Great Lakes Energy-Water Nexus Initiative
Environmental Rules to Classify Basins for Sensitivity from Future Energy Development

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From project discussions, four factors were selected as the primary influences of electric power production effects on the environment of the Great Lakes basin. The four factors are justified with a method to rate sensitivity to additional environmental stress at the sub-basin scale (8-digit hydrologic unit code land areas). All basins in the Great Lakes region can be rated for vulnerability to additional environmental impacts. Water quantity is in the Energy Water Power Simulation Model (Sandia National Laboratory model) allowing estimates of further energy production consequences on water for the environment. This can be done once for all basins using current conditions, and water quantity factors can be modified in future scenarios to investigate environmental consequences. Here the methods are presented for estimation for four factors, example computations, and results of the trial computations.

Factor 1 - Water Quantity

Modeling Approach

Many countries, states, provinces, and regions have addressed water needs on a river basin scale by establishing a general standard for water needed to maintain acceptable riverine ecosystem conditions. In some cases environmental needs for water allocation have been defined as a share of the original water resource availability. For the Great Lakes Energy-Water Nexus Initiative, we will be working with water availability and use on a scale that approximates a small river basin: estimates of total basin outflow and water uses. Consequently, a set of standards to estimate the current status of water for human and environmental needs on an average annual basis and for low flow periods.

Standards for river flows and environmental water needs have mainly been set using general hydrological data to produce look-up table values for water available for environmental or river protection (Tharme 2003). Most often these are stated as fixed-percentage of river flow or water availability (Table 1). This approach is considered appropriate for planning of water resource development on a regional scale thus it matches what we are striving for in the Great Lakes Energy-Water Nexus Initiative. Environmental water need may be defined as: the flows which are needed to sustain the desired ecosystem, to meet abstraction requirements, and to support basin water uses (Petts 1996).

The most widely used environmental standard setting method in the US and around the world was introduced by Tennant (1976) and is still commonly followed (Reiser et al.

Table 1. Summary of annual average standards applied to water needs for rivers and watershed environmental needs.

Region	Standard	Justification	Sources
Many US States and Canadian Provinces	≥30% of average annual flow provides good river conditions	Based on studies on 11 rivers in 3 western US states	Tennant (1976), Reiser et al. (1989)
South Africa	~40% of natural average annual flow maintains moderately modified river quality	Synthesis of flow depletion studies in South Africa	King and Brown (2006)
New Zealand	>30% average flow maintains 2/3rds of productive habitats	Comparison of findings and habitat analyses conducted on 22 New Zealand rivers	Jowett (1979)
Minnesota	~76% of original mean annual flow as a minimum flow	Synthesis of studies on river flows and habitat in 27 Minnesota Rivers	O'Shea (1995)
James River basin, Virginia	20 to 40% average annual flow provides habitat protection from acceptable to optimal	Comparison of findings from habitat simulations and standard setting methods of study area	Orth and Leonard (1990)
United Kingdom	60% of water need to maintain river ecosystems and allow abstraction needs	Review of research on water abstraction effects in the United Kingdom	Petts (1996)
United Kingdom	Maintain ≥60% of any hydrologic measure of river flow to maintain good ecological status.	Data and experts recommendation for environmental flows to meet the European Union standards	Acreman et al. (2009), Acreman et al. (2010)
Australia	Maintain flow regime attributes above 66% of the natural value to maintain healthy river status	Recommendation based on review of river abstraction studies in Australia	Jones (2002)
128 basins worldwide	Environmental need estimated as 38% of mean flow for Northeast US.	Hydrologic modeling of river basins across the world.	Smakhtin et al. (2004)
United Kingdom, groundwater-dominated rivers	Maintain ≥50% of total annual flow for acceptable river status.	Measured habitat quality for fish and invertebrates under varied flow levels.	Petts et al. (1999)
British Columbia	Maintain ≥78% of total annual flow for acceptable river status.	Recommendation based on review of study results, hydrology, and channel morphology of provincial rivers.	Hatfield et al. (2003)

1989, Dunbar et al. 1998, Tharme 2003). This method is based on a table that reports different percentages of mean annual flow that support different categories of river condition overall and during seasonal flows. The general aim is to specify a minimum discharge or portion of surface water flow to meet environmental quality thresholds such as poor, fair, good, optimum, and others. Other methods have been developed to set standards and these are reviewed in Table 1 with the recommendation for acceptable environmental conditions.

Estimator Method

Table 1 provides estimates of water need for environmental support as a percentage of annual river flow, water availability, or original conditions. There are 11 estimates ranging from 30 to 78%. Using the midpoint of ranges, the mean estimate is 51% and the median is 50%. For application in the Great Lakes Energy-Water Nexus Initiative, a set of standards using these results can be applied to overall water availability:

< 30% for environmental needs results in significant environmental losses
30-50% for environmental needs is likely to result in marginal environmental conditions
>50-80% for environmental needs will likely maintain good environmental conditions
>80% for environmental needs is likely to result in excellent environmental conditions

The following formulae computes a current status from data in the Energy Water Power Simulation Model:

X% = (mean basin total annual streamflow MGD) divided by
((mean basin total annual streamflow MGD)+(sum of all water uses in MGD))

If natural flow can be estimates by the model, this shorter formulae would provide a more direct estimate:

X% = (mean annual current streamflow MGD) / (natural or original streamflow MGD)

Once a percent mean streamflow is estimated as a percent of total water availability the following ratings can be assigned to each basin using standards above:

0.0	< 30% for environmental needs
0.3	30-50% for environmental needs
0.6	>50-80% for environmental needs
1.0	>80% for environmental needs

The ratings are prorated to a zero to one scale with zero being most vulnerable to new water uses and one being optimal for additional human water demands.

Results

Table 2 has the calculations for most HUC-8 basins in the Great Lakes region. All basins were rated 1.0 because on an annual average basis there is less than 20% of each basins total water volume used by people. Hence more than 80% of all water is available for environmental support and this rates excellent using the standards above. This indicates that region wide there is plenty of water for environmental support on an annual basis. This is not surprising because the Great Lakes region is the most water rich region in the world. The use of overall water availability (Factor 1) will not separate the HUC-8 basins so this factor is not useful in Great Lakes region application for distinquishing environmentally vulnerable basins from those that can accommodate more power production. This result justifies dropping this factor for the Great Lakes scenario analyses. However, in other parts of the word this may be a good overall indicator of sensitivity for water use and power production.

Table 2. Annual average water quantity calculations for factor 1.

