequencies, than the hydrographs to fit these definitions would need to be adjusted. While that is beyond the scope of this project, it may be pursued by relevant state agencies that rely on these hydrological measures, such as MDOT. The same is true for flow measures based on percentiles. Higher flow levels through time would mean the 90th percentile level would be exceeded more than 10 percent of the time. So the level defined as 90th percentile would have to be adjusted upward, i.e. a higher flow volume is defined as the 90th percentile and/or the old 90th percentile becomes a lower percentile, such as the new 85th percentile.

Even though the most extreme flow levels do not exhibit strong statistical changes, the increased baseline (median) flows and more frequent 10 to 20-year flood events could be evidenced by a trend toward increasing infrastructure damages. The evidence from the data must be couched in terms of limitations of data availability in terms of temporal and spatial scales: i.e. too few years of water levels are available to show long-term trends and too few flow measures have been taken within watersheds at the levels of tributaries or smaller in the five major basins. Downscaling of data may be necessary to enhance understanding of flooding patterns. Catastrophic events such as the southeastern MN flood of 2007 that severely damaged Rushford and the surrounding area must also be recognized even though data availability may make it hard to place these extreme events in context. The economic evidence below does include these extremely damaging events even though they may be difficult to define in terms of evidence of climate change.

Another nuance of the merging of evidence on streamflows and damages relates to the higher base flow levels, especially in late winter and spring as snow melt enters the major basins. This pattern worsens risks of spring flooding in ways that may be too difficult to discern from data available thus far. Higher base flows and greater snow melt create worse vulnerability to early spring rains putting rivers and streams even higher above flood stage. The extreme flood event in the Red River Valley in 1997 was unusual given the record snow depths of that winter, but increased likelihood of rain at this time would exacerbate the problem. The 1997 floods show up in the damage records below. Our retrieval efforts for data on damages to transportation infrastructure was most intensive for that year given its severity and for illustrative purposes.

It is essential to recognize that many variables are changing through time and some in consistent directions that would indicate historical trends for more or less flood damages. One factor suggesting that historical trends would be toward more damages is simply the inflation of the resources and materials that are lost. Increasing development also places more valuable assets in harm's way. MNDOT personnel (Frank Pafko and Luane Tasa, personal correspondence) note these and other changes that make dollar amounts difficult to compare over the years. Policy has been in place for some time to invest in prevention of future damages by making scheduled replacement of transportation infrastructure (roads, bridges, culverts, etc.) to withstand high flow events. Furthermore when damages occur and emergency repairs are needed thee too are being done to provide a buffer or guard against the failure of infrastructure repeating itself. This policy should lead to a decrease in damages over time. (State Aid and Design manuals for highways, culverts and stormwater cited in Section III reflect these policies.) Historical trends are difficult to interpret given outcomes on damages result from a combination of influences, some positive and some negative. As noted above, overall changes in the measures of water quality in MN lakes provide another important example of how complex processes make it difficult to isolate separate impacts of climate change. Multiple variables that influence infrastructure damages are in flux in MN so that the data on damages must be interpreted with caution.

While damages to transportation infrastructure as a result in changing streamflows were emphasized in the workplan, non-transportation infrastructure also merits attention. Some of the most expensive repairs are needed when drinking water facilities are overcome, especially if in conjunction with inundation of wastewater treatment plants. Precautions for human health make emergency water supply and long term repair have made this category of damages very costly when the occur. The evidence in MN would indicate that these catastrophic damages are not increasing as dramatically as more numerous washouts of less costly infrastructure such as secondary roads and culverts associated with 10 to 20-year flood events. The data on damages reported below warrants explicit mention of some basic arithmetic: total damages amass just as much through many incidents of low to moderate cost as with fewer incidents of high cost. The former, if not the latter, would appear to be occurring more frequently in MN as a result of climate change.

Before moving on to a discussion of damage figures, greater dispersion of flows, including more extreme low flows should also be mentioned. Project findings on generally higher flows should not mask the possibility of economic costs of extreme low flows during extended droughts. The basins that show the most significant changes in flow are the Red River of the North and the MN River. Concerns over dependable water supply in the Red River of the North (Fargo-Moorhead and Grand Forks-East Grand Forks) have led to research and policy discussions as to these vulnerabilities and possible remedies. Again climate change makes this situation more risky.

Damage figures below are presented in order of most general categories of infrastructure to data more specific to transportation at the end. Table VI.1 provides figures from a NOAA study (2002) that reports the history of U.S. flood damages from 1955 to the most recent year, 2000. The report re-examines date back to the 1920s but only details damages state-by-state from 1955- 2000. Damage figures for MN are included here.

Table VI.1. Flood Damage in Thousands of Current Dollars With Deflator to convert to 1995 $ (Note: constant dollars found by dividing by the implicit price deflator according to the U.S. Bureau of Economic Analysis, 2001. No estimates for 1980-1982.)

Year	Deflator	Current $	Constant 1995 $
1955	0.20163	0	0.000
1956	0.20846	11	52.768
1957	0.21539	9,128	42378.941
1958	0.22059	17	77.066
1959	0.22304	50	224.175
1960	0.2262	212	937.224
1961	0.22875	552	2413.115
1962	0.2318	1,290	5565.142
1963	0.23445	26	110.898
1964	0.23792	0	0.000
1965	0.24241	97,603	402636.030
1966	0.24934	4,300	17245.528
1967	0.25698	0	0.000
1968	0.26809	1,197	4464.918
1969	0.28124	67,168	238828.047
1970	0.29623	4,350	14684.536
1971	0.31111	15	48.214

1972	0.32436	64,318	198292.021
1973	0.34251	242	706.549
1974	0.37329	16,939	45377.588
1975	0.40805	139,726	342423.723
1976	0.43119	0	0.000
1977	0.45892	7,870	17148.958
1978	0.49164	65,000	132210.561
1979	0.53262	13,140	24670.497
1980	0.58145		
1981	0.63578		
1982	0.67533		
1983	0.70214	310	441.507
1984	0.72824	5,000	6865.868
1985	0.75117	500	665.628
1986	0.76769	1,501	1955.216
1987	0.79083	27,800	35152.941
1988	0.81764	555	678.783
1989	0.84883	17,600	20734.423
1990	0.88186	3,032	3438.187
1991	0.91397	1,280	1400.484
1992	0.93619	1,760	1879.960
1993	0.95872	964,050	1005559.496
1994	0.9787	1,867	1907.633
1995	1	3,750	3750.000
1996	1.01937	460	451.259
1997	1.03925	743,218	715148.424
1998	1.05199	2,529	2404.015
1999	1.06677	466	436.833
2000	1.09113	43,112	39511.332

The most informative column shows damages standardized in 1995 dollars, in thousands. This shows that from 1955 – 1970 there were three years with damages in the tens of millions of dollars and two in the hundreds of millions. From 1971 – 1984 (1980-82 missing) there were three years with damages in the tens of millions of dollars and three in the hundreds of millions. From 1985 – 2000 there were three years with damages in the tens of millions of dollars and the two years with the highest damages 1997 and 1993. The latter had damages in excess of $1 billion in constant 1995 dollars.

The MN Department of Public Safety's Division of Homeland Security & Emergency Management summarized damage information over the decade of the 1990s. The summary is more enlightening than the totals above being the damage figures are broken down into informative categories. The report "A Decade of Minnesota Disasters: A Historical Look at Minnesota Disasters in the 1990s" notes that the specter of climate change places increased importance on changing weather patterns and the increase in storm occurrence and intensity. The report focuses on weather related damages in Minnesota throughout the 1990s. According to the report, these damages are increasing and during the 1990s there was 14 presidential declarations of major disasters. Most of the damages were the result of flooding, ice storms, snow removal, straight-line winds, tornadoes, and heavy rain. From these disasters Minnesota taxpayers spent $827 million and the cost to insurance companies was more than $2 billion.

The types of aid used to finance these damages are listed below.
The Public Assistance Program totaled more than $370 million. This aid is used to rebuild schools, hospitals, fire stations, police stations, city offices, water and sewage treatment plants and other public buildings. Also included are non-profit electric cooperatives and transmission lines. Funds are given to state and local governments, school districts, Indian tribes, and certain private non-profit organizations, such as electric power co-operatives, and educational facilities. Money is used to repair, restore, or rebuild public infrastructure damaged during a presidentially declared disaster. Sub-categories and percentages paid include: building & equipment 25.9%, protective measures 20.9%, public utility systems 20.2%, roadways 12.6%, debris clearing 12.3%, park and recreational facilities 4.7%, and water control facilities 3.4%.

Another category is the Hazard Mitigation Grant Program: More than $51 million. This is intended to reduce or eliminate future damages. Funds are used for acquiring properties damaged by flooding, burying power lines, installing snow fences, and increasing weather radio coverage in the state. Sub-categories include: acquisition 64.7%, utility protective measures13.6% misc. projects 9.3%, stormwater management 9%, NOAA transmitters 1.10%, water and sewer protection .9%, management costs .3%, mitigation plans .2%, studies .1 %, and retrofitting .1%. This program provides 75% cost-share on the cost-effective mitigation measure of costs. Recipients include local communities, certain non-profits, and state agencies. Dollars are based on 15% of the Public Assistance and Individual Assistance Programs funds provided by FEMA.

The Individual and Family Grant Program helps cover expenses not covered by insurance, such as housing, personal property, medical and dental expenses caused by the disaster, funerals, and transportation. From 1990 – 1999 the USDA (Farm Service Agency) paid a total of $57,404,110. Eligibility within a county requires demonstration of 30% crop loss county-wide. The Small Business Administration (SBA) provides low-interest loans to homeowners and business affected by a disaster. More than $193 million was paid out of this program during the 1990s.

There are three types of SBA loans:
1. Home Disaster Loans: loans to repair or replace damages to real estate or personal property owned by victim. Renters are eligible for personal property losses.
2. Business Physical Disaster Loans: Businesses of any size are eligible to repair or replace losses such as real estate, machinery and equipment, inventory and supplies..
3. Economic Injury Disaster Loans: Loans for working capital to small businesses and small agricultural cooperatives.

