Title: **Climate signals in groundwater and surface water systems: Spectral analysis of hydrologic processes**

Project I.D.: **WR05R005**

Investigator(s): **Hector R. Bravo, Associate Professor, Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee, PI; Reza Namdar-Ghanbari, Research Assistant, Department of Civil Engineering and Mechanics, University of Wisconsin-Milwaukee**

Period of Contract: **07/01/2005 – 06/30/2007**

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Background/Need:

A number of studies in the US and throughout the world have shown existing relations between variability in water resources and climate variability. However, the effect of climate variability on water resources has been largely neglected. Climate variability affects all hydrologic processes to a certain degree, directly or indirectly through other hydrologic or meteorological processes.

This study explores the effect of climate variability on hydrologic processes such as precipitation, streamflow, groundwater level, lake levels, and lake ice-cover duration at the regional (Wisconsin and Great Lakes Region), watershed (Trout Lake Basin) and local scales. Coherence analysis is applied to compute the squared coherency between four teleconnections and several climate and hydrologic time series. The teleconnections considered are the Southern Oscillation Index (SOI), Pacific Decadal Oscillation (PDO), Northern Atlantic Oscillation (NAO) and Northern Pacific index (NP).

Objectives:

The main objectives of this research were:
1. To identify periodic forcing in existing time series of precipitation, stream flow discharge, lake levels, groundwater level, collected in Wisconsin and in the Trout Lake Basin in particular. We explored the existence of a climate-related fingerprint in the mentioned time series, and in related data series on Great Lakes levels and lake ice cover duration.
2. To investigate the coherency between large scale climate signals, regional climate, local climate, regional hydrologic time series, and local hydrologic time series.
3. To investigate the phase lag between precipitation and groundwater level, for high frequencies.

Methods:

The methods of analysis used included trend analysis, estimation of coherency, estimation of cross correlations, spectral estimation, and singular spectrum analysis (SSA). The statistical significance of trends was determined using the nonparametric Mann-Kendall test. Hydrologic time series are decomposed into their principal components, trend and noise using Singular Spectrum Analysis (SSA) and Multi-Taper Method (MTM) of spectral estimation. The percentage of variance explained by each component and the related frequency are computed using SSA.

Results and Discussion:

The results of coherence analysis showed the frequency bands where large-scale signals, climate and hydrologic time series have similar behavior in terms of oscillatory components.

Large-scale climate signals affect Great Lakes levels. The effect is verified by significant coherence between teleconnections and lake level time series, between teleconnections and over lake precipitation and lake evaporation series, and between precipitation and evaporation and lake levels series. The relations are clear for the upstream lakes, and more complex for the downstream lakes, where lake levels are affected by stream flow from the upstream lakes and their contributing watersheds.

Teleconnections affect groundwater level in Wisconsin. The effect is verified by significant coherence between teleconnections and groundwater level time series, between teleconnections and precipitation series, and between precipitation and groundwater level series. The relations are clear for the forested area of Wisconsin and more complex for the agricultural area of the State.

At the watershed scale (Trout Lake watershed), there is significant coherence between precipitation and groundwater level at high frequencies (of the order of days) and low frequencies (of the order of years), between precipitation and lake levels (at low frequencies), and between groundwater level and lake levels (at low frequencies). The use of spectral methods in the Trout Lake watershed showed that there are significant low frequency oscillations (of the order of 10 years) in lake levels, and significant oscillations in streamflow. These identified oscillations can help to improve groundwater- lake level modeling.

Teleconnections affect the ice cover duration in Lake Mendota, Wisconsin. The effect is verified by significant coherence between teleconnections and ice cover variables (ice cover duration, ice-on and ice-off dates), between teleconnections and local climate (air temperature, snowfall and snow depth), and between local climate and ice duration variables.

Conclusions/Implications/Recommendations:

The results obtained through the three techniques show significant links between large scale climate signals and hydrologic processes. The study estimated time scales of the principal components of important hydrologic time series and the relative importance of the components in explaining the variance of the time series.

The estimated time scales and their relative importance in the time series overall variance can be used to provide more meaningful inputs to groundwater or surface water models. For example, the recharge rate in groundwater models can be simulated more accurately using knowledge of its important oscillatory components, instead of using overall averages.

Related Publications:

Namdar-Ghanbari, R, 2007. Climate signals in groundwater and surface water systems: Spectral analysis of hydrologic processes, PhD Dissertation, University of Wisconsin-Milwaukee.

Namdar-Ghanbari, R. and Bravo, H.R., 2008. Coherence between teleconnections, regional climate and Great Lakes levels, Advances in Water Resources, doi: 10.1016/j.advwatres.2008.05.002.

Namdar G. R., Bravo H. R., 2007. Trend and Oscillations in the Ice Cover Duration of Lake Mendota, Wisconsin, presented at the 32nd Congress of the International Association of Hydraulic Engineering and Research, IAHR, Venice, Italy.

Key Words: Teleconnections; time series analysis; surface hydrology; subsurface hydrology

INTRODUCTION –

Numerous investigations in the area of climate variability effects on water resources indicate that the water resources sustainability in the United States is related to climate change (i.e., Hanson et al., 2004). Hydrologists have frequently constructed groundwater models with time frames of 1 to 10 years, using a recharge rate as an input or boundary condition that is based on a long-term average for each zone defined in the model domain. Depending on the simulation period and the presence of climate extremes, we could find large errors in the results predicted by groundwater simulation models.

