An Index of Water Use Intensity for Minnesota

1 Introduction

Sustainable water management is of concern both globally (Vorosmarty et al., 2000; Hoekstra et al., 2012) and in Minnesota (VanBuren and Wells, 2007). Sustainability implies finding a balance point where the current uses of water do not create a deficit in the quantity or quality in water resources that will adversely impact other current or future users. Water use and its management is considered a primary component of sustainable water management and influences many aspects of the environment, ranging from direct effects on water quality and ecological factors such as abundance and habitat of aquatic organisms, and directly influences how people use water both off-stream and in-stream. Maintaining or improving the current ecological health of aquatic ecosystems in some cases is a fundamental concept of sustainability and is a requirement for ensuring adequate water resources for future users.

Sustainable water management considers that; 1) surface water and groundwater as a single limited resource, and that 2) the entire hydrograph including its annual variability is fundamental to the ecological structure and function of a watershed (Richter et al., 2003; Bunn and Arthington, 2002). The goal was to examine the intensity of water use across Minnesota, and develop an indicator of water use intensity that can be used to monitor current conditions and identify trends, considers both surface and groundwater use, and compares use to an ecologically and hydrologically relevant measure of water conditions. The most widely used measure of water stress is a ratio of total withdrawals to basin outflow, predevelopement (Weiskel et al., 2007). Hoekstra et al. (2012) suggest adjusting this measure by using consumptive use instead of total withdrawals. Brown and Matlock (2011) provide a review of this metric and other measures. The Hoekstra et al. (2012) approach is taken, adjusting for consumptive use. Annual discharge was used as the measure of water availability for several reasons including:

- annual discharge is ecologically relevant, serving as an indicator of all of the flows that in combination influence species abundance and physical habitat conditions,
- water availability captures hydrologic variability across space and time, which can be important to both in-stream resources and off-stream users,
- water availability is influenced by both surface and groundwater uses,
- and water availability has been used previously in water use intensity calculations in the literature.

The measure of water use intensity is the reported annual consumptive water use for a catchment and its contributing area divided by the estimated annual discharge for the catchment and its contributing area. Water use intensity was calculated annually for the years 1989-2011, while the index value reported is the five year average for 2007-2011.

2 Methods

Water use intensity as mentioned above and as used in this analysis includes two parts: 1) water use and 2) water availability. Both water use and water availability (i.e. annual discharge) can be highly variable, both spatially and temporally. Because the variability and the extremes of water use and water availability are an important ecological restriction and are important to off-stream users, water use intensity must be examined at a scale that can capture the relevant variability. For example, a statewide average over the last ten years will impart little information on the actual conditions experienced by off-stream water users and the water dependent ecosystems. Although individual points of water use can have a localized impact on a surface water resource, this general statewide analysis and management requires some simplification. Therefore, this analysis uses DNR Level 08 Catchments as the spatial grain and examines water use intensity on an annual basis by using annual water use and an estimate of the annual discharge. The DNR Level 08 catchments range in size from less than 1 mi to 822 mi^2 with an average of 10 ^{2}, and number 10,018 in Minnesota. By using the annual discharge, year to year variation can be examined, however, seasonal variability is not captured. A future goal is to summarize water use by month and to estimate monthly discharge. Water use intensity was also examined secondarily at a finer spatial scale, the DNR Level 09 catchments, and the results are available. Critical elements in the development of the water use intensity index include:

- Reported water use is considered the water use (not permitted volume).
- An annual volume of water used is reported so monthly variability in water use could not be addressed at this time.
- Surface water and groundwater use are considered together and compared to a single measure of water availability. Groundwater provides baseflow conditions for streams and surface and groundwater tend to be in long-term equilibrium (i.e. recharge of the groundwater equals discharge of the groundwater either as flowing water to surface waters or as evapotranspiration). If groundwater is removed the water must be balanced with capture, either inducing recharge (i.e. pulling water from surface stream or lakes) or decreasing discharge (i.e. decreasing baseflow) to the surface (Sophocleous, 2002; Zhou, 2009).
- Both surface and groundwater reported use are summarized by the catchment where the permit is located. Groundwater wells despite being in one catchment could, potentially capture water from an adjacent catchment. This capture will be more of an issue for wells near the catchment boundaries if a surface water feature in the adjacent catchments is nearer the well. One future refinement that can help address this issue is to assign groundwater permits to the nearest surface water instead of restricting it to a catchment.

