Water quality responses during historical climate regimes (*scenarios*)
To detect the effects of extreme seasonal weather on water quality we used the water quality data and climate regimes developed as part of Result 2 of this project (summarized in Appendix D and reported in the LCCMR2005 project: Impacts on Minnesota's aquatic resources from climate change Phase I - W-12).

Methods: We used the following water quality indicators to test for responses in years with temperatures and precipitation outside of the 'normal' range: secchi depth, surface temperature, specific electrical conductivity (EC25), thermocline depth, trophic state index (TSI: the mean of TSI-secchi, TSI-chlorophyll *a,* and TSI-phosphorus), surface levels of chlorophyll-*a*, and surface levels of total phosphorus (TP). Surface measurements which included measurements from zero to two meters deep were averaged across these depths, or were collected from a two meter tube sampler.

Each variable was tested independently over 3 different *extreme* weather scenarios developed in Result 2 of this project: warm and dry, warm and wet, or cold and wet. A region was considered 'warm' for a particular year if the temperature of that region for that year, or the portion of year used in the analysis (i.e. Jun-Sep) was greater than 1.5 standard deviations above the mean temperature for that region over all years. Similarly a year was considered to be 'cold' for a region when the temperature for that year or portion of year was 1.5 standard deviations below the mean temperature. 'Wet' and 'dry' were identified with the same process using precipitation for the year or portion of year and 1.5 standard deviations above or below the mean precipitation levels, respectively. Only years that were extreme in both temperature and precipitation were included in these analyses: warm and dry, warm and wet, or cold and wet. During the 100 year weather data set, simultaneous 'wet and warm' and also 'cold and dry' scenarios were uncommon, especially during the ice-free growing season and summer when the vast majority of lake data is collected. Cold-dry was not used in these analyses due to the lack of years with water quality data that would be classified as 'cold and dry.' A lake's value for a particular water quality parameter for an extreme climate was the average of the lake's values for that variable over all years that were considered within that combination of extreme climate for which there were data.

The effect that extreme climate potentially had on water quality was tested using two methods. Lakes that had water quality data for any two types of extreme climate were compared using a Mann-Wilcox paired test (McLeod 2009). This paired comparison analysis was completed for all lakes statewide as well as for lakes considered shallow across the state using a combination of lakes identified by MN DNR Wildlife (Shallow Lakes Program, http://www.dnr.state.mn.us/wildlife/shallowlakes/index.html) and Minnesota Pollution Control Agency.

Shallow lakes were further examined on a regional basis, using Minnesota's nine climate divisions (www.esrl.noaa.gov/psd/data/usclimdivs/data/map.html#Minnesota) to group lakes geographically. This allowed lakes to be pooled by assuming that the sample set included lakes fairly homogeneous in water quality because they were likely to be located in the same Ecoregion (as per MPCA 2004) and depth (i.e. all shallow). This analysis tested the effect extreme weather has on water quality within a region by performing a Mann-U test (also known as the Wilcoxon rank-sum test) on all lakes within that region over all three possible extreme weather contrasts (McLeod 2009). Non-parametric tests were used for both sets of analyses because of the non-normality of the data.

MPCA. 2004a. Minnesota's Water Quality Monitoring Strategy 2004-2014. Minnesota Pollution Control Agency, St. Paul, MN 55155. http://www.pca.state.mn.us/publications/reports/p-gen1-10.pdf

McLeod, A.I. 2009. Package 'Kendall' Version 2.1. Kendall rank correlation and Mann-Kendall trend test in Project "R" http://cran.r-project.org/web/packages/Kendall/Kendall.pdf.

Table 1. Summary of statistically significant water quality responses comparing years that were warm and dry, warm and wet, or cold and wet (based on at least 1.5 standard deviations from the mean temperature and precipitation) for all lakes across Minnesota, and for shallow lakes by climate division as well as statewide (see METHODS for classification details). n=sample size; Δ = difference between compared climate regimes; NS=none significant (p>0.05)

	Type of Analysis		
Water Quality Parameter	**All Lakes: Statewide[a]** (pairwise comparisons)	**Shallow Lakes: Statewide[b]** (pairwise comparisons)	**Shallow Lakes: by climate division[c]**
Secchi depth (m)	cold-wet< warm wet (n=235; p<0.0001; Δ 0.18 m) warm-wet> warm-dry (n=72; p<0.0001; Δ 0.38 m)	cold-wet> warm-wet (n=42; p<0.05; Δ 0.17 m)	South Central: cold-wet> warm-wet (n=19,37; p<0.02; Δ 0.17 m)
Trophic State Index (mean TSI)	cold-wet< warm-dry (n=90; p<0.05; Δ 1.3) warm-wet< warm-dry (n=72; p<0.01; Δ 2.2)	cold-wet< warm-dry (n=41; p<0.01; Δ 3.6) cold-wet< warm-wet (n=43; p<0.001; Δ 3.4) warm-dry to warm-wet NS, n=252	South Central: cold-wet< warm-wet (n=21,37; p<0.05; Δ 3.4) West Central: warm-wet< warm-dry (n=76,61; p= 0.08; Δ 4.0)
Specific electrical conductivity (EC25, μS /cm)	cold-wet< warm-wet (n=23; p<0.001; Δ 140 μS /cm)	warm-wet< warm-dry (n=42; p<0.001; Δ 31 μS/cm)	NS
Surface water temperature (°C)	cold-wet< warm-dry (n=11; p<0.05; Δ 2.6°C) cold-wet< warm-wet (n=44; p<0.001; Δ 4.0°C)	cold-wet< warm-dry (n=6; p<0.05; Δ 3.4°C) cold-wet< warm-wet (n=7; p<0.05; Δ 3.2°C)	South Central: cold-wet< warm-dry (n=6,10; p<0.05, Δ 2.0°C) cold-wet< warm-wet (n=6,10; p<0.05, Δ 1.3°C) West Central: cold-wet< warm-dry (n=8,16; p<0.05; Δ 2.1°C) cold-wet< warm-wet (n=8,17; p<0.01; Δ