Groundwater level data has been collected at a Groundwater Observation Well (GWOW) network in Wisconsin for a long period of time; the US Geological Survey collects data nationwide. However, this valuable data set has not yet played a role in critical decisions on water resources planning and management in Wisconsin because the bridge necessary to convey the hydrologic information to decision makers in a usable format is missing. In addition, a remarkable data set hydrologic time series, longer than a decade for some variables, has been collected in the Trout Lake Basin in Northern Wisconsin; within the framework of the Northern Temperate Lakes "Water, Energy, and Biogeochemical Budget" (WEBB) and Long Term Ecological Research (LTER) projects supported by the US Geological Survey and the National Science Foundation (NSF), respectively. These two existing data sets give a unique opportunity to evaluate groundwater system dynamics, and its interaction with surface water. Other existing, long-term data sets provide the opportunity to explore the relations between climate and hydrologic processes at different scales. These include records related to the Great Lakes water level and water budget, and ice cover duration in Midwest lakes.

The transience of the hydrologic processes and the climate variability effects were not fully quantified in the previous investigations, at least in a way appropriate to address the problems associated with groundwater management and modeling that originate in the different time scales of the hydrologic processes and the climate variability effects on water resources. The present study is expected to help in bridging the research gap addressed above. Existing frequencies embedded in hydrologic series such as groundwater level, precipitation, stream flow discharge rate, precipitation, lake levels and ice cover duration are extracted, and relations between different time series in regional scale (Wisconsin), watershed scale (Trout Lake Basin), and local scales are explored. The relations between each hydrologic time series and well-known climatic signals such as El Niño Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO) and Northern Pacific (NP) index are explored. The effects of climate variability on the Great Lakes water levels and Lake Mendota ice cover duration were investigated to improve our understanding of effects at the regional and local scale.

The main objectives of this research were:
4. To identify periodic forcing in existing time series of precipitation, stream flow discharge, lake levels, groundwater level, collected in Wisconsin and in the Trout Lake Basin in particular. I explored the existence of a climate-related fingerprint in the mentioned time series, and in related data series on Great Lakes levels and lake ice cover duration.
5. To investigate the coherency between large scale climate signals, regional climate, local climate, regional hydrologic time series, and local hydrologic time series.
6. To investigate the phase lag between precipitation and groundwater level, for high frequency components (of the order of days). This objective required the estimation of coherency and phase functions between several pairs of data series.

The main questions that this study attempted to answer using spectral analysis are:
1. Are there measurable effects of large scale climate signals on hydrologic processes such as precipitation, streamflow, lake levels, groundwater level and ice cover duration in Wisconsin and the region?

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2. If there measurable effects, how are different hydrologic processes affected?
3. How do the impacts of large scale climate signals on hydrologic processes vary at the regional, watershed and local scales?

PROCEDURES AND METHODS –

The methods of analysis used included trend analysis, estimation of coherency, estimation of cross correlations, spectral estimation, and singular spectrum analysis (SSA). The statistical significance of trends was determined using the nonparametric Mann-Kendall test (Press et al., 1988). We used coherence analysis between time series (Jenkins and Watts 1968; Bloomfield 1976) to evaluate trends and oscillations and to quantify the relations between hydrologic variables and teleconnections.

Coherence analysis, or cross-spectral analysis, may be used to identify variations that have similar spectral properties (high power in the same spectral frequency bands). This method can be thought of splitting the time series into two components: high (H) and low (L) frequencies: $x_t = x_t(H) + x_t(L)$, and $y_t = y_t(H) + y_t(L)$. We may want to know whether the slow components of x and y vary together in some way. Coherency analysis is applied to regional, watershed and local scale to find the coherency between large scale climate signals, regional or local climate variables, and hydrologic time series . The results are given in frequency bands where a pair of time series is significantly coherent. A 95% confidence limit is also built upon the coherency computations using the F test, which is based on F distribution and is explained in detail later in this chapter.

The Singular Spectrum Analysis technique (Vautard et al., 1992) along with other spectral estimation methods and coherency analysis, included in the Singular Spectrum Analysis-Multi-taper Method (SSA-MTM) toolkit (Dettinger et al., 1995), the MATLAB Signal Processing Toolbox (The Math Works, 2004) and Numerical Algorithm (NAG) Routines (1999) were applied to carry out the time series analysis in the frequency domain.

The data sets to be analyzed include 4 large scale climate signals and hydrologic variables that can be classified into three different scales: regional, watershed and local scales. The source and definition of the 4 large climate signals used in the analysis are the following:

The SOI is defined as the normalized pressure difference between Tahiti and Darwin, Ropelewski and Jones (1987). The data was obtained from the website http://jisao.washington.edu/pacs/additional_analyses/soi.html. The PDO Index (Mantua and Hare, 2002), derived as the leading PC of monthly SST anomalies in the North Pacific Ocean, pole ward of 20N, was obtained from the website http://jisao.washington.edu/pdo/PDO.latest. The NAO index is based on the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur/Reykjavik, Iceland since 1864. The NAO Index was obtained from the website http://www.cgd.ucar.edu/cas/jhurrell/indices.data.html#naostatmon. The NP Index is the area-weighted sea level pressure over the region 30N-65N, 160E-140W, available since 1899, and was obtained form the website http://www.cgd.ucar.edu/cas/jhurrell/npindex.html.