Annual discharge was not available so a model to predict to annual discharge was developed for the years that water use data were accessible (1989-2011). Requirements for the model were to:

1) estimate annual discharge at any point in Minnesota and, 2) estimate annual discharge for each year from 1989 through 2011 and to do so using some combination of readily available information, including, drainage area, precipitation, temperature, and geographic location.

Complete results (i.e., statewide) can be found in the Minnesota Watershed Health Assessment Framework (WHAF, www.dnr.state.mn.us/whaf/index.html). Results reported in the WHAF include annual values for 1989-2011 and the five year average for 2007-2011. The results presented in the WHAF are converted from percent of available water used to percent of available water unused (e.g., no water use or a value of 0% of the available water used recieves a score of 100 in the WHAF). The following steps describe the calculation of water use intensity and the index:

- for each permit multiply the annual use by the consumptive use coefficient (additional detail provided below),
- accumulate the consumptive use in each catchment (both surface and groundwater included),
- for catchments with contributing catchments, i.e. upstream catchments, accumulate the water use,
- estimate the annual discharge for each catchment outflow,
- divide use by annual discharge, annually.

2.1 Data

As described above, water use was adjusted according to consumptive use coefficients (Table 1) and were based on those found in the literature (Shaffer, 2008; Shaffer and Runkle, 2007). Because a stream network accumulates inflow and in a sense depletion of water from upstream areas, the water use intensity value, while displayed graphically as representing a single catchment, actually represents the condition for that catchment and all of it's upstream catchments.

The water availability model (i.e., annual discharge or it equivalent runoff measured as inches of discharge over the drainage area) used the annual volume of discharge converted to runoff over the watershed for 90 USGS stream gages located throughout Minnesota and in neighboring states (Figure 1) as the dependent variable. The drainage area for the stream gages ranged from 7.7 to 36,800 square miles and averaged 3,167. The period of record for each gage ranged from 1 to 23 years and averaged 19 years covering the years 1989-2011, resulting in 1,706 individual gage-years.

Independent variables included information that can be assessed at any point throughout Minnesota, including, geographic location, precipitation, temperature, and drainage area. Precipitation and temperature data were downloaded from the PRISM Climate Group web site (www.prism.oregonstate.edu) as raster data on April 5th, 2013. An annual value for each individual catchment was estimated as the average raster value. The annual precipitation for the catchment and its upstream area was calculated as an area weighed value of upstream catchments. The mean annual temperature was calculated by averaging the mean monthly values which were calculated as the average of the minimum and maximum monthly temperatures.