		warm-dry< warm-wet (n=80; p<0.01; Δ 0.4°C)	2.5°C) <u>East Central</u>: warm-dry< warm-wet (n=86,227; p<0.001; Δ 0.9°C)
Thermocline depth (m)	NS	NS	NS
Chlorophyll-*<u>a</u>* *<u>(ug/L)</u>*	NS	NS	NS
Total phosphorus (ug/L)	NS	NS	NS

[a] May-Oct Climate data, June-Sept WQ data
[b] May-Oct Climate data, June-Sept WQ data, (same results with water year Climate data)
[c] May-Oct Climate data, May-Oct WQ data

Summary:

The statistical analyses described above represent an important first step in combining 100 years of intensive weather records for the nine climate regions of Minnesota and the much more limited sets of “longer-term” water quality data from Minnesota’s lakes in order to better understand how changes in climate might affect the lakes. The approach taken here was to identify years in which weather was abnormally cold, warm, wet, or dry and to then examine the water quality available for lakes to determine if statistically valid associations could be identified. The lake data set, while seemingly enormous, is limited by the fact that there are relatively few lakes (~ 600) with water quality data spanning 15 different years, and within this set of lakes there is often only a single parameter, secchi depth (water clarity), to examine. Further, the lakes with longer term data are not randomly distributed across the state or across a gradient in water quality. The current set of heavily biased towards the Minneapolis-St-Paul metropolitan area and lake regions with long history of intensive shoreline development. More work is needed to examine individual lake records to see if these general trends are consistent for well monitored lakes.

Despite the limitations noted above, a number of patterns were observed that were statistically defensible. Across all lakes and analyses, warmer air temperature scenarios resulted in warmer surface water temperatures. This pattern occurred for both warm-wet years and warm-dry relative to cold-wet years for all lakes state-wide, for shallow lakes state-wide, and for shallow lakes in the south-central and west-central climate divisions of the state (Table 1).

Additionally, warm years, tended to be associated with greater productivity, as indicated by TSI-mean, than cold years, with higher TSI values in warm-dry years in shallow lakes across the state, as well as when all lakes were analyzed. As might be expected since much of the TSI data was based upon secchi depth measurements, warmer scenarios whether wet or dry tended to be associated lower secchi depths. There were also strong associations between warm-wet years and higher TSI and lower secchi depths for shallow lakes in the South

Central climate division of Minnesota. We hypothesized that the most productive summer growing seasons would occur for wet-warm scenarios due to increased watershed runoff of nutrients and more wind mixing associated with storms, coupled with warmer temperatures. In fact, we found the opposite: warm-wet years had significantly clearer water (greater secchi depth) than either cold-wet or warm-dry years for all lakes statewide and warm-dry years were more productive (higher TSI) than either warm-wet or cold-wet years for the entire set of shallow lakes across the whole State. We caution that these apparently conflicting results are preliminary and that there are inherent assumptions, which may not be valid, that all lakes and all shallow lakes across the state are limnologically similar except for climate variables, and that all shallow lakes in a climate division are similarly "created equal." These assumptions have yet to be tested and were beyond the scope of the current project.

Specific electrical conductivity (EC25), a measure of the total amount of dissolved ions and dissolved salts in the water, was found to be higher in warm-wet years relative to cold-wet in the statewide analysis for all lakes, and higher than warm-dry years for shallow lakes statewide. Unfortunately, there was insufficient data to compare warm-wet to cold-wet years for the shallow lake set. This suggests a warm versus cold effect, which could be due to enhanced evaporation in summer when the water quality data was collected, The wet versus dry effect for the shallow lakes is also consistent with both increased runoff of salts from the watershed and with increased roadsalt in wetter (i.e. icier and snowier) winters. Again, these interpretations are speculative at this time but suggest further exploratory analyses that might be conducted.

Similar exploratory analyses were performed on the total phosphorus (TP), chlorophyll-*a,* thermocline depth, bottom water temperature, and bottom water dissolved oxygen but none were statistically significant.