Regional scale studies covered the State of Wisconsin and Great Lakes Region and the following hydrologic time series were considered in the analysis:

a. Great Lakes water level data, evaporation from Great Lakes, precipitation over Great Lakes and air temperature over Great Lakes, totaling 16 data sets (Figure 1).
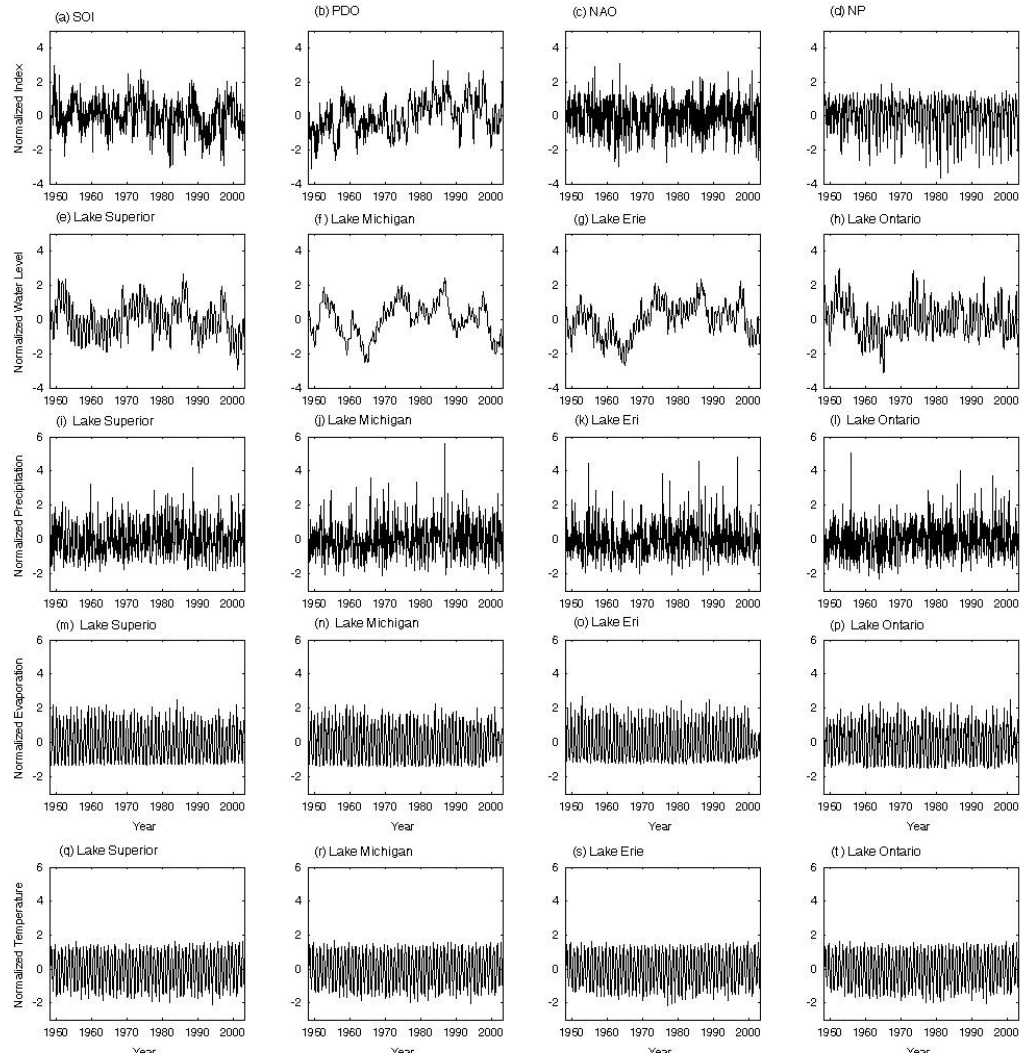
Figure 1. Normalized time series of a-d) SOI, PDO, NAO and NP; e, I, m, q) Lake Superior water level, precipitation, evaporation and temperature; f, j, n, r) Lake Michigan water level, precipitation, evaporation and temperature; g, k, o, s) Lake Erie water level, precipitation, evaporation and temperature; h, l, p, t) Lake Ontario water level, precipitation, evaporation and temperature.

      b.   Groundwater level and precipitation in 3 geographic areas, namely Agricultural, Forested and Drift-less areas in Wisconsin. Three groundwater sites and 3 precipitation station are selected in each area, i.e., collectively 18 data sets (Figure 2).

At the watershed scale the focus was on the Trout Lake Basin (Figure 3). The Trout Lake Basin is a part of Northern Highland Region with abundant surface water areas. There are approximately 3000 lakes ranging from 0.1 to 1500 hectares as well as streams, wetlands caused by coarse surficial deposits and relatively flat topography. Trout Lake Basin consists of 4 sub-watersheds as follows: Stevenson Creek Basin, Allequash Creek Basin, North Creek Basin, Mann Creek Basin.