Basin	Subbasin	HUC-8 number	Average annual stream flow (MGD)	Average annual water Use (MGD)	Average annual % non-used water	0 to 1 rating (1 is optimal)
Northwestern Lake Superior	Baptism-Brule	4010101	6,215.21	158.55	0.98	1.00
Northwestern Lake Superior	Beaver-Lester	4010102	956.92	133.97	0.88	1.00
St. Louis	St. Louis	4010201	14,347.87	196.64	0.99	1.00
St. Louis	Cloquet	4010202	1,024.37	1.88	1.00	1.00
Southwestern Lake Superior	Beartrap-Nemadji	4010301	15,803.31	3.30	1.00	1.00
Southwestern Lake Superior	Bad-Montreal	4010302	10,068.98	1.76	1.00	1.00
Southcentral Lake Superior	Black-Presque Isle	4020101	9,259.95	11.79	1.00	1.00
Southcentral Lake Superior	Ontonagan	4020102	11,437.88	1.41	1.00	1.00
Southcentral Lake Superior	Keweenaw Peninsula	4020103	12,806.30	3.10	1.00	1.00
Southcentral Lake Superior	Sturgeon	4020104	6,502.66	2.42	1.00	1.00
Southcentral Lake Superior	Dead-Kelsey	4020105	8,680.15	1.65	1.00	1.00
Southeastern Lake Superior	Betsy-Chocolay	4020201	10,744.44	3.85	1.00	1.00
Southeastern Lake Superior	Tahquamenon	4020202	7,556.01	1.59	1.00	1.00
Northwestern Lake Michigan	Manitowoc-Sheboygan	4030101	7,028.82	36.37	0.99	1.00
Northwestern Lake Michigan	Door-Kewaunee	4030102	3,551.87	8.52	1.00	1.00
Northwestern Lake Michigan	Duck-Pensaukee	4030103	1,559.58	10.55	0.99	1.00
Northwestern Lake Michigan	Oconto	4030104	6,147.45	3.99	1.00	1.00
Northwestern Lake Michigan	Peshtigo	4030105	8,108.24	8.98	1.00	1.00
Northwestern Lake Michigan	Brule	4030106	1,881.23	2.22	1.00	1.00
Northwestern Lake Michigan	Michigamme	4030107	896.51	0.81	1.00	1.00
Northwestern Lake Michigan	Menominee	4030108	8,935.87	57.20	0.99	1.00
Northwestern Lake Michigan	Cedar-Ford	4030109	7,137.18	3.02	1.00	1.00
Northwestern Lake Michigan	Escanaba	4030110	6,968.76	20.74	1.00	1.00
Northwestern Lake Michigan	Fishdam-Sturgeon	4030112	4,894.61	1.45	1.00	1.00
Fox	Upper Fox	4030201	2,267.40	32.91	0.99	1.00
Fox	Wolf	4030202	12,049.59	50.55	1.00	1.00
Fox	Lake Winnebago	4030203	283.44	12.74	0.96	1.00
Southwestern Lake Michigan	Little Calumet-Galien	4040001	3,701.08	284.65	0.93	1.00
Southwestern Lake Michigan	Pike-Root	4040002	1,267.14	29.30	0.98	1.00
Southwestern Lake Michigan	Milwaukee	4040003	5,040.28	194.05	0.96	1.00
Southeastern Lake Michigan	St. Joseph	4050001	38,173.40	207.85	0.99	1.00
Southeastern Lake Michigan	Black-Macatawa	4050002	11,262.58	72.46	0.99	1.00
Southeastern Lake Michigan	Kalamazoo	4050003	16,007.56	84.74	0.99	1.00
Southeastern Lake Michigan	Upper Grand	4050004	3,421.98	272.66	0.93	1.00
Southeastern Lake Michigan	Maple	4050005	982.39	13.31	0.99	1.00
Southeastern Lake Michigan	Lower Grand	4050006	4,522.24	214.79	0.95	1.00
Southeastern Lake Michigan	Thornapple	4050007	833.95	9.08	0.99	1.00
Northeastern Lake Michigan	Pere Marquette-White	4060101	51,293.66	32.74	1.00	1.00
Northeastern Lake Michigan	Muskegon	4060102	19,247.52	48.40	1.00	1.00
Northeastern Lake Michigan	Manistee	4060103	19,886.46	27.81	1.00	1.00
Northeastern Lake Michigan	Betsie-Platte	4060104	8,356.77	8.51	1.00	1.00
Northeastern Lake Michigan	Boardman-Charlevoix	4060105	39,912.85	25.62	1.00	1.00
Northeastern Lake Michigan	Manistique	4060106	15,346.21	6.60	1.00	1.00
Northeastern Lake Michigan	Brevoort-Millecoquins	4060107	5,884.34	0.77	1.00	1.00
Northwestern Lake Huron	Carp-Pine	4070002	4,383.19	1.06	1.00	1.00
Northwestern Lake Huron	Black	4070005	5,857.33	0.80	1.00	1.00
Northwestern Lake Huron	Thunder Bay	4070006	5,986.24	24.61	1.00	1.00
Northwestern Lake Huron	Au Sable	4070007	15,306.60	9.18	1.00	1.00
Southwestern Lake Huron	Au Gres-Rifle	4080101	6,914.08	6.21	1.00	1.00
Southwestern Lake Huron	Kawkawlin-Pine	4080102	2,828.76	5.80	1.00	1.00
Southwestern Lake Huron	Pigeon-Wiscoggin	4080103	5,231.47	477.76	0.92	1.00

Basin	Subbasin	HUC-8 number	Average annual stream flow (MGD)	Average annual water Use (MGD)	Average annual % non-used water	0 to 1 rating (1 is optimal)
Saginaw	Tittabawassee	4080201	1,900.10	41.29	0.98	1.00
Saginaw	Pine	4080202	979.84	11.65	0.99	1.00
Saginaw	Shiawassee	4080203	1,418.29	34.83	0.98	1.00
Saginaw	Flint	4080204	1,636.55	37.48	0.98	1.00
Saginaw	Cass	4080205	734.57	7.20	0.99	1.00
St. Clair-Detroit	St. Clair	4090001	5,358.51	21.26	1.00	1.00
St. Clair-Detroit	Clinton	4090003	5,110.06	38.57	0.99	1.00
St. Clair-Detroit	Huron	4090005	5,075.18	57.01	0.99	1.00
Western Lake Erie	Ottawa-Stony	4100001	7,822.05	53.77	0.99	1.00
Western Lake Erie	Raisin	4100002	5,632.17	12.89	1.00	1.00
Western Lake Erie	St. Joseph	4100003	1,233.73	35.83	0.97	1.00
Western Lake Erie	St. Marys	4100004	691.81	16.08	0.98	1.00
Western Lake Erie	Tiffin	4100006	646.44	6.13	0.99	1.00
Western Lake Erie	Auglaize	4100007	2,942.25	14.80	0.99	1.00
Western Lake Erie	Blanchard	4100008	621.74	40.75	0.94	1.00
Western Lake Erie	Lower Maumee	4100009	1,242.07	18.17	0.99	1.00
Western Lake Erie	Sandusky	4100011	13,145.67	17.74	1.00	1.00
Western Lake Erie	Huron-Vermilion	4100012	4,804.23	23.69	1.00	1.00
Southern Lake Erie	Black-Rocky	4110001	7,471.05	127.49	0.98	1.00
Southern Lake Erie	Cuyahoga	4110002	8,875.92	140.49	0.98	1.00
Southern Lake Erie	Ashtabula-Chagrin	4110003	14,419.61	36.87	1.00	1.00
Southern Lake Erie	Grand	4110004	7,388.47	52.80	0.99	1.00
Eastern Lake Erie	Chautauqua-Conneaut	4120101	4,873.40	22.91	1.00	1.00
Eastern Lake Erie	Cattaraugus	4120102	6,950.49	26.67	1.00	1.00
Eastern Lake Erie	Buffalo-Eighteenmile	4120103	9,586.50	64.23	0.99	1.00
Eastern Lake Erie	Niagara	4120104	9,877.12	708.64	0.93	1.00
Southwestern Lake Ontario	Oak Orchard-Twelvemile	4130001	3,163.90	11.98	1.00	1.00
Southwestern Lake Ontario	Upper Genesee	4130002	9,462.04	7.41	1.00	1.00
Southwestern Lake Ontario	Lower Genesee	4130003	4,487.71	135.61	0.97	1.00
Southeastern Lake Ontario	Irondequoit-Ninemile	4140101	6,706.29	15.61	1.00	1.00
Southeastern Lake Ontario	Salmon-Sandy	4140102	16,411.35	9.49	1.00	1.00
Oswego	Seneca	4140201	39,787.56	754.92	0.98	1.00
Oswego	Oneida	4140202	657.91	22.33	0.97	1.00
Oswego	Oswego	4140203	2,128.68	4.70	1.00	1.00
Northeastern Lake Ontario	Black	4150101	5,540.83	92.75	0.98	1.00
St. Lawrence	Oswegatchie	4150302	7,614.53	6.23	1.00	1.00
NOTE: not all basins included because some were missing values						
	Formulae used:				(D#)/(D# +E#)	0-1 rating, see text

Factor 2 - Low Flow Vulnerability

Modeling Approach

The general aim is to specify a portion of surface water flow to meet environmental quality during low flow periods using August as an index month for calculations. Table 3 has the environmental flow information that is oriented to low flow periods. The recommendations are used to specify a standards for application in the Great Lakes region at the basin scale for judging the vulnerability to increased future water need during low flow seasons.