The report also ranks MN hazards by category of loss that occurs. It is based on data from the Minnesota Hazard Mitigation Plan. The rankings are a composite of: likelihood of occurrence, frequency, and historical impacts as natural hazard affecting the state. Blizzards are the top cause of Deaths per year, first ranking for injuries per year (ice and sleet), and first ranking for economic impact per year (floods). Programs and policies to reduce future damages are: smart growth, efficient housing, uniform building codes, consumer education (flood insurance), comprehensive planning, policy formation, and hazard mitigation to reduce consequences before they happen.

Table VI.2 lists the 14 declared disasters for the 1990s, including totals by year. Some years had multiple declared disasters.

Table VI.2. FEMA Declared Disasters in MN During the 1990s

1. FEMA 1288 DR MN (1999) Total Cost $11.1 million
2. FEMA 1283 DR MN (1999) Total Cost $52.2 million
3. FEMA 1225 DR MN (1998) Total Cost $1.5 billion
4. FEMA 1212 DR MN (1998) Total Cost $246.1 million
5. FEMA 1187 DR MN (1997) Total Cost $85.4 million
6. FEMA 1175 DR MN (1997) Total Cost $545.0 million
7. FEMA 1158 DR MN (1997) Total Cost $82.4 million
8. FEMA 1151 DR MN (1997) Total Cost $20 million
9. FEMA 1116 DR MN (1996) Total Cost $48 million
10. FEMA 1078 DR MN (1996) Total Cost $6.7 million
11. FEMA 1064 DR MN (1995) Total Cost $18 million
12. FEMA 993 DR MN (1993) Total Cost $215.1 million
13. FEMA 946 DR MN (1992) Total Cost $32.5 million
14. FEMA 929 DR MN (1991) Total Cost $11.7 million

Totals by Year: Sum for Decade $2,874,200,000

Year	Totals
1999	63,300,000
1998	1,746,100,000
1997	732,800,000
1996	54,700,000
1995	18,000,000
1994	0
1993	215,100,000
1992	32,500,000
1991	11,700,000
Total	2,874,200,000

Denise Peterson of the Department of Public Safety was extremely helpful in sharing the most recent figures on damages over the past decade. While the decade 2000-2009 has not been summarized as yet into a report similar to the one for the 1990s, summary figures were provided for inclusion in this report. Damages are separated by categories A-G as follows.

FEMA Categories of Work

Emergency Work

Category A: Debris Removal	Clearance of trees and woody debris; certain building wreckage; damaged/ destroyed building contents; sand, mud, silt, and gravel; vehicles; and other disaster-related material deposited on public and, in very limited cases, private property.
Category B: Emergency Protective Measures	Measures taken before, during, and after a disaster to eliminate/reduce an immediate threat to life, public health, or safety, or to eliminate/reduce an immediate threat of significant damage to improved public and private property through cost-effective measures.

Permanent Work

Category C: Roads and Bridges	Repair of roads, bridges, and associated features, such as shoulders, ditches, culverts, lighting, and signs.
Category D: Water Control Facilities	Repair of drainage channels, pumping facilities, and some irrigation facilities. Repair of levees, dams, and flood control channels fall under Category D, but the eligibility of these facilities is restricted.
Category E: Buildings and Equipment	Repair or replacement of buildings, including their contents and systems; heavy equipment; and vehicles.
Category F: Utilities	Repair of water treatment and delivery systems; power generation facilities and distribution facilities; sewage collection and treatment facilities; and communications.
Category G: Parks, Recreational Facilities, and Other Facilities	Repair and restoration of parks, playgrounds, pools, cemeteries, mass transit facilities, and beaches. This category also is used for any work or facility that cannot be characterized adequately by Categories A-F.

Table VI.3.A. Damage Totals for FEMA Declared Disasters 2000-present

Eligible Damages by FEMA Category

* Disasters are "open" until all approved projects have been completed, reimbursed, and signed off by FEMA.
** Total includes only the federal and state share of funding paid under the Stafford Act. Other federal funds, special state appropriations, and local funds are not included.

	Public Assistance Program (PA)							
Declared	Category A Debris Removal	Category B Protective Measures	Category C Roads and Bridges	Category D Water Control Facilities	Category E Public Buildings	Category F Utilities	Category G Parks, Recreational/ Other Facilities	PA Total
04/19/2010	$ 2,364,969	$ 5,915,615	$ 7,412,674	$ 592,846	$ 23,917	$ 207,250	$ 1,389,798	$ 17,907,069
03/19/2010								$ -
04/09/2009	$ 2,273,264	$ 9,565,376	$ 20,490,489	$ 2,558,564	$ 287,597	$ 2,725,821	$ 320,740	$ 38,221,852
03/26/2009		$ 726,393						$ 726,393
06/25/2008	$ 358,976	$ 233,331	$ 6,485,242	$ 518,165	$ 39,599	$ 437,367	$ 165,383	$ 8,238,063
08/23/2007	$ 3,210,090	$ 3,344,675	$ 19,283,808	$ 964,055	$ 9,898,458	$ 3,232,683	$ 3,819,673	$ 43,753,443
06/05/2006	$ 360,922	$ 862,126	$ 4,914,017	$ 2,833,525	$ 1,877	$ 101,200	$ 50,243	$ 9,123,910
01/04/2006	$ 325,369	$ 866,692	$ -	$ -	$ -	$ 9,264,860	$ 8,450	$ 10,465,370
10/07/2004	$ 277,461	$ 368,535	$ 2,102,480	$ 833,865	$ 551,086	$ 545,368	$ 358,548	$ 5,037,343
06/14/2002	$ 2,168,277	$ 2,783,629	$ 18,052,322	$ 2,386,159	$ 2,301,735	$ 4,683,795	$ 1,567,348	$ 33,943,265
05/16/2001	$ 3,379,888	$ 8,059,208	$ 20,819,214	$ 2,329,718	$ 184,500	$ 9,661,881	$ 2,092,458	$ 46,526,867
06/27/2000	$ 2,636,168	$ 2,381,109	$ 5,380,831	$ 1,107,078	$ 883,210	$ 1,793,093	$ 659,441	$ 14,840,929

Table VI.3.B. Damage Totals for FEMA Declared Disasters 2000-present: Descriptions and Totals

* Disasters are "open" until all approved projects have been completed, reimbursed, and signed off by FEMA.
** Total includes only the federal and state share of funding paid under the Stafford Act. Other federal funds, special state appropriations, and local funds are not included.

	Description	Assistance Type	PA Total	Individual Assistance Program (IA)	Hazard Mitigation Grant Program (HMGP)	*Total
04/19/2010	Flooding (estimates)	PA, HMGP	$ 17,907,069		$ 2,686,060	$ 20,593,129
03/19/2010	Flooding	PA	$ -			$ -
04/09/2009	Severe Storms and Flooding	PA, IA, HMGP	$ 38,221,852	$ 3,100,059	$ 6,204,157	$ 47,526,068
03/26/2009	Severe Storms and Flooding	PA	$ 726,393			$ 726,393
06/25/2008	Severe Storms and Flooding	PA, HMGP	$ 8,238,063		$ 938,765	$ 9,176,828
08/23/2007	Severe Storms and Flooding	PA, IA, HMGP	$ 43,753,443	$ 31,506,210	$ 10,180,020	$ 85,439,673
06/05/2006	Flooding	PA, HMGP	$ 9,123,910		$ 510,479	$ 9,634,389
01/04/2006	Severe Winter Storm	PA, HMGP	$ 10,465,370		$ 624,188	$ 11,089,558
10/07/2004	Severe Storms and Flooding	PA, IA, HMGP	$ 5,037,343	$ 4,067,243	$ 607,510	$ 9,712,096
06/14/2002	Severe Storms, Flooding and Tornadoes	PA, IA, HMGP	$ 33,943,265	$ 10,573,453	$ 5,859,732	$ 50,376,450
05/16/2001	Flooding	PA, IA, HMGP	$ 46,526,867	$ 4,559,731	$ 5,625,419	$ 56,712,017
06/27/2000	Severe Storms, Flooding and Tornadoes	PA, IA, HMGP	$ 14,840,929	$ 5,012,976	$ 4,784,611	Declared

One of the infrastructure impacts anticipated in the literature is that extremely high streamflows will cause failure of dams. Consultation with MNDNR officials (Personal correspondence Jason Boyle, State Dam Safety Engineer) indicates that no dam failures have occurred in MN. We “don't have records on damage to dams or other infrastructure from floods or dam breaks. Several earthen dams experienced emergency spillway erosion caused by the flooding in SE MN in 2007 and 2008, though no dams we regulate actually failed.”

An extreme rain event occurred in SE MN in 2007. An excerpt from an email after the 2007 flooding sent out by the DNR Commissioner, is informative: “Now we are moving to the recovery phase, helping people and business to get back on their feet and to repair damages to public facilities. During the flood many DNR facilities were damaged. At the moment, based on preliminary damage assessments, those damages appear to total about $10.7 million. The damage occurred in state parks, wildlife management areas, in state forests, and at fish hatcheries.’

The southeastern MN flood event of 2007 caused considerable damage, but dam failure did not occur. Reviewing the damage amounts in the seven categories (A-G) for the FEMA declared disasters, reveals that Category C: Roads and Bridges typically suffer the largest damages. Further understanding can be gained by delving into transportation infrastructure as a category of damages.

Shawn Chambers, staff person of the Minnesota Department of Transportation, Office of Capital Programs and Performance Measures, assisted by sending available damage estimates for selected years in the last decade. She accessed summary information on the three most noteworthy flooding events in MN since 2000. Shawn Chambers (personal correspondence, 2010) described a statewide event in 2001 due to heavy rains and in 2002 and 2006 there were major springtime flooding events in the Red River Valley. She accessed information for the counties involved in the 2002 and 2006 flooding events and was able include damage estimates for counties in the 2001 flooding event as well.

She also noted the major flooding event in 1997 that included the counties of Big Stone, Blue Earth, Brown, Chippewa, Dakota, Grant, Lac Qui Parle, Le Sueur, Nicollet, Polk, Redwood, Renville, Sibley, Stevens, Swift, Traverse, Wilkin, and Yellow Medicine. The damage estimate reports were not collated electronically as were the more recent years so summary figures from MDOT was not available for 1997. Nor was it for the SE Minnesota flood in 2007. MNDOT staff noted these figures are for federal aid eligible routes only. Other road damage may have occurred but is not included if it was not eligible for Federal Highway Administration Emergency reimbursement. These damage figures are informative in indicating the level of transportation damages in recent years. But for the purposes of this study, the data span too short of a time to be more than illustrative of the magnitude of damages that have been occurring. Making projections about climate change impacts would not be sound with this limited data.