In local scale the ice cover duration data from Lake Mendota located in Madison area is used in coherency analysis. The coherency analysis is done in 3 levels including: 1) Coherency between large scale climate signals and ice duration, ice-on and ice-off dates. 2) Coherency between large scale climate

signals and local climate time series such as local air temperature, snow fall and snow depth. 3) Coherency between 3 local climate time series and ice duration, ice-off and ice-on dates.
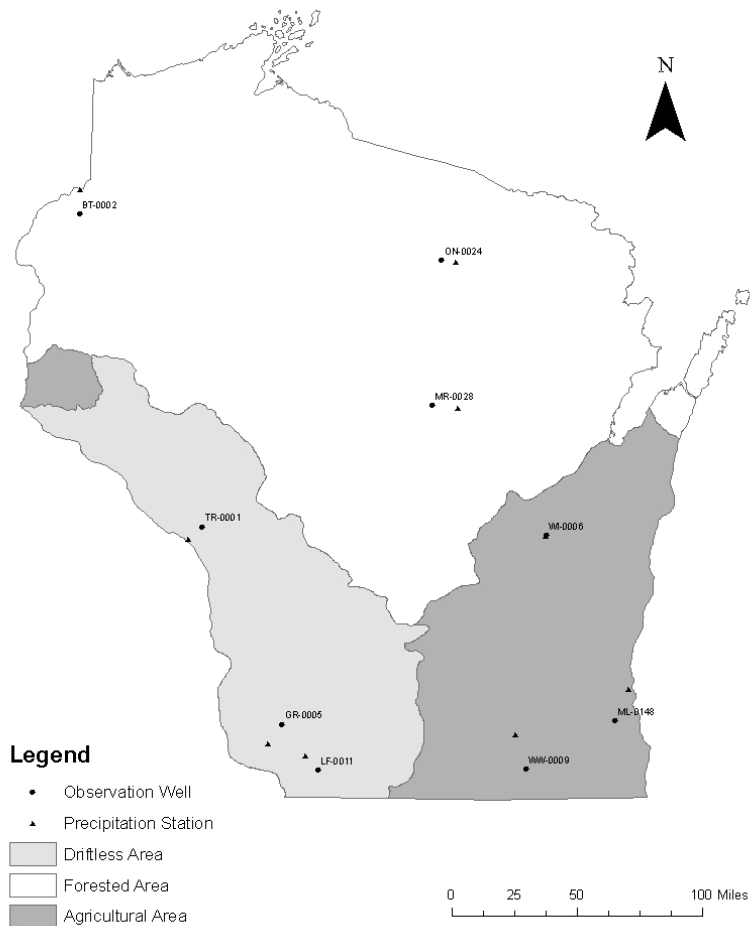

Figure 2. Groundwater sites and precipitation stations nearest to each site used in coherency analysis.

RESULTS AND DISCUSSION –

We investigated the frequency domain relationships between four large-scale climate signals (SOI, PDO, NAO, and NP), regional climate, and Great Lakes water level from 1948 to 2002 to quantify the coherence between these three levels. The mean and standard deviation of each time series were used to normalize the series. Figure 1 shows the normalized series. Three-tiered coherence analysis provides evidence that Great Lakes levels and the large-scale signals are significantly correlated at several inter-annual and a few inter-decadal frequencies. The results also show that significant coherence is transmitted through physical mechanisms linking the large-scale signals with lake levels, namely precipitation, evaporation and air temperature. The transmission of coherence through climate is especially clear for the SOI and PDO signals. The link through the climate variables seems less clear for Lake Ontario because precipitation over and evaporation from this lake are much smaller than the flows