Table 3. Summary of low flow season standards applied to water needs for rivers and watershed environmental needs.

Region	Standard	Justification	Sources
Many US States and Canadian Provinces	≥20% of average annual flow during low flow seasons	Based on studies on 11 rivers in 3 western US states	Tennant (1976), Reiser et al. (1989)
Michigan, USA	Maintain summer base flow to 60 to 80% of unimpaired flow based on river class	Habitat models for rivers differing in thermal class and size indicates that 20-50% of summer base flow can be used without adverse impact.	Zorn et al. (2008), Bartholic et al. (2009)
128 basins worldwide	Environmental need estimated as the median annual flow for low flow periods	Hydrologic modeling of river basins across the world.	Smakhtin et al. (2004)

Estimator Method

Table 3 provides estimates of water needs for environmental support during low flow periods. These three values specify a portion of river flow needed but they were computed that using three different basis: mean annual flow, average summer flow, and median annual flow. Thus it is not possible to average or directly compare these. Standards selected here are close to the Michigan Water Withdrawal Assessment Tool because it was well researched in the Great Lakes basin. Details of this method are reviewed in Michigan Department of Environmental Quality (2008), Zorn et al. (2008), and Bartholic et al. (2009). However, the lower flow value was reduced slightly because other state standards are less. A set of standards we recommend are:

< 50% for environmental needs results in significant environmental losses
50-80% for environmental needs will likely maintain good environmental conditions
>80% for environmental needs is likely to result in excellent environmental conditions

The month of August is a low flow month and one where human water uses remains high. Standards can be applied against the basin outflows and human uses during August.

The following formulae will compute a current status from data in our energy-water model:

X% = (mean basin August streamflow MGD) divided by
((mean basin August streamflow MGD)+(sum of all water uses in August MGD))

If natural flow can be estimates by the model, this shorter formulae would provide a more direct estimate:

X% = (mean August current streamflow MGD) / (natural August streamflow MGD)

Once a percent August streamflow abstraction is estimated as a percent of natural August streamflow, then the result can be given a rating based on the standards below:

0.0	< 50% for environmental needs	**<---- Threshold level ≥ 50%**
0.5	50-80% for environmental needs	
1.0	>80% for environmental needs	

This second measure of water quantity status will be combined with the first result (average annual standards) and others for an overall measure of vulnerability to increased effects on the basin environment.

Results

Table 4 has the calculations for most HUC-8 basins in the Great Lakes region. This factor clearly distinguished basins because there were many basins rated 0, 0.5, and 1. Basins that received the lowest rating (0) often had more water use than streamflow in August indicating that further water use would reduce streamflow and may impact other users. Some basins were rated in the middle category (0.5) and many were rated high for August water availability (1.0). Unlike overall water availability (Factor 1) this factor is useful in modeling environmentally vulnerable basins from those that can accommodate more power production. Finally this factor can be used to explore future scenarios because the Energy Water Power Simulation Model has August streamflow and water use by basin and can estimate the numbers with further power production facilities.

Table 4. Low flow water quantity calculations for factor 2.

Basin	Subbasin	HUC-8 number	Average August stream flow (MGD)	August water use (MGD)	August annual % non-used water	0 to 1 rating (1 is optimal)
Northwestern Lake Superior	Baptism-Brule	4010101	154.63	158.75	0.49	0.00
Northwestern Lake Superior	Beaver-Lester	4010102	23.81	134.25	0.15	0.00
St. Louis	St. Louis	4010201	726.67	198.50	0.79	0.50
St. Louis	Cloquet	4010202	51.88	2.11	0.96	1.00
Southwestern Lake Superior	Beartrap-Nemadji	4010301	822.19	3.90	1.00	1.00
Southwestern Lake Superior	Bad-Montreal	4010302	471.73	1.93	1.00	1.00
Southcentral Lake Superior	Black-Presque Isle	4020101	378.78	11.93	0.97	1.00
Southcentral Lake Superior	Ontonagan	4020102	539.68	2.02	1.00	1.00
Southcentral Lake Superior	Keweenaw Peninsula	4020103	370.24	3.68	0.99	1.00
Southcentral Lake Superior	Sturgeon	4020104	328.78	2.73	0.99	1.00
Southcentral Lake Superior	Dead-Kelsey	4020105	697.75	2.35	1.00	1.00
Southeastern Lake Superior	Betsy-Chocolay	4020201	472.38	4.93	0.99	1.00
Southeastern Lake Superior	Tahquamenon	4020202	330.64	2.30	0.99	1.00
Northwestern Lake Michigan	Manitowoc-Sheboygan	4030101	61.33	42.83	0.59	0.50
Northwestern Lake Michigan	Door-Kewaunee	4030102	52.40	10.45	0.83	1.00
Northwestern Lake Michigan	Duck-Pensaukee	4030103	13.67	12.11	0.53	0.50
Northwestern Lake Michigan	Oconto	4030104	333.11	4.95	0.99	1.00
Northwestern Lake Michigan	Peshtigo	4030105	398.91	10.36	0.97	1.00
Northwestern Lake Michigan	Brule	4030106	104.41	2.77	0.97	1.00
Northwestern Lake Michigan	Michigamme	4030107	49.76	1.57	0.97	1.00
Northwestern Lake Michigan	Menominee	4030108	495.94	62.16	0.89	1.00
Northwestern Lake Michigan	Cedar-Ford	4030109	292.80	3.86	0.99	1.00
Northwestern Lake Michigan	Escanaba	4030110	277.23	23.64	0.92	1.00
Northwestern Lake Michigan	Fishdam-Sturgeon	4030112	227.50	2.00	0.99	1.00
Fox	Upper Fox	4030201	101.35	37.73	0.73	0.50
Fox	Wolf	4030202	538.61	58.66	0.90	1.00
Fox	Lake Winnebago	4030203	12.67	16.09	0.44	0.00
Southwestern Lake Michigan	Little Calumet-Galien	4040001	124.66	317.11	0.28	0.00
Southwestern Lake Michigan	Pike-Root	4040002	42.68	40.82	0.51	0.50
Southwestern Lake Michigan	Milwaukee	4040003	182.41	215.80	0.46	0.00
Southeastern Lake Michigan	St. Joseph	4050001	1,966.84	406.34	0.83	1.00
Southeastern Lake Michigan	Black-Macatawa	4050002	285.62	86.69	0.77	0.50
Southeastern Lake Michigan	Kalamazoo	4050003	822.51	114.04	0.88	1.00
Southeastern Lake Michigan	Upper Grand	4050004	84.94	287.92	0.23	0.00
Southeastern Lake Michigan	Maple	4050005	24.38	19.10	0.56	0.50
Southeastern Lake Michigan	Lower Grand	4050006	112.25	267.04	0.30	0.00
Southeastern Lake Michigan	Thornapple	4050007	20.70	13.23	0.61	0.50
Northeastern Lake Michigan	Pere Marquette-White	4060101	3,648.14	42.82	0.99	1.00
Northeastern Lake Michigan	Muskegon	4060102	867.52	78.50	0.92	1.00
Northeastern Lake Michigan	Manistee	4060103	1,280.70	34.08	0.97	1.00
Northeastern Lake Michigan	Betsie-Platte	4060104	530.05	12.59	0.98	1.00
Northeastern Lake Michigan	Boardman-Charlevoix	4060105	3,195.19	35.58	0.99	1.00
Northeastern Lake Michigan	Manistique	4060106	731.29	7.63	0.99	1.00
Northeastern Lake Michigan	Brevoort-Millecoquins	4060107	343.02	1.10	1.00	1.00
Northwestern Lake Huron	Carp-Pine	4070002	151.61	0.92	0.99	1.00
Northwestern Lake Huron	Black	4070005	105.70	3.07	0.97	1.00
Northwestern Lake Huron	Thunder Bay	4070006	263.68	27.40	0.91	1.00
Northwestern Lake Huron	Au Sable	4070007	1,030.32	14.39	0.99	1.00
Southwestern Lake Huron	Au Gres-Rifle	4080101	175.31	8.73	0.95	1.00
Southwestern Lake Huron	Kawkawlin-Pine	4080102	35.47	7.50	0.83	1.00
Southwestern Lake Huron	Pigeon-Wiscoggin	4080103	77.05	481.43	0.14	0.00