Table VI.4. Statewide Flood Events: 2001, 2002, and 2006 Damage Estimates by County and Road Authority

A. 2001 Red River Flood Event
MnDOT Highways

County	County Total
Kittson	184,931
Norman	16,253
Polk	57,562
Total MnDOT Highways	**258,746.00$**

2001: Local Roadways (CSAH & some city streets)

County	County Total
Kittson	27,757
Marshall	130,063
Norman	225,140
Polk	415,168
Total Local Roadways	**798,128.00$**

B. 2002 Red River Flood Event
Damage Estimates by County and Road Authority
MnDOT Highways

County	County Total
Becker	24,420
Clay	45,676
Clearwater	6,195
Hubbard	11,125
Koochiching	153,939
Lake of the Woods	301,956
Norman	703,747
Polk	66,325
Red Lake	43,476
Roseau	100,573
Total MnDOT Highways	**1,457,432.00$**

Local Roadways (CSAH)

County	County Total
Clearwater	183,380
Kittson	52,437
Lake of the Woods	294,308
Marshall	31,925
Norman	227,626
Polk	103,410
RoseauRoseau	931372,
Total Local Roadways	**1,824,458.00$**

C. 2006 Red River Flood Event
Damage Estimates by County and Road Authority
MnDOT Highways

County	County Total
Clay	1,064,667
Kittson	22,314
Marshall	479,461
Norman	86,655
Otter Tail	1,076,242
Polk	91,370
Total MnDOT Highways	**2,820,709.00$**

Local Roadways (CSAH)

County	County Total
Becker	60,339
Clay	8,757
Kittson	227,335
Marshall	105,791
Norman	337,644
Otter Tail	3,052,806
Polk	110,441
Roseau	42,257
Wilkin	24,256
Total Local Roadways	**3,969,626.00$**

To provide further illustration of the magnitude and types of damages to transportation infrastructure that have occurred, hard copies of damage reports for the 1997 Red River Valley flood were collated by hand. This information is summarized in Table VI.5 below.

Table VI.5. 1997 District 2 Flood Data

County	Location	Type of Damage	Total Damage
Marshall	CSAH # 4 (Big Woods Twp)	Shoulder washing, debris removal, bit. Paving	31,558
Marshall	CSAH # 9, (Oak Park Strip)	Shoulder washing & debris removal	10,877.07
Marshall	CSAH # 4, (Middle River Twp.)	Shoulder washing & replace 7 entrances	9,162.35
Marshall	CSAH # 10, Sec. 5, T-155-49	Shoulder Washing and Debris Removal	3982.66
Marshall	CSAH #2, N. Road ditch	road ditch eroded, washed out field approach	7000
Marshall	CSAH # 10, (Bloomer Twp.)	Bridge approach & wingwall	21,093
Marshall	CSAH #5, (Fork Twp.)	Should washout & removal (3miles)	26,560.00
Marshall	Bridge on CSAH # 6	Rip Rap & slopes under bridge washed out.	5,000
Norman	CSAH No. 30 Sec. 1 & 2 T146 N	Ditch erosion and sedimentation	4700
Norman	CSAH No. 14, TH 200 to CSAH 39	Roadway washout, surface and shoulders	37,469.30
Norman	CSAH 25 at Hendrum	Rd.washout and surface and shoulders	152621.66
Norman	CSAH 3 West of Shelly	Shoulder damage, ditch erosion, flood debris	35,210.19
Norman	Bridge #54532, on CSAH # 29	Erosion repair @ ne. cor. And repair rip-rap	18,450
Norman	Bridge #54528 on CSAH #14	rip-rap erosion at both piers	3,250
Norman	Bridge # 93302 on CSAH #38	Rip rap at bridge	5,550
Norman	Bridge #93473 on CSAH 29	Erosion Repair and riprap and clean debris	3,904
Pennington	Intersection of TH 59 and CSAH 3	Culvert replacement/washout	14,485.11
Roseau	CSAH 23 (south of TH # 11)	water overtopped rd.	31,657.00
Roseau	CSAH 8 (from CSAH # 3 to TH 89	spring flooding eroded ditches, backslopes	27,685.30
Roseau	CSAH 7 (4 miles east of west co. line)	water overtopped rd, eroded roadtop	128,885.41
Clearwater	CSAH 4 at 2.50 miles E. of TH92	Washout of road and centerline pipe	11,106.85
Beltrami	CSAH 5	Road and Culvert Washout	6,356.44
Beltrami	CSAH 5	Culvert washout	4,152.24

Beltrami	CSAH 22	Road and colvert washout	10,855.43
Beltrami	CSAH 23	Road and colvert washout	12,064.82
Beltrami	CSAH 36	Culvert washout	8,250
Kittson	CSAH 5 Marshall Co. line to TH 11	Road washout , loss of rdway and roadway surface	5,800
Kittson	CSAH 7	Loss of shoulder	29,535
Kittson	Co. Rd. 68	Aggregate surface loss and & debris	12,930
Kittson	CSAH 28 north of CSAH 10	Approx. 950' of Bit. Wearing course	8,190
Kittson	CSAH 22 Br.no.35502	Loss of slope and riprap material	7,568
Kittson	CSAH 6	Bit. Wearing course	20,910
Kittson	CSAH 4 b/w CSAH 16 & 4 Mi.East	Loss of aggregate surface and debris	38,605
Kittson	CSAH 16 from TH 175 to 6 miles North	Debris and aggregate shoulder loss	54,022.50
Polk	23rd st. River rd. to HWY 220N	Erosion, Buckling, culvert sep.	246,892
Polk	5th ave. NE	sothbound lane settled	1,326,809
Polk	East Grand Forks Bike Path	Washout, damaged shoulders, erosion, collaspe	157,608
Polk	1st st se	Damage from hauling	3,402
Polk	Bygland Rd SE (3rd st se)	Damage from hauling	14,256
Polk	Central Ave.	Damage from hauling	1,508
Polk	5th ave. NE, 17th st.ne,20th st ne	Pavement failure	42,320
Polk	Central Ave. and MNTH2	Pavement failure	33,047
Polk	CSAH 44	Runoff damage, washed out culverts	23,440
Polk	CSAH 1 MP DO 1.2	Overtopped rds, should+surface damage	38,445
Polk	CSAH 9 MP do MP0.4	Debris removal, road and shoulder washout	20,512
Polk	CSAH 72 MP 2.10	Shoulder and inslope washout, debris	11,297
Polk	CSAH 19 MP 2.8	Shoulder and inslope washout, debris	6,275
Polk	Intersection of CSAH 20 and CSAH 23	Shoulder and inslope washout, debris	5,855
Polk	CSAH 64, Demers ave. to N city limits	Damage from hauling	14,155

Polk	CSAH 72 TH 220 -EGF city limits	Damage from hauling	13,250
Polk	CSAH 47	washed out culvert (replaced)	16,510
Polk	CSAH 22 MP 6.7 to MP 10.5	Road and Shoulder wash. Debris	139,697
		Total=	2,924,725

B. Potential Economic Impacts from Recreational Changes due to Shorter Ice Duration

Rabi Vandergon's Masters of Science Thesis at Bemidji State University is the basis for this section. His entire thesis is provided in the Appendix. Empirical analysis of potential economic impacts of climate change in Minnesota must be founded on evidence of environmental effects. This section utilizes as a cornerstone the work on trends in ice duration conducted by Virginia Card as part of the larger LCCMR project. The results on ice duration are summarized above in Section III.

A direct socio-economic impact of shorter ice duration will be the switch of recreational days for ice-related activities to open-water activities. The change in environmental conditions will cause positive and negative effects on opportunities for recreation. Patterns of gains and losses will impact different groups and different communities differently. Certainly activities dependent on ice and snow are likely to suffer based on climate evidence. An empirical question that cannot be specifically addressed given available data is how gains may offset or exceed losses in the transition periods in both spring and fall as ice duration becomes shorter. But it is important to note that there will be both gains and losses from the resulting changes. A recurring theme of the economic perspective in this report is that it is both important to consider the change in the expected value - in this case the net change from gains and losses - but also to recognize the socio-economic consequences in increasing the variability of these impacts. In other words, analysis of expected values would yield be incomplete picture given the dispersion of outcomes will probably be wider.

Indirect socio-economic effects are also likely to occur from shorter ice duration as one aspect of changing conditions in the aquatic ecosystem. There is an important linkage between ice-on/ice-off periods, limnological conditions/water quality, fish habitat and species distribution/abundance. The effects described in Sections II and III imply that some species will thrive on changed conditions resulting from climate change and others will suffer. Increases in runoff from climate change (due to changes in precipitation patterns) and increases in temperature both have potential to decrease the amount of dissolved oxygen (DO) in water bodies, which could potentially impact fish populations. Within the project team, the work of Kristal Schneider on the potential fisheries changes provides another cornerstone of this analysis. Evidence already suggests that cold-water species will decline in Minnesota and other species will expand in range and abundance. Economic implications of these potential direct and indirect impacts are considered below.

The thesis research is summarized as follows: The main goal of this study is to determine what impact climate change may pose to recreational benefits provided by the activity of angling. Creel surveys from the Minnesota Department of Natural Resources Creel Database were utilized to determine statewide angler effort and preferences for certain species. Lake ice duration observations were gathered to determine current trends and future projections. These data were utilized and combined with fishing valuation literature to determine an economic impact from climate change. Statistical analysis shows that lake ice duration is significantly decreasing statewide. Since more anglers fish during the summer months, this could lead to a net economic gain. On the other hand, bodies of water such as East Upper Red Lake see more anglers during the ice-fishing season, so could potentially see an economic loss. The project also utilized creel surveys to test the hypothesis indicating a statewide decline of trout species and northeastern shift of largemouth bass and sunfish from the onset of climate change. A multiple regression was performed on historical creel data to determine if there was a change in effort over time across different climate regions by species group. These variables were tested to see their influence on the amount of fish caught. The regression indicates a positive relationship between the amount of effort and the amount of yield, but effort does not appear to be shifting regionally in response to climate change predictions.