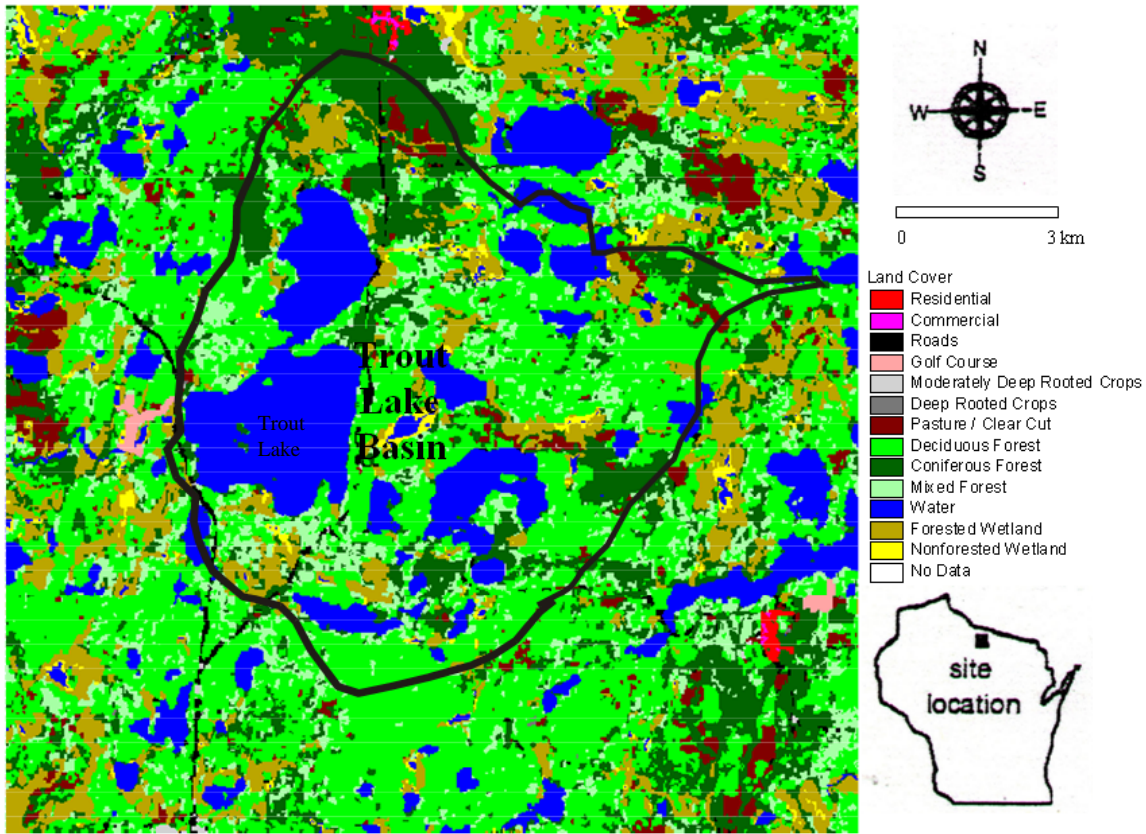in connecting channels, and the latter depend on the cumulative effect of upstream lakes and their watersheds.

Figure 3. Trout Lake Basin (after Dripps 2003)

Table 1 and Figure 4 summarize some results of the coherency analysis. The values of frequencies are shown in terms of its inverse, the return period, i.e., $\omega = T^{-1}$, and the horizontal line in Figure 4 indicates the 95% confidence level. The entries in Table 1 indicate the frequency bands where coherence in a given pair of variables is statistically significant at the 95% level. It should be read as pairs of values (frequency, square coherency). Frequency is given as a range (cycles year^{-1}) and squared coherency is given by the maximum value in the frequency range.

Figure 4 and Table 1 show 4 x 4= 16 possible pairs that summarize the direct effect of each large scale climate signal (SOI, PDO, NAO, and NP) on each Great Lake water level fluctuation. Further analysis thereof showed the following results regarding the direct effect of large-scale signals on two or more lakes.

SOI directly affects all lake levels in the $(8.1\text{-}8.5)^{-1}$ cycles year^{-1} frequency band, and directly affects levels on Lakes Superior, Erie and Ontario at $(2.3)^{-1}$ cycles year^{-1} frequency. PDO directly affects levels in Lakes Michigan, Erie and Ontario at $(12.2)^{-1}$ cycles year^{-1} frequency, affects levels in Lakes Superior, Michigan and Erie (western lakes) at $(7.7)^{-1}$ cycles year^{-1} frequency, and affects levels in Lakes Michigan and Ontario at $(2.1)^{-1}$ cycles year^{-1} frequency. NAO directly affects levels in Lakes Michigan, Erie and Ontario (eastern lakes) in the $(6.6\text{-}7.4)^{-1}$ and $(2.4\text{-}2.6)^{-1}$ cycles year^{-1} frequency ranges, and Lakes Superior and Michigan in the $(3.6\text{-}4.0)^{-1}$ cycles year^{-1} frequency range. NP directly affects levels in all lakes in the $(>20)^{-1}$ frequency range, and Lakes Michigan, Erie and Ontario at $(2.1)^{-1}$ cycles year^{-1} frequency.

		Superior	Michigan	Erie	Ontario
SOI	Frequency, cycles year^{-1}	$(8.1\text{-}11.4)^{-1}$ $(2.6\text{-}4.0)^{-1}$ $(2.2\text{-}2.3)^{-1}$	$(6.1\text{-}10.7)^{-1}$ $(3.0\text{-}3.9)^{-1}$	$(6.9\text{-}10.7)^{-1}$ $(3.0\text{-}3.9)^{-1}$ $(2.3\text{-}2.7)^{-1}$	$(6.8\text{-}8.5)^{-1}$ $(2.3\text{-}2.8)^{-1}$
	Squared coherency	0.53 0.87 0.44	0.8 0.98	0.69 0.87 0.61	0.57 0.78
PDO	Frequency, cycles year^{-1}	$(7.4\text{-}7.7)^{-1}$ $(2.2\text{-}2.5)^{-1}$	$(>12.2)^{-1}$ $(6.5\text{-}8.5)^{-1}$ $(2.1)^{-1}$	$(>11.4)^{-1}$ $(7.7)^{-1}$	$(>6.8)^{-1}$ $(2.1)^{-1}$
	Squared coherency	0.41 0.82	0.91 0.58 0.77	0.82 0.4	0.0.69 0.82
NAO	Frequency, cycles year^{-1}	$(3.2\text{-}4.3)^{-1}$	$(5.9\text{-}7.4)^{-1}$ $(3.5\text{-}4.0)^{-1}$ $(2.3\text{-}2.6)^{-1}$	$(6.3\text{-}7.7)^{-1}$ $(2.2\text{-}2.9)^{-1}$	$(6.6\text{-}9.0)^{-1}$ $(2.3\text{-}2.9)^{-1}$
	Squared coherency	0.63	0.68 0.61 0.44	0.60 0.90	0.63 0.76
NP	Frequency, cycles year^{-1}	$(>21.3)^{-1}$ $(3.3\text{-}4.0)^{-1}$ $(2.3\text{-}2.8)^{-1}$	$(>17.1)^{-1}$ $(7.1\text{-}8.1)^{-1}$ $(2.1)^{-1}$	$(>15.5)^{-1}$ $(2.1)^{-1}$	$(>21.3)^{-1}$ $(6.8\text{-}9.0)^{-1}$ $(2.1)^{-1}$
	Squared coherency	0.60 0.51 0.56	0.75 0.46 0.86	0.75 0.77	0.76 0.56 0.94