Basin	Subbasin	HUC-8 number	Average August stream flow (MGD)	August water use (MGD)	August annual % non-used water	0 to 1 rating (1 is optimal)
Saginaw	Tittabawassee	4080201	25.66	44.17	0.37	0.00
Saginaw	Pine	4080202	13.23	19.36	0.41	0.00
Saginaw	Shiawassee	4080203	19.15	51.85	0.27	0.00
Saginaw	Flint	4080204	22.10	51.40	0.30	0.00
Saginaw	Cass	4080205	9.92	10.33	0.49	0.00
St. Clair-Detroit	St. Clair	4090001	17.15	27.06	0.39	0.00
St. Clair-Detroit	Clinton	4090003	897.86	58.05	0.94	1.00
St. Clair-Detroit	Huron	4090005	206.21	79.91	0.72	0.50
Western Lake Erie	Ottawa-Stony	4100001	203.45	74.66	0.73	0.50
Western Lake Erie	Raisin	4100002	82.42	20.43	0.80	1.00
Western Lake Erie	St. Joseph	4100003	20.01	42.54	0.32	0.00
Western Lake Erie	St. Marys	4100004	11.22	19.76	0.36	0.00
Western Lake Erie	Tiffin	4100006	10.48	8.86	0.54	0.50
Western Lake Erie	Auglaize	4100007	47.71	20.29	0.70	0.50
Western Lake Erie	Blanchard	4100008	10.08	48.51	0.17	0.00
Western Lake Erie	Lower Maumee	4100009	20.14	23.82	0.46	0.00
Western Lake Erie	Sandusky	4100011	202.07	21.72	0.90	1.00
Western Lake Erie	Huron-Vermilion	4100012	77.53	38.23	0.67	0.50
Southern Lake Erie	Black-Rocky	4110001	166.90	153.73	0.52	0.50
Southern Lake Erie	Cuyahoga	4110002	265.40	162.38	0.62	0.50
Southern Lake Erie	Ashtabula-Chagrin	4110003	242.17	55.75	0.81	1.00
Southern Lake Erie	Grand	4110004	90.96	58.58	0.61	0.50
Eastern Lake Erie	Chautauqua-Conneaut	4120101	168.06	27.68	0.86	1.00
Eastern Lake Erie	Cattaraugus	4120102	145.58	34.98	0.81	1.00
Eastern Lake Erie	Buffalo-Eighteenmile	4120103	84.21	91.44	0.48	0.00
Eastern Lake Erie	Niagara	4120104	9.88	720.92	0.01	0.00
Southwestern Lake Ontario	Oak Orchard-Twelvemile	4130001	66.02	18.41	0.78	0.50
Southwestern Lake Ontario	Upper Genesee	4130002	179.50	10.13	0.95	1.00
Southwestern Lake Ontario	Lower Genesee	4130003	100.50	142.37	0.41	0.00
Southeastern Lake Ontario	Irondequoit-Ninemile	4140101	128.07	20.29	0.86	1.00
Southeastern Lake Ontario	Salmon-Sandy	4140102	146.45	12.94	0.92	1.00
Oswego	Seneca	4140201	355.04	796.18	0.31	0.00
Oswego	Oneida	4140202	65.88	30.47	0.68	0.50
Oswego	Oswego	4140203	0.57	6.00	0.09	0.00
Northeastern Lake Ontario	Black	4150101	889.43	95.80	0.90	1.00
St. Lawrence	Oswegatchie	4150302	270.58	8.07	0.97	1.00
NOTE: not all basins included because some were missing values						
	Formulae used:				(D#)/(D# +E#)	0-1 rating, see text

Factor 3 - Thermal Vulnerability

Modeling Approach

Water temperature patterns have a strong effect on the nature of streams and rivers and alteration of thermal conditions affect the health of aquatic ecosystems (Coutant 1999). Water temperatures vary due to position in the basin (headwaters closest to groundwater temperature), climate conditions, gradient, groundwater inputs and other factors. Human alterations also change thermal conditions, especially climate change, deforestation, and thermal loading of streams and rivers.

The primary determinant of water temperatures is solar radiation because it largely determines the total energy input to waterways (Cassie 2006). In unaltered streams, most (82%) of the energy flux water occurs at the air-water interface (Evans et al. 1998) with much less at the streambed (groundwater, 15%) with minor other sources. Much research has investigated the influence of forestry and removal of riparian shading because this can be a significant local factor in thermal alteration (Feller 1981, Hewlett and Fortson 1982, Rutherford et al. 1997). Increases on the scale of 8 C in Oregon and 7 C in North Carolina (Brown and Krygier 1967, Swift and Messer 1971) were the result of riparian forest removal. Other stream modifications can also alter thermal conditions: thermal effluents; reductions in river flow, and water releases from upstream dams and lakes. Therefore, thermal regime is complex and affected by numerous human alterations of the landscape and waterways.

Thermal loading from power plants can elevate water temperatures. Wright et al. (1999) estimated that power plants significantly effected thermal regime of the Missouri River by raising water temperature from 2 to 2.5 C compared to background levels. Although this was less than expected from future climate warming (3 C increase). Nevertheless, additional of thermal loading from power plants can be a significant addition to other anthropogenic changes in thermal conditions (Langford 1990).

A model of vulnerability of Great Lakes basins to thermal loading from power generation can be based on the most influential factors that shape thermal conditions. This will require measures closely related to influential factors and weighting the factors for the overall effect on thermal change. Such a model would represent the general sensitivity of a basin to thermal loading, and be one more key factor in an environmental index of power generation impact sensitivity. Another dimension of the thermal alteration impact is the extent of coldwater stream miles, or coldwater resource in the basin. When thermal vulnerability is matched with coldwater resource we can consider this a measure of threat to coldwater resources.