Future changes in recreation patterns are difficult to predict based on past records of recreational activity. The analysis requires some caveats due to limitations of available data to support estimation of changing trends. Major disclaimers of the analysis are:

- The results contain information from DNR data that was aggregated into seasonal estimates. The conclusions drawn from the results would have been more accurate if they were drawn from stratified seasonal data. For example, the conclusions assume that every day experiences the same amount of pressure throughout a season. Since there are differences in use in different periods of a season, the results in this section must be considered only a representation of a potential method to model climate change impacts.
- The following results assume that an ice-fishing day is worth the same as an open-water fishing day. A travel cost analysis for ice anglers could reveal a different valuation for an ice-fishing day. In fact, statistical evidence shows that an ice-fishing day is slightly longer than an open-water day, which suggests a higher valuation by anglers.
- The following results also assume that a fishing day is worth the same regardless of the species being sought. Willingness-to-pay literature provides evidence to the contrary. For example, trout species are more highly valued than average and are amongst the most vulnerable in Minnesota to the effects of climate change.
- Benefits Transfer based on the average expenditure of $35 for a fishing day in Minnesota understates the full economic value as it excludes consumer surplus. Willingness to Pay for a fishing day would be greater than the average daily expenditure.
- The multiple regression testing the hypothesis of shifting species ranges and abundance was based on DNR data that contained many empty fields. The results were statistically significant, but were not based on a complete dataset.

These changes in fish populations and ice conditions are important concepts for the state to consider, due to the high popularity of the activity of angling statewide. The U.S. Fish and Wildlife Service estimated that Minnesota residents and nonresidents spent roughly 24 million days fishing in 2006 (U.S. Department of the Interior [USDI], Fish and Wildlife Service [FWS], and U.S. Department of Commerce, U.S. Census Bureau [USCB], 2008).

Fishing as an activity has an economic value. It has use values as conceptualized in Section IV. The U.S. Department of the Interior (2008) estimated in 2006 roughly $2.7 billion was spent in Minnesota on goods associated with angling. By conducting interviews on trip expenditures, the U.S. Fish and Wildlife Service estimated that individuals spent roughly $35 per day on the activity of fishing in Minnesota (USDI, FWS, USCB, 2008). The same study estimated that roughly $466 million was spent on angling activities in Minnesota by nonresidents alone (USDI, 2008). As noted above, these expenditures do not include the additional consumer surplus given that willingness to pay would generally exceed the expenditures actually paid in market transactions. Changing the abundance of available fish for the sport as well as the conditions in which an angler may pursue his or her prey could both potentially have an economic impact on the state.

This study utilized statewide statistics from creel surveys and from lake ice observations to determine a potential economic impact on the recreational benefits of angling. The economic estimate was performed utilizing benefit transfer, which is an economic tool for estimating value when the resources for conducting a primary study do not exist. Three different scenarios were tested to determine potential impacts to recreational benefits: these scenarios took into account the variation in the amount of use that some lakes see in each season, whether each day was worth the same amount of money per angler regardless of season, and if there might have been a change in the amount of species present in these lakes. This analysis provides an estimate of potential impacts under these three different scenarios.

Periodically, the Minnesota Department of Natural Resources (MN DNR) conducts summer and winter creel surveys to assess the amount of use certain lakes experience. These surveys analyze how many hours are spent recreating and how many fish are caught and kept or released by anglers. This survey database is used for the empirical analysis below of fishing activities. It contains information on fishing pressure gathered from 763 lakes. Out of these lakes, 400 contained information regarding winter pressure. These lakes are dispersed throughout Minnesota.

Main Hypotheses and Scenarios

The hypotheses tested in this thesis are represented by the function: $B = f(x_1, x_2, x_3, x_4)$. The components of this function include:
B = Recreational benefits from fishing
x_1 = Ice-on days
x_2 = Open-water days
x_3 = Angler hours per acre
x_4= Species

Recreational benefits are hypothesized to be a function of the above variables. When one of these variables is shifted, it is assumed that there will be an impact on the recreational benefits (B). In other words, it is assumed that a change in ice-on days, ice-off days and angler hours per acre will all have an impact on recreational benefits. These assumptions are represented below:
Assume: $\Delta B/\Delta x_1 > 0$; $\Delta B/\Delta x_2 > 0$; $\Delta B/\Delta x_3 > 0$

As mentioned above, three different scenarios are tested. The first tests the notion that the change in recreational benefits from a change in ice-on date is equal to the change in marginal benefits from a change in ice-off date. In other words, ice-fishing is not worth any more than open-water fishing.
Scenario 1: $\Delta B/\Delta x_1 = \Delta B/\Delta x_2$

The second scenario looks at the possibility of the change in recreational benefits being unequal from a change in ice-on and ice-off dates. Scenario 2a represents the case of locations such as East Upper Red Lake, MN, which have seen a higher proportion of anglers visiting in the winter than in the summer (MN DNR, 1997). This difference is mainly due to the ease of access in the winter. In the summer the geography of the lake results in large waves when wind is present, which makes open water fishing difficult.

Scenario 2a: $\Delta B/\Delta x_1 < \Delta B/\Delta x_2$

Scenario 2b applies to other areas around the state. The statistical analysis of fishing activity in Minnesota reveals a higher amount of angler hours on lakes during the summer months (see results). Therefore, an increase in the amount of ice-off days will have a greater positive impact on recreational benefits than the loss due to fewer ice-on days.

Scenario 2b: $\Delta B/\Delta x_1 > \Delta B/\Delta x_2$

The third scenario examines the impact of species on the marginal recreational benefits. The literature has indicated that certain species have had a higher willingness to pay (WTP) by anglers than others (Johnston, Ranson, & Helm, 2006). For example, trout species have had a higher WTP than species such as panfish and walleye (Johnston et al., 2006). Under this assumption, a change in abundance of one species, or decrease in abundance of another may have a significant impact on the recreational benefits.

Scenario 3: $\Delta B/\Delta x_4 > 0$

Using ice duration statistics (including ice-on and ice-off data), the estimated impact on the total number of days fished was determined. Lake ice records were tested to see if the ice duration was significantly increasing or decreasing.

Lake Ice Observation Methodology

Lake ice records were obtained from Dr. Virginia Card at Metropolitan State University, Saint Paul, MN. Her ice records were gathered from the Minnesota Pollution Control Agency (MPCA) and the Minnesota Ice Records Database. The Minnesota Ice Records Database consists of a combination of observations recorded in newspapers and from individual correspondence. She submitted to this project data from 40 lakes that contain both ice-on and ice-off observations dates, which made it possible to estimate ice duration. These 40 lakes are a set from another subset of her data consisting of 106 lakes. The set of 106 lakes were chosen from her dataset, because they contain information regarding gill net and water quality data. The ice trends are reported in days lost or gained and determine how many angler days would impacted.

Using the creel survey data, the average number of angler hours per season per acre was determined. The total amount of angler days was determined using the number of angler hours per fishing trip in the open-water and ice-fishing seasons (separately). The average number of angler days in each season per acre was then extrapolated with the total acreage of lakes in Minnesota.

In order to determine an impact on the number of open-water days and ice-on days, a baseline for the current total number of these days needed to be determined (seen below in the equation). To create this baseline, data from 1971-2000 was utilized from the 40 lakes in the ice coverage dataset.

Total Lake Acreage

The total lake acreage was determined using a GIS layer obtained from the GIS coordinator for the MN DNR, Lyn Bergquist. The layer contains all lakes that have division of waters (DOW) identification numbers, which totals to 16,141 lakes. This layer was specifically prepared to represent Minnesota lakes acreage. The portions of lakes that exist outside state boundaries were excluded from the acreage assessment. Out of these lakes, the DNR has sampled fish populations on 4,295 lakes. Using the sum feature in GIS, the acreage for the group of 16,141 lakes and the group of 4,295 lakes were each determined. The acreage for the 16,141 lakes is 4,555,898.54, and the acreage for the 4,295 lakes is 3,923,292.62. The different acreage estimates provide upper and lower bound numbers allowing a sensitivity analysis for the effect of the total amount of lake acreage in Minnesota.

Explanation of the Benefits Calculation

The result of combining angler days with the total lake acreage provides an estimate of the total number of trips (angler days) that occur in the open-water or ice-fishing seasons for the entire state. The total estimate can then be divided by the number of days in a season, which yielded the average number of trips per day. The number of trips per day was multiplied by the number of lost or gained days using the ice duration statistics. This provided an approximation of the number of angler days lost or gained from changing ice duration.

The estimated lost or gained fishing days was then transferred into an economic estimate to represent the economic gain or loss. Data from the U.S. Census Bureau valuing a fishing day was utilized as an estimate at $35 per day. Since a fishing day may be variable between seasons, the number of hours in a fishing day was found for each season using statistical analysis.