Table 1. Large scale climate signals and Great Lake water levels: squared coherencies at or above the 95% confidence level and corresponding frequencies.

In watershed scale four types of time series (groundwater level, precipitation, streamflow and lake levels in Trout Lake Basin) are analyzed in the frequency domain using coherency and phase analysis techniques, Singular Spectrum Analysis (SSA), and Multi-Taper Method of spectral estimation. The results for these analyses are given in Namdar-Ghanbari (2007) in three sections. The first section is a (high-frequencies) coherence analysis between precipitation and groundwater level, the second section is a (low-frequencies) coherence analysis between precipitation, groundwater levels and lake levels, and the third section is an analysis of low frequency oscillations in streamflow and lake levels.

Long term data sets in Trout Lake Basin were used to explore the low frequency bands of significant coherency between precipitation, groundwater level and lake levels. The data sets include quarterly data collected from 1985 to 2003, i.e., 19 years in total. Precipitation data collected at Minocqua Dam precipitation station serves as precipitation data in this analysis (Figure 5-a). There is a network of 12 wells in the area with long term records, and all of them have the same oscillatory behavior in terms of water level fluctuations over the time (Figure 5-b). Therefore one well (well # K2) is selected to represent the groundwater level fluctuation in the area around Big Muskellunge Lake (Figure 5-c). The lake level time series used in the analysis is the Big Muskellunge Lake water level (Figure 5-d). The results of the analysis are given below.

Figure 6-a and the first 2 rows of Table 2 shows the results from coherence analysis between precipitation and groundwater level. As it is seen in the figure and the numerical values in the table, precipitation and groundwater level are significantly coherent in the frequency bands of $(2\text{-}8)^{-1}$ cycles year^{-1}, $(1.4\text{-}1.6)^{-1}$ cycles year^{-1}, $(0.9\text{-}1.1)^{-1}$ cycles year^{-1}, and $(0.67\text{-}0.7)^{-1}$ cycles year^{-1}. Figure 6-b and the third and fourth

rows of Table 2 shows the results from coherence analysis between precipitation and lake level. As it is seen in the figure and the numerical values in the table, precipitation and lake level are significantly coherent in the frequency bands of $(2.2-8)^{-1}$ cycles year^{-1}, $(1.3-1.6)^{-1}$ cycles year^{-1}, $(0.9-1.0)^{-1}$ cycles year^{-1}, and $(0.6-0.7)^{-1}$ cycles year^{-1}. Figure 6-c and the last two rows of Table 2 shows the results from coherence analysis between groundwater level and lake levels. As it is seen both in the figure and the table, the groundwater level and lake levels are significantly coherent in the frequency bands of $(>2.4)^{-1}$ cycles year^{-1}, and $(0.9-1.3)^{-1}$ cycles year^{-1}.
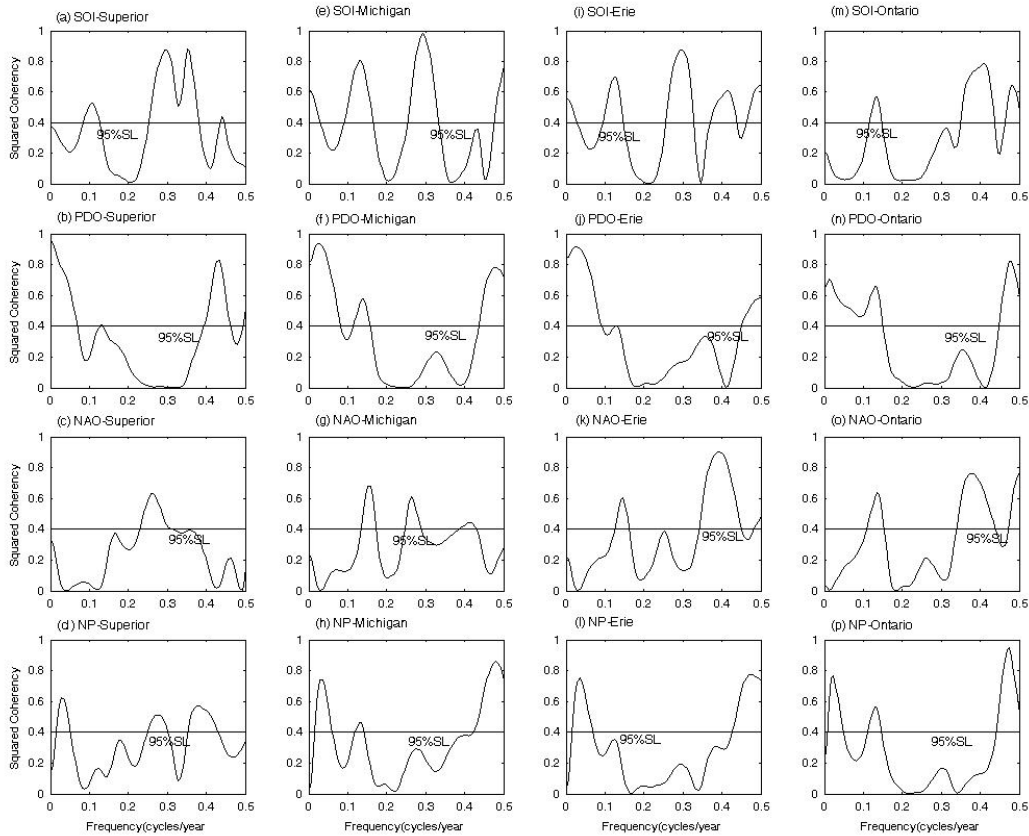