Estimator Method

Chu et al. (2010a, 2010b) conducted an extensive study of the spatial variability in stream thermal regimes and fish community composition across Ontario's portion of the

Great Lakes basin. The data included daily water temperature data from 73 data loggers and the analysis considered 18 variables that could predict thermal dynamics of streams and rivers. The key variables that were associated with variability of thermal conditions were: mean annual air temperature, groundwater discharge potential, surface water extent, and riparian forest cover. These were consistent with the main factors shaping thermal conditions in streams in other reviews and modeling studies (Poole and Berman 2001, Wang et al. 2003, Caissie 2006). They also found that thermal conditions explained 16% of the variation in fish communities. The results from this study is especially relevant for integration of thermal vulnerability in the Great Lakes watersheds for modeling sensitivity to thermal loading from power plants.

Chu et al. (2010b) multivariate analyses of the 18 factors on thermal regime indicated there are four factors should be included in modeling basin sensitivity and their analysis also estimated the strength of their influence. Using the statistical results reported, I assign weights to these variables to reflect their role in determining stream thermal regime.

52	Mean annual air temperature
22	Percent surface water (lakes, ponds, reservoirs)
18	Percent riparian forest intact
8	Groundwater discharge potential

Mean annual air temperature for each basin can be readily obtained from weather data. The percent of the basin area composed of surface waters are readily obtained from basin scale land cover data. Percent of riparian forest intact will be substantial GIS work to compute. For this study, we will substitute the percent forest cover for the basin assuming that extensive forest land will also relate to the extent of forests along streams. Groundwater discharge potential can be obtained from the Energy Water Power Simulation Model. Weights above determine the relative influence of each variable, so the data used by variable needs to be standardized. Using the ranks each basin will achieve this. The ranking should be ordered from warmest (1) to coldest (max number of basins). The others will need to follow the pattern with the smallest rank (1) being the largest surface water area, smallest forest cover percent, and the least groundwater potential. The final formulae will be:

Thermal vulnerability index =
(52(mean annual air temperature rank) +
22(percent surface water rank) +
18(percent non-forest cover rank) +
8(inverse of groundwater potential rank))/100

The above formulae will produce an thermal vulnerability product that correlates with potential warming of stream and river water on a whole basin scale. That series of numbers can be ranked with the highest ranking be most vulnerable to warming. This is an inverse order for the component ranks but that is needed for the next step: combining vulnerability with coldwater resource level by basin.

The Great Lakes Commission provided an estimate of coldwater stream miles per HUC-8 basin. This is a measure of coldwater resource quantity. Although in miles, the larger the number the more coldwater resource is is exposed to warming. The product of the thermal vulnerability rank and the miles of coldwater resource yields resource threat level. The product can be ranked to reveal the resource threat with a rank of 1 being the most coldwater resource exposed to thermal warming potential.

For convenience the ranks were converted to a rating on a zero to one scale with one being optimal and zero the largest basin scale threat to loss of coldwater stream resource:

0.00	< 25 ranks
0.33	25-50 ranks
0.66	75- >50 ranks
1.00	>75 ranks

There is about about 100 HUC-8 basins in the Great Lakes region and many ties in ranks. Therefore, the ratings were based on quartiles of the ranks.

Results

Table 5 has the calculations for most HUC-8 basins in the Great Lakes region. This factor clearly distinguished basins because there were many basins rated 0.00, 0.33, 0.66, and 1.00. Basins that received the lowest rating (0) had either significant coldwater resources and high warming potential. Basins rated 1.00 were considered at low threat for loss of coldwater resources because either the warming potential was low or little or none coldwater resource existing in the basin. This factor can be used to map and color code all HUC-8 basins for vulnerability to coldwater resource loss. The Energy Water Power Simulation Model will report the current rating for vulnerability to coldwater resource loss.. This rating will provide an indication of thermal vulnerability. However, the Energy Water Power Simulation Model does not include information to change the ratings under future scenarios. This factor will not change by scenario but the ratings or a map showing basin ratings can be used in consideration of basin suitability for additional water cooling use. So this information is static but nevertheless useful for considering threat to coldwater resources for future energy development distribution on a basin scale.

Table 5. Thermal vulnerability and coldwater threat calculations for factor 3.