Mathematical Description of the Benefits Calculation

The procedure, mentioned above, for estimating the potential economic impact is as follows:
$X1_w$, $X1_s$ = Mean angler hours per acre per season
$X2$ = Total fishable acres (two estimates)
$X3_w$, $X3_s$ = Mean angler hours per trip in each season (trip length)
$X4_w$, $X4_s$ = Angler days per season in each climate region
$X5_w$, $X5_s$ = Days lost or gained in each season per decade
$X6$ = Value of a fishing day
$Y1_w$, $Y1_s$ = Total trips/season
$Y2$ = Average trips/day
$Y3_w$, $Y3_s$ = Trips lost/gained per season
$Y4_w$, $Y4_s$ = Economic estimate per season
$Y5$ = Total economic impact

$X5_w + X5_s = 0$

$Y3_w + Y3_s = 0$

$Y1_{w/s} = X1_{w/s} * X2/X3_{w/s}$
$Y2_{w/s} = Y1_{w/s} / X4_{w/s}$
$Y3_{w/s} = Y2 * X5_{w/s}$
$Y4_{w/s} = X6 * Y3_{w/s}$
$Y5 = Y4_w + Y4_s$

Multiple Regression on Shifts over Time of Harvest, Effort and Species

In addition to the above hypothesis, another hypothesis proposed by Schneider, Newman, Card, Weisberg, and Pereira (2009) was examined. This hypothesis indicated that largemouth bass and sunfish are predicted to shift their range north and east in response to climate change. In addition, the literature indicated trout species are predicted to decline in abundance. Angler surveys provided species-sought percentages and species yield (in pounds) that were examined across climate regions over time. Species included in the analysis were walleye (due to its high economic demand), largemouth bass, sunfish, and all trout species. These species elicited some of the highest rates of preference by anglers from the creel database (See Table 25 in the Appendix). Some of these values totaled to more than 100% due to multiple responses being coded for 100% in the same category. These inaccuracies were corrected for the benefits estimation calculation. Any remaining species were categorized as "other species." The variables examined were species, percentage of "species-sought", climate region and year. These variables were placed in a multiple regression (using dummy variables for climate regions and species) to determine their impact on total yield across the state. The multiple regression equation reads as follows:
$Y = f(x_1, x_2, x_3, x_4)$

$Y = \text{Weight}_{species}$
$x_1 = \text{Hours}_{species}$
x_2 = Climate region
x_3 = Survey year
x_4 = Percentage of anglers seeking each particular species

GIS was utilized to assign all of the survey lakes to one of the nine climate regions defined within the larger project. Besides running a multiple regression on all Minnesota lakes, separate regressions were run on Red Lake, as well as 9 out of 10 of the large walleye lakes in Minnesota that are important for economic reasons (MN DNR, 1997). The nine large walleye lakes are Lake Vermillion, Lake Mille Lacs, Cass Lake, Lake Winnibigoshish, Rainy Lake, Leech Lake, East Upper Red Lake, Lake of the Woods and Kabetogama.

The mean number of angler hours per acre in each season proved to be significantly different from one another at the 1% level based on an independent samples t-test. The mean angler hours per acre in the summer were 45.14 hours and in the winter were 8.88 hours.

The mean angler hours per trip were compared between seasons suing an independent samples t-test. Trip length is significantly different at the 1% level with mean summer trip length of 3.35 hours and winter at 3.77 hours.

As noted in Section III, based on the data and findings of Card (2010) it was found that lake ice duration in the Minnesota sample is significantly decreasing at a mean rate of 3.3 days per decade from the time period of 1970 to 2008. These values were used to calculate the potential losses from 3.3 fewer ice fishing days annually than a decade ago. These were compared to potential gains from 3.3 more open-water fishing days. Absent any available estimates for Minnesota on differences between the value of an ice-fishing day versus an open-water fishing day, the US Census figure for Minnesota of $35 per day was utilized. Given the two estimates of lake acreage, a lower and upper-bound estimate of changes in the dollar value of fishing is estimated for each of the nine climate regions. More detail on these computations is provided in the appendix containing the Vandergon Thesis.

Summary results statewide are provided here as an overview. The lower bound estimate of ice fishing trips per season is 9,241,071.2, and the upper bound is 10,731,135.0. By comparison, open-water trips per season had a lower-bound of 52,864,904.1 and upper bound of 61,389,032.9 trips per season. It is noteworthy that the lower-bound estimate based on the lower acreage calculation yields estimate from the creel surveys that are more consistent with the estimates of 24 million fishing days in 2006 according to the US Fish and Wildlife Service.

Total Impact Statewide (Across all Climate Regions)

The values below were calculated by summing the results above in each climate region. The typical number of anglers recreating on an ice-fishing day versus an open-water day are calculated for each climate region. The difference was determined between seasons individually for the upper and lower bounds. Because there are generally fewer anglers using Minnesota lakes on the typical ice-fishing day than the typical open-water day, the reduction of ice-fishing days due to climate change causes less of a loss in recreational value than the gain in open-water values. The net economic impact statewide is estimated as follows:

Lower Bound = $177,725,196.9 gain due to 3.3 fewer days ice duration

Upper Bound = $206,382,251.8 gain due to 3.3 fewer days ice duration

Multiple Regression Results

Regression Results for the State

The multiple regression model was created to show how angler effort has an impact on yield (in pounds) across climate regions over time. The aim was to see if yield per unit of effort of some species in some areas was improving in the climate regions with greater abundance as predicted by Schneider et al (2009). The model has a high F-statistic yielding the conclusion that the model is significant at the 1% level. The variable of effort (spphrs) was significant at the 1% level, indicating for every extra hour spent fishing .002 pounds of fish were caught. This finding was significant and the slope was identical in both of the regressions, with and without the constant.

The dummy variables for each species were significant at the 1% level. This indicated that the amount of effort that was devoted to angling for a specific species resulted in a significant relationship with the amount of yield. In other words, more time spent fishing for a certain species represents a relationship with the amount of catch for that species. The negative numbers for each species represents a significantly lower amount of influence from the four main species categories in comparison to the “other species” category (the “other species” category was the baseline, and assigned a zero in each of the four dummy categories). This result suggests that the influence of the “other species” category dominated the results for the weight category and that the “other species” category has a higher rate of pounds harvested per hour.

The dummy variable for climate region 2 was significant at the 10% level with a one-tailed test. These results indicate that the affect of angling effort on the amount of yield is significantly higher in this region (north central MN) compared to other climate regions. Interestingly, the amount of pounds caught in climate region 2 was the highest of all. Climate region 2 has over double the amount of fish caught in comparison to the mean elsewhere.

While greater effort results in higher harvest, greater reward for effort does not seem to be occurring in regions where populations of certain species are increasing. Another way to test whether anglers are changing behavior in response to species changes is to compare effort thru time for selected species in the regions where these species are increasing in abundance. The regression below tests this hypothesis.

Many of the same relationships described above hold in this model. Again climate region two has more hours of effort compared to the other regions. There is not a significant increase in angler hours in the regions where sunfish and bass are increasing in abundance.

Table VI.6. Multiple Regression Results: Fishing Effort (hours for species) by Climate Region

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.273[a]	.075	.070	1.19060E7

a. Predictors: (Constant), Dclmt8, Dwae, Dclmt1, Dclmt7, Dclmt5, SurveyYr, Dclmt2, Dlmb, Dclmt4, Dtrt, Dclmt3, Dsun, Dclmt6

ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	2.876E16	13	2.212E15	15.604	.000[a]
	Residual	3.568E17	2517	1.418E14		
	Total	3.855E17	2530			

a. Predictors: (Constant), Dclmt8, Dwae, Dclmt1, Dclmt7, Dclmt5, SurveyYr, Dclmt2, Dlmb, Dclmt4, Dtrt, Dclmt3, Dsun, Dclmt6

b. Dependent Variable: spphrs

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-9.082E7	5.459E7		-1.664	.096
	SurveyYr	45400.005	27293.197	.033	1.663	.096
	Dlmb	-2117239.393	802317.805	-.061	-2.639	.008
	Dsun	-1766307.781	725991.105	-.058	-2.433	.015
	Dtrt	-2312267.224	727063.507	-.076	-3.180	.001
	Dwae	5507432.503	720596.759	.184	7.643	.000
	Dclmt1	291984.395	4249273.296	.002	.069	.945
	Dclmt2	5706776.641	3502669.369	.153	1.629	.103
	Dclmt3	2803131.098	3481431.338	.090	.805	.421
	Dclmt4	1384243.877	3497827.193	.039	.396	.692
	Dclmt5	1636370.302	3536631.429	.037	.463	.644
	Dclmt6	3000398.053	3465298.380	.116	.866	.387
	Dclmt7	735854.799	3844732.800	.008	.191	.848
	Dclmt8	1148167.178	3562417.971	.024	.322	.747

a. Dependent Variable: spphrs

SECTION VII.
CONCLUSIONS AND IMPLICATIONS FOR FURTHER RESEARCH

A. Conclusions

The relative emphases of the economic analyses and the empirical estimation are dependent upon the findings of the other environmental components of this research effort. To a certain extent, the findings on environmental impacts at this juncture are predicated on available data that are constrained in both temporal and spatial scale. So while evidence is mounting that Minnesota's water resources are vulnerable to the effects described in the workplan (higher surface water levels/streamflow, increased sedimentation, degraded water quality, infrastructure implications) some of the more extreme impacts anticipated at the global or regional scale are difficult to detect statistically at the smaller statewide scale. This is due in part to lack of small spatial scale data over the length of time needed to detect statistically meaningful trends.

The economics literature on risk-aversion should inform decisions on climate change. The potential damages from climate change are the types of risks that people typically wish to guard against. Most citizens place a value on risk reduction and are willing to pay for the insurance value this yields. Public policy that provides this is a public good to all those who have risk-averse preferences. It is a collective value derived from the sort of individual value many people place on private insurance. Fundamental aspects of climate change involve risks and this conceptual economic approach is enlightening.

Policies to reduce risks from climate change can be to reduce GHG emissions and/or to mitigate impacts in other ways (enhance ecosystem integrity and resilience, adaptation through precautionary infrastructure design, etc.) Economic efficiency and equity goals are relevant to these decisions. If avoiding potential damages is deemed to generate net benefits and/or enhance equity, ways of achieving these goals at least cost should be pursued. Increasing the percentages of best land-use practices applied in many watersheds may be a cost-effective way to offset ecological stress on Minnesota's water resources.

Flood Damages

Consistent with the approaches advocated by the WICCI Working Groups, MN should identify settings with the greatest vulnerability to catastrophic failure such as loss of life and property if structures fail. Most of the MN topography does not cause as great of danger of flash flooding as in more mountainous areas. The severe flood in southeastern MN in 2007 demonstrates that the topography of that part of the state makes it more vulnerable to severe flash floods. Elsewhere, overland flooding is more likely to occur rather than the deep rush of water with floods in hills and valleys. The tragedy of loss of life in the June 2010 disaster at the Albert Pike Recreation Area in Arkansas is an example of the type of worst-case scenario from flash flooding. MN should adopt a two-pronged approach to risk management to the degree that MN can inventory watersheds for combinations of two groups of characteristics. Greatest vulnerability to damages from flash floods exists in watersheds that have: 1) geomorphology conducive to flash floods and 2) human and natural environments that put highly valued assets and human life in harm's way.