Figure 4. Squared coherencies of (teleconnections, Great Lakes water level) pairs

Figure 6 and Table 2 show the results from coherency analysis between precipitation, groundwater level and lake level.

CONCLUSIONS AND RECOMMENDATIONS –

Large-scale climate signals affect Great Lakes levels. The effect is verified by significant coherence between signals and lake level time series, between signals and over lake precipitation and lake evaporation series, and between precipitation and evaporation and lake levels series. The relations are clear for the upstream lakes, and more complex for the downstream lakes, where lake levels are affected by stream flow from the upstream lakes and their contributing watersheds.

Large-scale signals affect groundwater level in Wisconsin. The effect is verified by significant coherence between signals and groundwater level time series, between signals and precipitation series, and between

precipitation and groundwater level series. The relations are clear for the forested area of Wisconsin and more complex for the agricultural area of the State.

At the watershed scale (Trout Lake watershed), there is significant coherence between precipitation and groundwater level at high frequencies (of the order of days) and low frequencies (of the order of years), between precipitation and lake levels (at low frequencies), and between groundwater level and lake levels (at low frequencies).
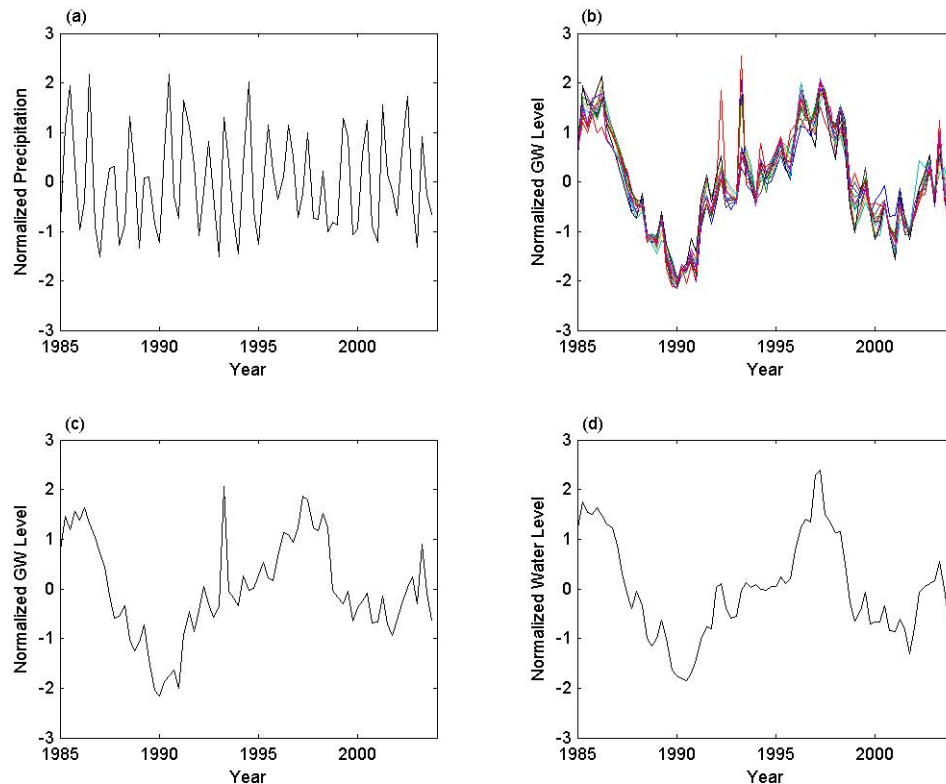

Figure 5. Time series used in coherency analysis: a) quarterly precipitation time series at Minocqua Dam; b) Quarterly groundwater level time series in the whole well network; c) Quarterly groundwater level time series at well # K2; d) Quarterly Big Muskellunge Lake water level time series

The use of spectral methods in the Trout Lake watershed showed that there are significant low frequency oscillations (of the order of 10 years) in lake levels, and significant oscillations in streamflow. These identified oscillations can help to improve groundwater- lake level modeling.