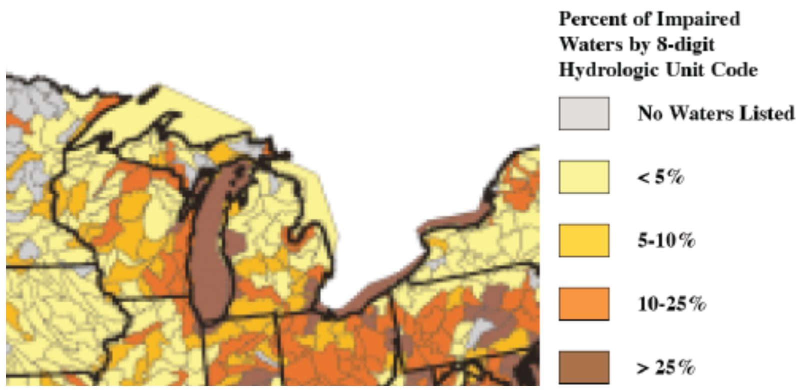
Basin	Subbasin	HUC-8 number	Average annual air temperature (C)	Average annual air temperature (rank)	% open water in basin	% open water in basin (rank)	% forest cover	% non-forest cover (inverted)	% non-forest cover (rank)	Base flow average (mgd)	Base flow average inverted (5000-mgd)	Base flow average inverted (rank)	Thermal Vulnerability formulae result	Thermal Vulnerability (rank)	Coldwater stream miles	Product of thermal rank and coldwater miles	Coldwater resource threat (rank)	Summary rating
Northwestern Lake Superior	Baptism-Brule	4010101	3.28	86	5.98	10	81.89	18.11	79	44	4956	23	62.98	12	573	6876	36	0.33
Northwestern Lake Superior	Beaver-Lester	4010102	3.28	86	1.12	61	71.70	28.30	72	16	4984	10	71.9	2	345	690	65	0.66
St. Louis	St. Louis	4010201	3.62	84	3.78	19	57.30	42.70	59	2	4998	1	58.56	19	893	16967	18	0.00
St. Louis	Cloquet	4010202	3.62	84	6.06	8	71.26	28.74	71	140	4860	43	61.66	15	274	4110	47	0.33
Southwestern Lake Superior	Beartrap-Nemadji	4010301	4.78	77	2.02	38	53.68	46.32	54	103	4897	38	61.16	16	275	4400	46	0.33
Southwestern Lake Superior	Bad-Montreal	4010302	4.79	76	2.27	34	79.60	20.40	77	188	4812	50	64.86	8	212	1696	57	0.66
Southcentral Lake Superior	Black-Presque Isle	4020101	4.37	82	3.08	23	86.80	13.20	86	27	4973	15	64.38	9	143	1287	58	0.66
Southcentral Lake Superior	Ontonagan	4020102	4.36	83	4.94	11	82.35	17.65	80	515	4485	69	65.5	7	374	2618	52	0.66
Southcentral Lake Superior	Keweenaw Peninsula	4020103	4.93	72	3.42	21	83.41	16.59	82	15	4985	8	57.46	21	617	12957	25	0.00
Southcentral Lake Superior	Sturgeon	4020104	4.66	81	1.83	44	84.42	15.58	84	348	4652	63	71.96	1	522	522	66	0.66
Southcentral Lake Superior	Dead-Kelsey	4020105	4.86	74	2.95	24	87.94	12.06	87	26	4974	14	60.54	17	769	13073	24	0.00
Southeastern Lake Superior	Betsy-Chocolay	4020201	5.12	70	2.17	36	76.78	23.22	76	12	4988	7	58.56	19	422	8018	32	0.33
Southeastern Lake Superior	Tahquamenon	4020202	4.86	75	0.85	66	63.18	36.82	65	386	4614	64	70.34	4	215	860	63	0.66
Northwestern Lake Michigan	Manitowoc-Sheboygan	4030101	7.44	49	0.55	75	13.15	86.85	10	70	4930	28	46.02	39	9	351	69	0.66
Northwestern Lake Michigan	Door-Kewaunee	4030102	6.74	55	9.54	2	46.19	53.81	45	22	4978	13	38.18	51	1	51	75	0.66
Northwestern Lake Michigan	Duck-Pensaukee	4030103	6.68	56	0.45	79	24.23	75.77	19	21	4979	12	50.88	33	1	33	76	1.00
Northwestern Lake Michigan	Oconto	4030104	5.98	63	2.23	35	56.59	43.41	57	197	4803	53	54.96	26	47	1222	60	0.66
Northwestern Lake Michigan	Peshtigo	4030105	5.63	65	2.40	32	58.51	41.49	61	275	4725	59	56.54	23	32	736	64	0.66
Northwestern Lake Michigan	Brule	4030106	4.75	78	2.75	27	83.64	16.36	83	246	4754	55	65.84	6	50	300	70	0.66
Northwestern Lake Michigan	Michigamme	4030107	4.75	78	6.04	9	86.77	13.23	85	293	4707	61	62.72	13	11	143	73	0.66
Northwestern Lake Michigan	Menominee	4030108	4.75	78	2.52	28	72.57	27.43	73	1293	3707	79	66.18	5	75	375	68	0.66
Northwestern Lake Michigan	Cedar-Ford	4030109	5.44	67	0.37	83	82.48	17.52	81	125	4875	40	70.88	3	21	63	74	0.66
Northwestern Lake Michigan	Escanaba	4030110	4.87	73	2.37	33	81.61	18.39	78	314	4686	62	64.22	10	115	1150	61	0.66
Northwestern Lake Michigan	Fishdam-Sturgeon	4030112	5.54	66	1.44	54	76.10	23.90	75	83	4917	33	62.34	14	19	266	71	0.66
Fox	Upper Fox	4030201	6.75	52	9.54	2	46.19	53.81	45	608	4392	70	41.18	48	64	3072	50	0.33
Fox	Wolf	4030202	6.75	52	2.94	25	45.87	54.13	44	879	4121	73	46.3	38	117	4446	45	0.33
Fox	Lake Winnebago	4030203	6.75	52	35.94	1	4.11	95.89	1	7	4993	3	27.68	69	31	2139	55	0.66
Southwestern Lake Michigan	Little Calumet-Galien	4040001	9.46	12	1.69	47	26.98	73.02	26	56	4944	27	23.42	76	102	7752	33	0.33
Southwestern Lake Michigan	Pike-Root	4040002	9.46	12	0.44	80	11.88	88.12	9									
Southwestern Lake Michigan	Milwaukee	4040003	7.82	45	1.02	63	18.60	81.40	15	186	4814	49	43.88	45	10	450	67	0.66
Southeastern Lake Michigan	St. Joseph	4050001	9.35	15	2.43	30	22.13	77.87	17	2104	2896	82	24.02	73	902	65846	2	0.00
Southeastern Lake Michigan	Black-Macatawa	4050002	9.25	16	1.46	52	30.27	69.73	32	42	4958	22	27.28	70	89	6230	39	0.33
Southeastern Lake Michigan	Kalamazoo	4050003	9.03	22	2.51	29	29.29	70.71	29	861	4139	72	28.8	66	146	9636	28	0.33
Southeastern Lake Michigan	Upper Grand	4050004	8.60	25	1.48	50	24.38	75.62	20	397	4603	65	32.8	58	0	0	77	1.00
Southeastern Lake Michigan	Maple	4050005	8.60	25	0.91	64	14.86	85.14	12	88	4912	35	32.04	61	37	2257	53	0.66
Southeastern Lake Michigan	Lower Grand	4050006	8.60	25	2.00	39	25.80	74.20	23	2295	2705	83	32.36	59	120	7080	35	0.33
Southeastern Lake Michigan	Thornapple	4050007	8.60	25	1.61	48	26.00	74.00	24	128	4872	41	31.16	63	35	2205	54	0.66
Northeastern Lake Michigan	Pere Marquette-White	4060101	8.10	39	1.91	42	56.75	43.25	58	403	4597	66	45.24	40	553	22120	12	0.00
Northeastern Lake Michigan	Muskegon	4060102	6.93	50	4.09	14	50.85	49.15	50	1430	3570	80	44.48	43	517	22231	11	0.00
Northeastern Lake Michigan	Manistee	4060103	6.65	57	1.35	57	65.15	34.85	66	1046	3954	76	60.14	18	756	13608	23	0.00
Northeastern Lake Michigan	Betsie-Platte	4060104	7.46	48	8.84	4	52.84	47.16	52	78	4922	31	37.68	52	172	8944	30	0.33
Northeastern Lake Michigan	Boardman-Charlevoix	4060105	6.58	59	6.41	6	53.57	46.43	53	106	4894	39	44.66	42	659	27678	5	0.00
Northeastern Lake Michigan	Manistique	4060106	5.42	68	4.48	12	54.05	45.95	55	934	4066	74	53.82	27	136	3672	49	0.33
Northeastern Lake Michigan	Brevoort-Millecoquins	4060107	5.21	69	3.80	17	62.43	37.57	64	11	4989	5	51.54	31	145	4495	44	0.33
Northwestern Lake Huron	Carp-Pine	4070002	5.05	71	1.21	60	61.52	38.48	62	83	4917	32	63.84	11	112	1232	59	0.66
Northwestern Lake Huron	Black	4070005	6.12	62	3.80	16	67.43	32.57	68	164	4836	46	51.68	30	62	1860	56	0.66
Northwestern Lake Huron	Thunder Bay	4070006	6.34	61	3.23	22	66.14	33.86	67	289	4711	60	53.42	28	301	8428	31	0.33
Northwestern Lake Huron	Au Sable	4070007	6.38	60	2.06	37	69.49	30.51	69	722	4278	71	57.44	22	291	6402	38	0.33
Southwestern Lake Huron	Au Gres-Rifle	4080101	6.77	51	1.83	45	57.5	42.50	60	35	4965	20	48.82	35	195	6825	37	0.33
Southwestern Lake Huron	Kawkawlin-Pine	4080102	7.80	46	0.52	76	32.35	67.65	34	12	4988	6	47.24	36	0	0	77	1.00
Southwestern Lake Huron	Pigeon-Wiscoggin	4080103	8.07	40	0.23	86	8.34	91.66	6	16	4984	11	41.68	47	0	0	77	1.00
Saginaw	Tittabawassee	4080201	8.18	34	1.55	49	49.10	50.90	49	470	4530	67	42.64	46	116	5336	40	0.33
Saginaw	Pine	4080202	8.18	34	1.38	55	33.38	66.62	36	173	4827	48	40.1	49	95	4655	43	0.33
Saginaw	Shiawassee	4080203	8.18	34	1.71	46	24.87	75.13	21	161	4839	45	35.18	55	0	0	77	1.00
Saginaw	Flint	4080204	8.18	34	1.27	59	28.02	71.98	27	253	4747	56	40	50	0	0	77	1.00
Saginaw	Cass	4080205	8.18	34	0.29	85	28.16	71.84	28	138	4862	42	44.78	41	0	0	77	1.00
St. Clair-Detroit	St. Clair	4090001	8.55	29	0.76	70	22.86	77.14	18									
St. Clair-Detroit	Clinton	4090003	9.12	19	2.81	26	25.75	74.25	22									
St. Clair-Detroit	Huron	4090005	9.16	18	4.12	13	34.13	65.87	37	15	4985	9	19.6	83	0	0	77	1.00
Western Lake Erie	Ottawa-Stony	4100001	9.74	10	1.12	62	13.97	86.03	11	8	4992	4	21.14	80	35	2800	51	0.66
Western Lake Erie	Raisin	4100002	9.11	20	1.47	51	15.35	84.65	13	234	4766	54	28.28	67	0	0	77	1.00
Western Lake Erie	St. Joseph	4100003	9.89	3	1.37	56	17.54	82.46	14	259	4741	57	20.96	81	144	11664	26	0.33
Western Lake Erie	St. Marys	4100004	9.89	3	0.04	87	5.49	94.51	2	93	4907	36	23.94	75	14	1050	62	0.66
Western Lake Erie	Tiffin	4100006	9.89	3	0.64	73	11.62	88.38	8	94	4906	37	22.02	78	130	10140	27	0.33
Western Lake Erie	Auglaize	4100007	9.89	3	0.51	77	5.62	94.38	3	193	4807	52	23.2	77	69	5313	41	0.33
Western Lake Erie	Blanchard	4100008	9.89	3	0.41	81	6.02	93.98	4	35	4965	18	21.54	79	49	3871	48	0.33
Western Lake Erie	Lower Maumee	4100009	9.89	3	1.29	58	6.60	93.40	5	28	4972	16	16.5	84	212	17808	17	0.00
Western Lake Erie	Sandusky	4100011	10.07	1	0.84	67	8.49	91.51	7	160	4840	44	20.04	82	224	18368	16	0.00
Western Lake Erie	Huron-Vermilion	4100012	9.72	11	0.67	71	19.38	80.62	16	33	4967	17	25.58	72	102	7344	34	0.33