Findings from the component of the project on streamflow reported in Section IIIC below indicate that the Minnesota River Basin and the Red River of the North have larger increases in streamflow than the other three basins in the state. Even though extreme precipitation events are likely to be randomly located across the state, it would be a wise investment to protect against such disasters in the most vulnerable locations. This would be a sound application of the Precautionary Principle and risk aversion discussed further below in Section IV.

The longest yearly record for weather-related damages in MN comes from figures reported in a NOAA study (2002) that re-examines damage figures from 1925-2000. Figures are provided state-by-state from 1955 to 2000. It is most informative to compare damages that are standardized in constant dollars: this data series used 1995 dollars. From 1955-2000 occasional weather events caused damages in the tens of millions of dollars. Damages in the hundreds of millions of dollars also occurred over this time period. By far the two years with the highest damages were 1997 and 1993. The floods of 1993 caused damages in excess of $1 billion in constant 1995 dollars.

The MN Department of Public Safety's Division of Homeland Security & Emergency Management provided summarized damage information over the past two decades. The damage figures for the 1990s are contained in a report "A Decade of Minnesota Disasters: A Historical Look at Minnesota Disasters in the 1990s." According to the report, these damages are increasing and during the 1990s there were 14 presidential declarations of major disasters. Most of the damages were the result of flooding, ice storms, snow removal, straight-line winds, tornadoes, and heavy rain. From the disasters of the 1990s, Minnesota taxpayers spent $827 million and the cost to insurance companies was more than $2 billion.

Examination of transportation infrastructure as a major category of damages revealed that numerous weather-related events have occurred in the last two decades that caused damages to roads, bridges and culverts in the millions or tens of millions of dollars, per event.

Ice Duration and Recreational Fishing

Analysis conducted by Virginia Card as part of the larger project found that ice duration is getting shorter in the state. The trend analysis indicated that ice-duration has on average been getting shorter by a third of a day in a typical year, or 3.3 days over the course of a decade. A direct socio-economic impact of shorter ice duration will be the switch of recreational days for ice-related activities to open-water activities. The change in environmental conditions will cause positive and negative effects on opportunities for recreation. Patterns of gains and losses will impact different groups and different communities differently. Certainly activities dependent on ice and snow are likely to suffer based on climate evidence. Indirect socio-economic effects are also likely to occur from shorter ice duration as one aspect of changing conditions in the aquatic ecosystem. There is an important linkage between ice-on/ice-off periods, limnological conditions/water quality, fish habitat and species distribution/abundance.

An empirical question that cannot be specifically addressed given available data is how gains may offset or exceed losses in the transition periods in both spring and fall as ice duration becomes shorter. But it is important to note that there will be both gains and losses from the resulting changes. A recurring theme of the economic perspective in this report is that it is both important to consider the change in the expected value - in this case the net change from gains and losses - but also to recognize the socio-economic consequences in increasing the variability of these impacts. In other words, analysis of expected values would yield an incomplete picture given the dispersion of outcomes will probably be wider.

Creel survey data on recreational fishing in MN was utilized to discern patterns in activity and how it might relate to changes in ice duration and species distribution/abundance. Three scenarios were developed for modeling purposes.

Results from Three Fishing Scenarios

Scenario 1 assumes ice fishing days lost will lead to a loss equal to the open-water activity that will take its place on those days of transition: ice days that are now open-water.
The results from the benefits estimation calculations indicate that this scenario will not prove to be likely. All climate regions reveal that there may be net positive benefits from the onset of climate change and decreasing ice duration. However, this does not mean this may be a preferable result for those who enjoy the activity of ice fishing in the winter.

Scenario 2a recognizes that some lakes, most notably Upper Red Lake, are extremely popular for ice fishing. Results from East Upper Red Lake show that there are differences in the amount of pressure between the winter and the summer. Since Red Lake sees such a higher use in the winter months, the onset of climate change through decreasing lake ice will likely have a net negative impact on recreational benefits from use of this lake.

Scenario 2b looked at the large walleye lakes in the state. These generate a very large portion of the overall fishing activity in the state. In contrast to Upper Red Lake, other large walleye lakes (and statewide data for smaller lakes) show that summer effort significantly exceeds effort in the winter. A higher amount of angler effort in the open-water season is likely to lead to a net positive impact from the onset of climate change.

Scenario 3 investigates whether changes already occurring in species distribution and abundance are leading to changing patterns of fishing effort. The results from the multiple regressions did not show significant results for a change in yield per unit of effort in response to change in species abundance over certain regions of the state over time. As mentioned in the literature, certain species, such as trout, have a higher WTP than walleye and panfish. Therefore, a change in these species abundances could have a significant impact on the WTP by anglers. For example, fewer trout (which are predicted to decline from climate change) would be detrimental to recreational benefits. The net impact from these changes in species abundance and the economic consequences cannot be estimated given limitations of available data. However, further inquiries into these possibilities with better data on WTP by species and longer time periods would be warranted.

B. Implications for Further Research

Changes to lake ice duration impact the fishing that occurs at the beginning and the end of the ice season. Maintaining a strong dataset with these types of divisions would aid with understanding how much usage occurs in these transitional periods between ice and open-water fishing. For example, some anglers may fish more at the beginning of the ice fishing season when fish such as walleye may be biting and then wane off as the season progresses. In the spring, a renewed effort for species such as perch and crappie may ensue. In the fall, a large percentage of the angling population may be off of lakes after Labor Day. To explore these issues further, creel data would need to be determined for more specific seasonal strata such as early spring, late fall, early winter and late winter. Better understanding of how WTP varies across species of fish sought would strengthen the type of preliminary analysis performed here. Knowledge of these preferences and related behaviors would help with future studies.

The economic estimate of a fishing day provided by the U.S. Department of the Interior does not provide a distinct value for an ice fishing day. Angling on the ice has its own set of expenditures such as ice houses, augers and tackle that could amount to different travel cost estimation for individuals participating in this type of activity. Valuing ice fishing at a different rate would have the potential to alter the economic estimates.

The larger project identified future needs for data at scales appropriate to understanding climate change impacts in Minnesota. Much of the discussion in the research community at the national and state level is emphasizing the need to "downscale" data to allow meaningful analyses for smaller geographic areas, such as states. Needs to improve scale are:

1. Spatial Scale: consensus on need for "downscaling." Scaling Down Global and Regional Patterns to Minnesota
2. Temporal Scale
   a. Data to Determine variations over long enough time span
   b. Hydrologic Data to Determine variations in Stream Flows that occur within 7-day period, such as extreme flows within a 24-hour period

One major example of limitations due to too short of time span is described in an earlier project summary. It pertains to projecting biological responses to changing climate. Fish populations and other biological communities will be affected by warmer water temperatures, and altered thermal regimes, changes in flow regimes, total flows, water level, and water quality. These changes will affect the health of aquatic ecosystems, with impacts on productivity, species diversity, and species distributions. The paucity of historic data makes it difficult to assess past changes and predict biological responses to climate change.

The overall project, and the economic component, has generated useful information as an indication of where the state might be headed in terms of climate change. It also indicates how much remains to be done in order to generate more precise empirical evidence. A great deal is being learned about how climate change may impact the future and what options exist to address it. Climate change has implications in time scales longer than most institutions are equipped to handle. Research design and policy formulation needs to reckon with these long time horizons in determining actions today that will benefit the future.

SECTION VIII.
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APPENDIX A
KEY EXCERPTS FROM THE LITERATURE ON ENVIRONMENTAL AND ECONOMIC IMPACTS

US Global Change Research Program reports impacts by sectors (water resources covered above in Section II of this report):

Changes by Sector Water Resources pages 41-52, Energy Supply and Use 53-60, Transportation 61-70, Agriculture 71-78, Ecosystems 79-88, Human Health 89-98, Society 99-106

"Energy Supply and Use

- *Warming will be accompanied by decreases in demand for heating energy and increases in demand for cooling energy. The latter will result in significant increases in electricity use and peak demand in most regions.*
- *Energy production is likely to be constrained by rising temperatures and limited water supplies in many regions.*
- *Energy production and delivery systems are exposed to sea-level rise and extreme weather events in vulnerable regions.*
- *Climate change is likely to affect some renewable energy sources across the nation, such as hydropower production in regions subject to changing patterns of precipitation or snowmelt."*

"Transportation KEY MESSAGES:

- *Sea-level rise and storm surge will increase the risk of major coastal impacts, including both temporary and permanent flooding of airports, roads, rail lines, and tunnels.*
- *Flooding from increasingly intense downpours will increase the risk of disruptions and delays in air, rail, and road transportation, and damage from mudslides in some areas.*
- *The increase in extreme heat will limit some transportation operations and cause pavement and track damage. Decreased extreme cold will provide some benefits such as reduced snow and ice removal costs.*
- *Increased intensity of strong hurricanes would lead to more evacuations, infrastructure damage and failure, and transportation interruptions.*
- *Arctic warming will continue to reduce sea ice, lengthening the ocean transport season, but also resulting in greater coastal erosion due to waves.*
- *Permafrost thaw in Alaska will damage infrastructure. The ice road season will become shorter."*

"Agriculture KEY MESSAGES:

- *Many crops show positive responses to elevated carbon dioxide and lower levels of warming, but higher levels of warming often negatively affect growth and yields.*

- *Extreme events such as heavy downpours and droughts are likely to reduce crop yields because excesses or deficits of water have negative impacts on plant growth.*
- *Forage quality in pastures and rangelands generally declines with increasing carbon dioxide concentration because of the effects on plant nitrogen and protein content, reducing the land's ability to supply adequate livestock feed.*
- *Increased heat, disease, and weather extremes are likely to reduce livestock productivity."*

"Ecosystems KEY MESSAGES*:*

- *Ecosystem processes, such as those that control growth and decomposition, have been affected by climate change.*
- *Large-scale shifts have occurred in the ranges of species and the timing of the seasons and animal migration, and are very likely to continue.*
- *Fires, insect pests, disease pathogens, and invasive weed species have increased, and these trends are likely to continue.*
- *Deserts and drylands are likely to become hotter and drier, feeding a self-reinforcing cycle of invasive plants, fire, and erosion.*
- *Coastal and near-shore ecosystems are already under multiple stresses. Climate change and ocean acidification will exacerbate these stresses.*
- *Arctic sea ice ecosystems are already being adversely affected by the loss of summer sea ice and further changes are expected.*
- *The habitats of some mountain species and coldwater fish, such as salmon and trout, are very likely to contract in response to warming.*
- *Some of the benefits ecosystems provide to society will be threatened by climate change, while others will be enhanced."*