Large-scale signals affect the ice cover duration in Lake Mendota, Wisconsin. The effect is verified by significant coherence between signals and ice cover variables (ice cover duration, ice-on and ice-off dates), between signals and local climate (air temperature, snowfall and snow depth), and between local climate and ice duration variables.

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Precipitation and Groundwater Level	Frequency Cycles year^{-1}	$(2.0\text{-}8.0)^{-1}$
		$(1.4\text{-}1.6)^{-1}$
		$(0.9\text{-}1.1)^{-1}$
		$(0.66\text{-}0.7)^{-1}$
	Squared Coherency	0.65
		0.57
		0.73
		0.53
Precipitation and Lake Level	Frequency Cycles year^{-1}	$(2.2\text{-}8.0)^{-1}$
		$(1.3\text{-}1.6)^{-1}$
		$(0.9\text{-}1.0)^{-1}$
		$(0.6\text{-}0.67)^{-1}$
	Squared Coherency	0.71
		0.66
		0.55
		0.61
Groundwater Level and Lake Level	Frequency Cycles	$(>2.4)^{-1\ 1}$
		$(0.9\text{-}1.25)^{-1}$
	Squared Coherency	0.99
		0.77

Table 2. Squared coherency and significant frequency bands between precipitation, groundwater level and lake level in Trout Lake basin
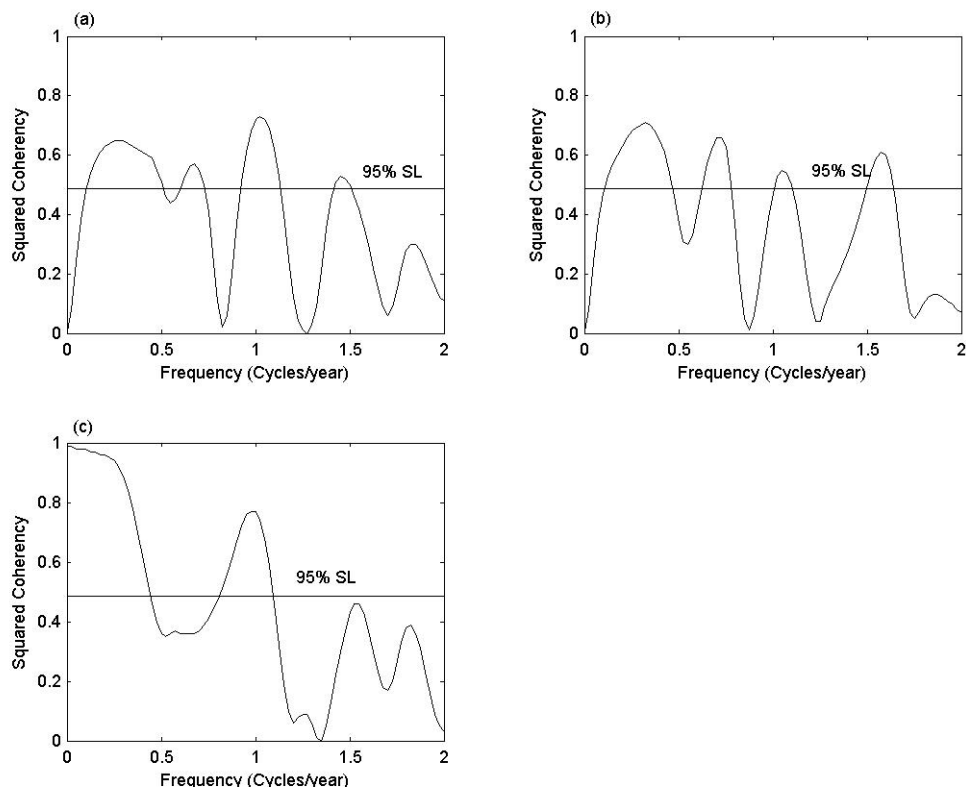

Figure 6. Coherency analysis results: a) squared coherency between precipitation and groundwater level; b) squared coherency between precipitation and lake level; c) squared coherency between groundwater level and lake level

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APPENDIX A: Awards, Publications, Reports, Patents and Presentations –

Namdar-Ghanbari, R, 2007. Climate signals in groundwater and surface water systems: Spectral analysis of hydrologic processes, PhD Dissertation, University of Wisconsin-Milwaukee.

Namdar-Ghanbari, R. and Bravo, H.R., 2008. Coherence between teleconnections, regional climate and Great Lakes levels, Advances in Water Resources, doi: 10.1016/j.advwatres.2008.05.002.

Namdar G. R., Bravo H. R., 2007. Trend and Oscillations in the Ice Cover Duration of Lake Mendota, Wisconsin, presented at the 32nd Congress of the International Association of Hydraulic Engineering and Research, IAHR, Venice, Italy.

Namdar Ghanbari, R., Bravo, H.R, Magnuson, J.J., Hyzer, W.G. and Benson, B.J., 2008. Coherence between lake ice cover, local climate and teleconnections (Lake Mendota, Wisconsin), submitted to Journal of Hydrology.