Basin	Subbasin	HUC-8 number	Average annual air temperature (C)	Average annual air temperature (rank)	% open water in basin	% open water in basin (rank)	% forest cover	% non-forest cover (inverted)	% non-forest cover (rank)	Base flow average (mgd)	Base flow average inverted (5000-mgd)	Base flow average inverted (rank)	Thermal Vulnerability formulae result	Thermal Vulnerability (rank)	Coldwater stream miles	Product of thermal rank and coldwater miles	Coldwater resource threat (rank)	Summary rating
Southern Lake Erie	Black-Rocky	4110001	9.94	2	0.65	72	29.51	70.49	30	41	4959	21	23.96	74	327	24198	9	0.00
Southern Lake Erie	Cuyahoga	4110002	9.87	9	2.00	40	36.73	63.27	38	498	4502	68	25.76	71	224	15904	21	0.00
Southern Lake Erie	Ashtabula-Chagrin	4110003	9.44	14	0.78	68	40.56	59.44	40	73	4927	30	31.84	62	227	14074	22	0.00
Southern Lake Erie	Grand	4110004	9.10	21	0.87	65	44.97	55.03	41	169	4831	47	36.36	53	319	16907	19	0.00
Eastern Lake Erie	Chautauqua-Conneaut	4120101	9.22	17	0.61	74	47.44	52.56	47	45	4955	25	35.58	54	94	5076	42	0.33
Eastern Lake Erie	Cattaraugus	4120102	7.86	44	0.40	82	54.69	45.31	56	189	4811	51	55.08	25	360	9000	29	0.33
Eastern Lake Erie	Buffalo-Eighteenmile	4120103	8.02	41	0.31	84	45.02	54.98	42	44	4956	24	49.28	34	614	20876	14	0.00
Eastern Lake Erie	Niagara	4120104	8.52	30	2.43	31	33.30	66.70	35	35	4965	19	30.24	65	349	22685	10	0.00
Southwestern Lake Ontario	Oak Orchard-Twelvemile	4130001	8.92	23	0.77	69	30.05	69.95	31	4	4996	2	32.88	57	373	21261	13	0.00
Southwestern Lake Ontario	Upper Genesee	4130002	8.00	42	0.45	78	52.25	47.75	51	88	4912	34	50.9	32	854	27328	6	0.00
Southwestern Lake Ontario	Lower Genesee	4130003	8.00	42	1.46	53	26.92	73.08	25	951	4049	75	44	44	599	26356	7	0.00
Southeastern Lake Ontario	Irondequoit-Ninemile	4140101	8.90	24	1.88	43	39.15	60.85	39	48	4952	26	31.04	64	256	16384	20	0.00
Southeastern Lake Ontario	Salmon-Sandy	4140102	7.51	47	1.97	41	61.62	38.38	63	71	4929	29	47.12	37	516	19092	15	0.00
Oswego	Seneca	4140201	8.24	31	6.35	7	31.03	68.97	33	272	4728	58	28.24	68	2895	196860	1	0.00
Oswego	Oneida	4140202	8.24	31	6.60	5	47.45	52.55	48	1191	3809	78	32.1	60	613	36780	3	0.00
Oswego	Oswego	4140203	8.24	31	3.58	20	45.14	54.86	43	3131	1869	84	34.98	56	3	168	72	0.66
Northeastern Lake Ontario	Black	4150101	5.90	64	3.80	18	70.26	29.74	70	1629	3371	81	56.32	24	1228	29472	4	0.00
St. Lawrence	Oswegatchie	4150302	6.59	58	3.94	15	75.32	24.68	74	1077	3923	77	52.94	29	879	25491	8	0.00
NOTE: not all basins included because some were missing values																		
	Formulae used:			**AA rank;** low=more vulnerable		**OW rank;** low=more vulnerable			**NF rank;** low=more vulnerable			**BF rank;** low=more vulnerable	((52*(AA rank)) +(22*(OW rank)) +(18*(NF rank)) +(8*(BF rank)))/ 10	TV; High=more vulnerable Note: inverted, need to be this way for a step	**Miles**	**TV X Miles**	Low=highest threat	IF (R13>75,1,IF (R13>50,0.66, IF (R13>25,0.33, IF (R13>0,0))))

Factor 4 - Water Quality Sensitivity

Modeling Approach

Water quality vulnerability will be assessed using the current status of water quality by HUC-8 basin. Under the Clean Water Act, states report to the US Environmental Protection Agency (EPA) all waters that are too polluted or degraded to meet the water quality standards. These waters are labelled *impaired* because they failing to meet one or more water quality standards. Common pollutants and water quality stressors are sediment, excess nutrients, pathogens, metals, mercury, pesticides, and other regulated constituents. The EPA compiles these data by state and has a database of impaired waters for each 8-digit hydrologic unit code (EPA 2000). The map below is a portion of a National map showing the extent of impaired waters. We can use these data by HUC-8 basins to represent vulnerability of to further water quality stressors.



The map represents threatened and impaired waters by 8-digit hydrologic unit code (HUC) divided by the total number of water miles within the basin.

Estimator Method

EPA data on the extent of impaired waters by 8-digit HUC is classified by six classes on a zero to one scale:

No impaired waters, assigned a vulnerability score of 1.00
<5% impaired waters, assigned a vulnerability score of 0.75
5-10% impaired waters, assigned a vulnerability score of 0.50
10-25% impaired waters, assigned a vulnerability score of 0.25
>25% impaired waters, assigned a vulnerability score of 0.00

Data by these classes can be obtained from EPA at their online data set:

http://www.epa.gov/OWOW/tmdl/

These classes can be used directly to rate vulnerability to further water quality stresses: greater the extent of impaired waters in the basin the greater the vulnerability.