"Human Health KEY MESSAGES*:*

- *significant increases in the risk of illness and death related to extreme heat and heat waves are very likely. Some reduction in the risk of death related to extreme cold is expected.*
- *Warming is likely to make it more challenging to meet air quality standards necessary to protect human health.*
- *Extreme weather events cause physical and mental health problems. Some of these events are projected to increase.*
- *Some diseases transmitted by food, water, and insects are likely to increase.*
- *Rising temperature and carbon dioxide concentration increase pollen production and prolong the pollen season in a number of plants with highly allergenic pollen, presenting a health risk.*
- *Certain groups, including children, the elderly, and the poor, are most vulnerable to a range of climate-related health effects."*

"Society KEY MESSAGES*:*

- *Population shifts and development choices are making more Americans vulnerable to the expected impacts of climate change.*
- *Vulnerability is greater for those who have few resources and few choices.*
- *City residents and city infrastructure have unique vulnerabilities to climate change.*
- *Climate change affects communities through changes in climate-sensitive resources that occur both locally and at great distances.*
- *Insurance is one of the industries particularly vulnerable to increasing extreme weather events such as severe storms, but it can also help society manage the risks.*
- *The United States is connected to a world that is unevenly vulnerable to climate change and thus will be affected by impacts in other parts of the world."*

Additional content from the WICCI Stormwater Working Group:
"Adaptation Strategies
There is a growing consensus that scientific knowledge about the potential increase in magnitude and frequency of large rainfalls is sufficient to warrant immediate changes in the methods used to design and manage storm water-related infrastructure. For example, the following steps have been identified by the Stormwater working group:

- *Synthesize existing historical and model data for rainfall in the upper Midwestern U.S. to provide a more accurate account of current and future precipitation;*
- *Use a risk/consequence approach to evaluating and modifying existing infrastructure to accommodate observed and predicted changes in climate.*
- *Develop and evaluate alternative tools and strategies for the design of storm water-related infrastructure, using a collaborative process that includes climate scientists, water resource managers, design engineers, and regulators, and members of relevant business communities;*
- *Communicate findings and recommendations to water resource managers, design engineers, relevant government entities and other decision makers."*

"Adaptation Science
Now imagine being a city planner or hydrologic engineer responsible for designing and implementing new storm water structures that are meant to last for the next fifty years. If you design these structures based on the weather from the last fifty years, they might lack sufficient capacity to handle rain storms of increasing intensity and frequency, perhaps leading to flooded streets and homes. On the other hand, if you plan for the worst-case scenario even though there is a small probability of it happening, you may over-design the system at a significant cost to the taxpayer if those extreme events do not materialize."

"This conundrum represents the world of adaptation science. At a fundamental level, there are only two parts to adaptation science; calculating the probability of a future event, and creating contingency plans for those events most likely to materialize. Adaptation should focus on the greatest vulnerabilities. In short, where are the greatest risks if climate changes occur? Identifying these vulnerable locations or situations, and then creating a range of contingency plans, is the focus of many WICCI Working Groups."

"Coastal Communities: Potential Risks

- *Coastal Flooding: Climate change may cause the water levels on Lakes Superior and Michigan to extend beyond the range measured since 1860.*
- *Coastal Erosion: An increase in intense precipitation and storm events along with the impacts of warmer and wetter winters (more freeze/thaw cycles and less lake ice cover) could increase coastal erosion and may lead to more frequent episoidal deep-seated landslides.*

Vulnerabilities

- *Residential and commercial structures and property on the coast are vulnerable to erosion and flooding. The migration of the Ordinary High Water Mark (OHWM) towards the lake during extended periods of low lake levels may encourage development in hazardous areas.*
- *Harbors and marinas are susceptible to extreme water levels.*
- *Industrial facilities such as power plants and water/sewer treatment facilities are vulnerable to extreme water levels that exceed their design.*
- *Infrastructure such as roads and drainage are susceptible to coastal erosion and flooding.*
- *Shore protection structures need to be maintained over time and may not be effective if lake levels extend beyond their design parameters.*
- *Natural plant communities along the Great Lakes, including coastal wetlands, may be impacted by persistent extreme lake levels.*
- *Water intakes may be impacted by low water levels.*
- *Climate change may impact tourism in coastal communities. Issues include beach health and aesthetics for hotels.*
- *Changes in water temperatures and circulation patterns could affect mixing patterns in coastal waters.*
- *More intense coastal storms could impact dredging and re-suspend contaminated sediments. "*

The MN Sea Grant Program also discusses likely impacts on Lake Superior.
"Lake Superior's surface water temperature in summer has warmed twice as much as the air above it since 1980.

> *Per decade since 1980, surface water temperature in summer has increased about 2 °F (1 °C), while regional air temperature has increased 1 °F (0.5 °C).*

Lake Superior's ice cover is diminishing.

> *The area covered by ice each winter is decreasing by about 0.5% per year.1 Ice cover in Lake Superior has decreased from 23% to 12% over the last century.*

Wind speeds over Lake Superior are increasing.

Since 1985, wind speeds have increased by nearly 5% per decade, exceeding trends over land. Scientists believe the faster winds could accelerate the speed of Lake Superior's water currents, which in turn could affect the aquatic food web.

Lake Superior's summer stratification season is longer.

Spring turnover has become earlier by about 1/2 day per year, leading to earlier summer stratification. The sun-warmed upper layer extends farther into the water column, making fall mixing later. The length of the positively stratified season has increased from 145 to 170 days over the last century.

From Heal and Kristrom (2002) "Uncertainty and Climate Change"
"The reference to scientific uncertainty here implies, for the authors, the possible resolution of this uncertainty by research and learning. Most economists, if asked to think of a justification for this principle, would probably couch it in terms of learning, irreversibilities and option values, so intuitively we think the two are related. Gollier et al note that in fact the precautionary principle can be given a formal justification without invoking irreversibilities, just assuming a stock damage effect and possible learning over time. . . . there are two contradictory effects. One is that we invest less in prevention in the economy which may learn more because this investment may be inefficient: when we know more we
may be able to choose better investments. They describe this as the "learn then act" strategy. The opposing tendency is generated by the fact that if we follow this strategy then the risk that society faces in the future will be greater. The principle result of the Gollier et al paper is that the balance between these two effects depends on the shape of the utility function and in particular on whether or not society shows 'prudence'." Page 26

From Berz (1999) *"The present problems will be dramatically aggravated if the greenhouse predictions come true. The changing probability distributions of many processes in the atmosphere will force up the frequency and severity of heat waves, droughts, bush fires, tropical and extratropical cyclones, tornados, hailstorms, floods and storm surges in many parts of the world with serious consequences for all types of property insurance, apart from the consequences of the stratospheric ozone destruction for health and life insurance.*

Rates will have to be raised and in certain areas insurance cover will only be available after considerable restrictions have been imposed, as for example significant deductibles and low liability or loss limits. In areas of high insurance density the loss potential of individual catastrophes can reach a level at which the national and international insurance industries will run into serious capacity problems. Recent disasters showed the disproportionately high participation of reinsurers in extreme disaster losses and the need for more risk transparency if the insurance industry is to fulfill its obligations in an increasingly hostile environment."

From the World Wildlife Fund for Nature and Allianz Insurance Company report (2009)
"Climate change resulting from emissions of CO2 and other greenhouse gases (GHGs) is widely regarded to be the greatest environmental challenge facing the world today. It also represents one of the greatest social and economic threats facing the planet and the welfare of humankind." "The phrase 'tipping point' captures the intuitive notion that "a small change can make a big difference" for some systems (1). In addition, the term 'tipping element' has been introduced to describe those large-scale components of the Earth system that could be forced

past a 'tipping point' and would then undergo a transition to a quite different state. In its general form, the definition of tipping points may be applied to any time in Earth history (or future) and might apply to a number of candidate tipping elements. However, from the perspective of climate policy and this report we are most concerned with 'policy-relevant' tipping elements which might be triggered by human activities in the near future and would lead to significant societal impacts within this century."

APPENDIX B
ANALYTICAL FRAMEWORK FOR EXPECTED UTILITY AND OPTION VALUE

The conceptual framework for the application of option value to protecting against climate change impacts is adapted from the model in Freeman (1985). The literature distinguishes values yielded by reducing demand-side risks (based on probabilities $0 \leq$ prob. $<$ 100% of future income or preferences) and supply-side risks which threaten the availability of a resource. The former is known as demand-side option value and the latter is supply-side option value. While Freeman's model allows for both supply and demand uncertainty, it is his modeling of supply-side option value that is most illuminating for applying option value to the potential impacts of climate change.

The concepts can be demonstrated in the simplest case (Case 1) showing the income equivalent (loss) attached to the more risky world that exists due to the threat of climate change. The income equivalent is defined as the equivalent surplus, ES, for avoiding climate change damages:

$$U(Y,Wb) = U(Y\text{-}ES, Wa) = U \qquad (1)$$

where individual utility (U), is a function of income (Y), and the quality and quantity of water resources (W). If climate change does not impact water resources the preferred state of the world is shown at the right-most point, a, on the graph in Figure B.1. But the non-zero probability of damages from climate change introduces the threat that the future state of the world could be the left-most point, b. The expected loss (expected ES) from the possibility that climate change could damage water resources is shown by the horizontal movement on the Income axis to point c. The loss to risk neutral individuals from possible climate change damages would be the difference between income at a and c, or Ya – Yc. Expected utility theory suggests that a risk-averse individual would prefer to insure against the worst-case scenario at b so would be willing to pay more than the expected loss, expected ES. The loss of well-being to the risk-averse individual is seen by moving to point d, because the person would sacrifice more income to achieve a certain but lower level of water resources, $\underline{W}$, rather than face the worst-case scenario of water resources as low as b. The income equivalent measure of loss is Ya – Yd. This is a greater loss than that for the risk-neutral individual above. The widening of the dispersion of likely future states of the world due to climate change is the reason option value must be considered as an economic loss from potential climate change.