Results

Table 6 has the EPA data set for most Great Lakes HUC-8 basins and calculations for that yield a rating for each basin shown. This factor clearly distinguished basins because there were many basins rated 0.00, 0.25, 0.50, 0.75, and 1.00. This factor can be used to map and color code all HUC-8 basins for additional water quality vulnerability. The Energy Water Power Simulation Model will report the current rating for water quality status. This rating will provide an indication of vulnerability to further water quality stress. However, the Energy Water Power Simulation Model does not include information to change the ratings under future scenarios. This factor will not change by scenario but the ratings or a map showing basin ratings can be used in consideration of basin water quality status. So this information is static but nevertheless useful for considering water quality for future energy development distribution on a basin scale.

Table 6. Water quality rating calculations for factor 4.

Basin	Subbasin	HUC-8 number	water quality index	Water quality rating
Northwestern Lake Superior	Baptism-Brule	4010101	0.86	0.75
Northwestern Lake Superior	Beaver-Lester	4010102	10.69	0.25
St. Louis	St. Louis	4010201	5.26	0.50
St. Louis	Cloquet	4010202	0.00	1.00
Southwestern Lake Superior	Beartrap-Nemadji	4010301	8.33	0.50
Southwestern Lake Superior	Bad-Montreal	4010302	2.29	0.75
Southcentral Lake Superior	Black-Presque Isle	4020101	0.48	0.75
Southcentral Lake Superior	Ontonagan	4020102	3.56	0.75
Southcentral Lake Superior	Keweenaw Peninsula	4020103	2.95	0.75
Southcentral Lake Superior	Sturgeon	4020104	1.42	0.75
Southcentral Lake Superior	Dead-Kelsey	4020105	3.47	0.75
Southeastern Lake Superior	Betsy-Chocolay	4020201	1.26	0.75
Southeastern Lake Superior	Tahquamenon	4020202	11.32	0.25
Northwestern Lake Michigan	Manitowoc-Sheboygan	4030101	13.86	0.25
Northwestern Lake Michigan	Door-Kewaunee	4030102	19.93	0.25
Northwestern Lake Michigan	Duck-Pensaukee	4030103	5.86	0.50
Northwestern Lake Michigan	Oconto	4030104	2.79	0.75
Northwestern Lake Michigan	Peshtigo	4030105	3.99	0.75
Northwestern Lake Michigan	Brule	4030106	3.79	0.75
Northwestern Lake Michigan	Michigamme	4030107	15.29	0.25
Northwestern Lake Michigan	Menominee	4030108	10.80	0.25
Northwestern Lake Michigan	Cedar-Ford	4030109	0.00	1.00
Northwestern Lake Michigan	Escanaba	4030110	1.71	0.75
Northwestern Lake Michigan	Fishdam-Sturgeon	4030112	2.29	0.75
Fox	Upper Fox	4030201	7.18	0.50
Fox	Wolf	4030202	5.56	0.50
Fox	Lake Winnebago	4030203	38.37	0.00
Southwestern Lake Michigan	Little Calumet-Galien	4040001	37.46	0.00
Southwestern Lake Michigan	Pike-Root	4040002	23.37	0.25
Southwestern Lake Michigan	Milwaukee	4040003	21.61	0.25
Southeastern Lake Michigan	St. Joseph	4050001	12.51	0.25
Southeastern Lake Michigan	Black-Macatawa	4050002	2.22	0.75
Southeastern Lake Michigan	Kalamazoo	4050003	2.96	0.75
Southeastern Lake Michigan	Upper Grand	4050004	3.60	0.75
Southeastern Lake Michigan	Maple	4050005	3.21	0.75
Southeastern Lake Michigan	Lower Grand	4050006	5.21	0.50
Southeastern Lake Michigan	Thornapple	4050007	2.03	0.75
Northeastern Lake Michigan	Pere Marquette-White	4060101	3.72	0.75
Northeastern Lake Michigan	Muskegon	4060102	4.99	0.75
Northeastern Lake Michigan	Manistee	4060103	0.66	0.75
Northeastern Lake Michigan	Betsie-Platte	4060104	4.84	0.75
Northeastern Lake Michigan	Boardman-Charlevoix	4060105	9.69	0.50
Northeastern Lake Michigan	Manistique	4060106	5.99	0.50
Northeastern Lake Michigan	Brevoort-Millecoquins	4060107	4.07	0.75
Northwestern Lake Huron	Carp-Pine	4070002	1.81	0.75
Northwestern Lake Huron	Black	4070005	0.00	1.00
Northwestern Lake Huron	Thunder Bay	4070006	3.04	0.75
Northwestern Lake Huron	Au Sable	4070007	3.59	0.75
Southwestern Lake Huron	Au Gres-Rifle	4080101	0.38	0.75
Southwestern Lake Huron	Kawkawlin-Pine	4080102	2.93	0.75
Southwestern Lake Huron	Pigeon-Wiscoggin	4080103	4.33	0.75
Saginaw	Tittabawassee	4080201	1.47	0.75
Saginaw	Pine	4080202	2.37	0.75

Basin	Subbasin	HUC-8 number	water quality index	Water quality rating
Saginaw	Shiawassee	4080203	3.37	0.75
Saginaw	Flint	4080204	5.97	0.50
Saginaw	Cass	4080205	1.47	0.75
St. Clair-Detroit	St. Clair	4090001	2.80	0.75
St. Clair-Detroit	Clinton	4090003	12.09	0.25
St. Clair-Detroit	Huron	4090005	6.93	0.50
Western Lake Erie	Ottawa-Stony	4100001	16.30	0.25
Western Lake Erie	Raisin	4100002	5.76	0.50
Western Lake Erie	St. Joseph	4100003	35.09	0.00
Western Lake Erie	St. Marys	4100004	75.48	0.00
Western Lake Erie	Tiffin	4100006	81.37	0.00
Western Lake Erie	Auglaize	4100007	63.52	0.00
Western Lake Erie	Blanchard	4100008	99.60	0.00
Western Lake Erie	Lower Maumee	4100009	91.54	0.00
Western Lake Erie	Sandusky	4100011	43.21	0.00
Western Lake Erie	Huron-Vermilion	4100012	37.50	0.00
Southern Lake Erie	Black-Rocky	4110001	99.96	0.00
Southern Lake Erie	Cuyahoga	4110002	91.06	0.00
Southern Lake Erie	Ashtabula-Chagrin	4110003	56.46	0.00
Southern Lake Erie	Grand	4110004	100.09	0.00
Eastern Lake Erie	Chautauqua-Conneaut	4120101	4.99	0.75
Eastern Lake Erie	Cattaraugus	4120102	0.19	0.75
Eastern Lake Erie	Buffalo-Eighteenmile	4120103	6.55	0.50
Eastern Lake Erie	Niagara	4120104	46.65	0.00
Southwestern Lake Ontario	Oak Orchard-Twelvemile	4130001	14.21	0.25
Southwestern Lake Ontario	Upper Genesee	4130002	2.68	0.75
Southwestern Lake Ontario	Lower Genesee	4130003	17.17	0.25
Southeastern Lake Ontario	Irondequoit-Ninemile	4140101	16.08	0.25
Southeastern Lake Ontario	Salmon-Sandy	4140102	7.17	0.50
Oswego	Seneca	4140201	14.47	0.25
Oswego	Oneida	4140202	2.15	0.75
Oswego	Oswego	4140203	6.32	0.50
Northeastern Lake Ontario	Black	4150101	6.27	0.50
St. Lawrence	Oswegatchie	4150302	8.79	0.50
NOTE: not all basins included because some were missing values				
	Formulae used:			IF(D15>25,0,IF (D15>10,0.25,IF (D15>5,0.5,IF (D15>0,0.75,IF (D15=0,1)))))

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