The more realistic characterization of the economic loss due to the threat of climate change is adding risk to an already risky situation. There are multiple levels of W, the quality and quantity of water resources, which could occur in the future. For the sake of modeling in Case 2, these multiple possibilities will be narrowed to four. See Figure B.2. For Case 2, the initial risk with climate change is shown as the chance (assume a 50-50 chance of the two outcomes) that W will be available at point a or at point b. Compared to Case 1 the premise is that background risks to water exist regardless of climate change. It is assumed further that equal magnitudes of positive or negative changes in water resources could occur in the future due to climate change and these are equally likely. With mitigation, however, these changes, both positive and negative, would be reduced. Under climate change mitigation, future levels of W could be at a2 or b2. As discussed in Section IV, being these are equal movements in a positive or negative direction, the expected level of W is identical between the more risky situation given the threat of climate change and the less risky situation due to mitigation. The more risky world due to climate change poses a 50-50 chance that W will be available at either point a or b. Again this assumes equally likely influences of climate change on water resources, W, that will be either positive or negative in equal magnitudes.

A risk-neutral individual would be indifferent between the risky scenarios modeled in Cases 1 and 2. Being expected surplus dependent on W is unchanged, the expected utility halfway between points a and c would be equal to the expected utility halfway between points a2 and c2. But being risk-averse preferences are held by the typical person, the income equivalent measure of loss due to climate change would be greater in Case 2 without mitigation. The loss in well-being from climate change in this more risky situation is shown by expected utility at point d being lower than at point d2. The loss to the risk-averse individual increases as the dispersion of the outcomes widens. Being climate change widens the dispersion, there would be a positive option value to reduce this risk representing a risk-aversion premium.

For Case 2

$$U(Y,Wb2) = U(Y-ES,Wa2) = U \qquad (2)$$

As in Case 1, Expected utility with no control of climate change is represented:

$$EU = q1\ U(Y,Wa) + q2\ U(Y,Wb) \qquad (3)$$

where q1 = 1 - q2. The probability of preserving environmental quality as a result of climate change mitigation is r2, (r1 = 1 - r2) such that r2 > q2 yields a probability increase denoted r2 - q2. Option price, OP, is a state independent payment which is the income equivalent for the improvement in expected utility as a result of the policy. Hence, OP is such that, with mitigation,

$$EUm = r1\ U(Y-OP,Wa2) + r2\ U(Y-OP,Wb2) \qquad (4)$$

and EU = EUm due to the payment of OP. Option price is related to equivalent surplus as follows:

$$q1\ U(Y-\underline{ES},Wa) + q2\ U(Y,Wb) = r1\ U(Y-OP,Wa2) + r2\ U(Y-OP,Wb2) \qquad (5)$$

While Case 2 is designed to yield expected incomes that are equal with and without mitigation, the higher expected utility under mitigation indicates a positive economic benefit from narrowing the dispersion of the risky situations. In addition to comparing the expected utility of the tow risky situations in Case 2 , the willingness to pay for a certainty equivalent to reduce the risk is also informative. The option price to reduce the eisk is much higher in the more risky (more dispersed) situation. The option value (OP – expected ES) is larger as a risk-aversion premium in the more risky situation shown in Case 2.

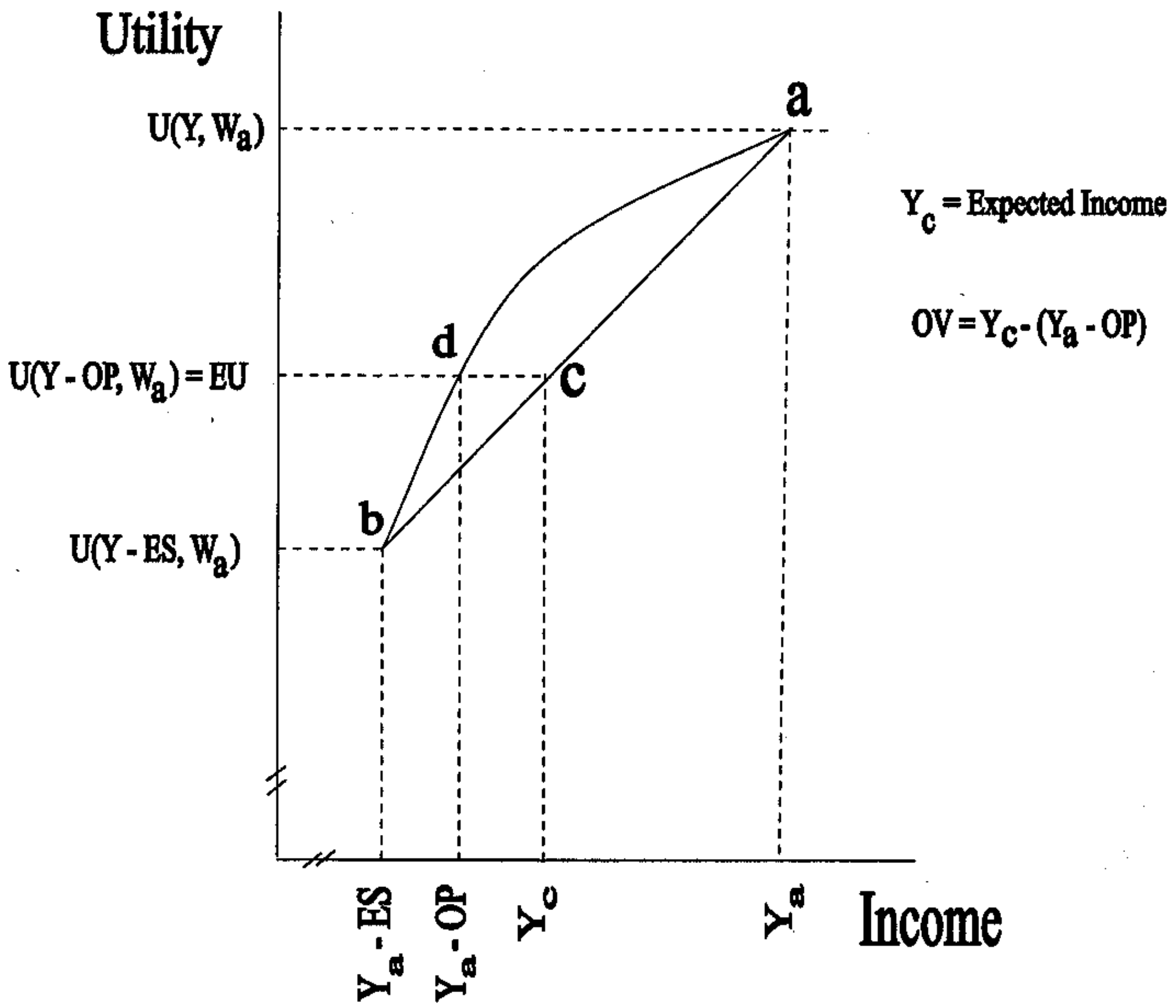
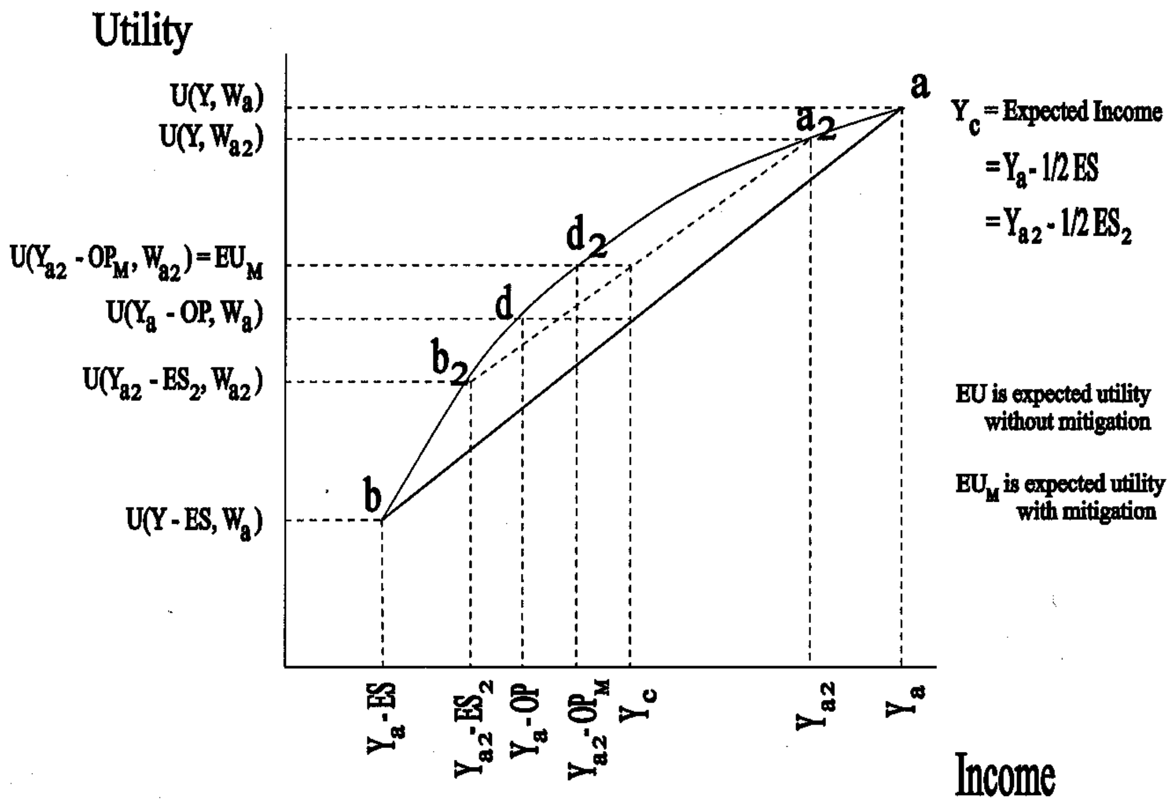


Figure B.1. Expected Utility and Option Value of Reduced Risks: Case 1



Figtre B.2. Expected Utility and Option Value of Reduced Risks: Case 2