2.2 Analysis Methods

An annual flow prediction equation using a generalized additive mixed model (Wood, 2006) with gaging station as the random effect was developed using flow records. This model allows for non-linear patterns and accounts for the non-idependence of multiple observations collected at a single location, such as, stream gage (Venables and Ripley, 2002). Annual discharge was converted to runoff in inches over the drainage area. The period of record for the gages ranged from 1 to 23 years for the years 1989 through 2011. The equation developed in this analysis used a smooth function of geographic coordinates (utmx and utmy) for each year, a linear function of annual precipitation and a smooth function of the past year's precipitation total, a smooth function of mean annual temperature and the past year's mean annual temperature, year as a factor and a a linear function of drainage area. By using a smoothed function of geographic location for each year and year as a factor allowed the model to capture unmeasured climactic and geomorphic information. The drawback of this method is that the model can only be used for Minnesota and for the years 1989-2011. Future calculation of the water use intensity index will require updating the regression equation with additional years of gage data. The annual runoff, inches of runoff per drainage area generally decreased moving from east to west, and as temperature increased and as drainage area increased. Annual runoff increased as precipitation increased. The equation accurately describes the observed values of annual discharge, measured as runoff in inches (Figure 2 with an R^2=0.90 and an adjusted R^2=0.86 in the original model units (i.e. square root of the runoff coefficient). The standard error as a percent when converted to runoff in inches was 18%. The results averaged over all years compare favorably to the estimated runoff coefficients in Vandegrift and Stefan (2010) for Minnesota basins, providing assurance as to the validity of these results. Model assumptions of independence and normality for within-group errors and for random effects was a reasonable. Graphical tools described in (Zuur et al., 2009) were used to assess model assumptions and included: 1) examining auto-correlation across years at stream gages with 23 years of record with an auto-correlation function, and 2) examining spatial correlation using a non-parametric spline correlogram (Bjornstad and Falck, 2001). All statistical analysis was performed using R (R Core Team, 2014).

3 Results

The histograms of water use intensity (Figure 3) displays the effect of spatial scale with finer scales capturing greater variability and the more intensive use in more localized areas. Maps of the geographic distribution of water use intensity (measured as the mean of the years 2007-2011) are displayed for the major watershed (Figure 4) and the smaller DNR Level 08 catchments (Figure 5).

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Table 1: Consumptive use coefficients by water use category.

Use Code	Use Code Name	Consumptive Coefficient	Use Code	Use Code Name	Consumptive Coefficient
211	Municpal	0.15	252	Construction (dewatering)	1.00
212	Private waterworks	0.15	253	Pipeline and tank testing	1.00
213	Commercial and Institutional	0.15	254	Landscape watering	1.00
214	Cooperative waterworks	0.15	255	Pollution containment	1.00
215	Fire protection	0.15	256	Water level maintenance	0.00
216	Campgrounds, waysides, highway rest areas	0.15	257	Livestock waste treatment	1.00
217	Rural Water Districs	0.15	258	Temporary ag irrigation	1.00
219	Waterworks	0.15	259	Temporary	1.00
221	Hydropower	0.00	261	Basin (lake) level	0.00
222	Steam power cooling-once through	0.03	262	Mine dewatering	0.00
223	Steam power cooling-wet tower	0.03	263	Quarry dewatering	0.00
224	Steam power cooling-ponds	0.03	264	Sand and gravel pit dewatering	0.00
225	Steam power other than cooling	0.03	265	Tile drainage and pumped sumps	0.00
226	Nuclear power plant	0.03	266	Dewatering	0.00
229	Power generation	0.03	269	Water level maintenance	0.00
231	Commercial building A/C	0.13	271	Pollution containment	1.00
232	Institutions (school, hospital)	0.13	272	Aquaculture (hatcheries, fisheries)	0.10
233	Heat pumps	0.13	273	Snow making	1.00
234	Coolant pumps	0.13	274	Peat fire control	1.00
235	District heating	0.13	275	Livestock watering	1.00
238	Once-through heating or A/C	0.13	276	Pipeline and tank testing	1.00
239	Air conditioning	0.13	277	Sewage treatment	1.00
241	Agricultural processing (food and livestock)	0.50	279	Special categories	1.00
242	Pulp and paper processing	0.25	281	Golf course	1.00
243	Mine processing (not sand and gravel washing)	0.25	282	Cemetery	1.00
244	Sand and gravel washing	0.25	283	Landscaping	1.00
245	Industrial process cooling once-through	0.25	284	Sod farms	1.00
246	Petroleum-chemical processing, ethanol	0.25	285	Nursery	1.00
247	Metal processing	0.25	286	Orchard	1.00
248	Non-metallic processing (rubber, plastic, glass)	0.25	289	Non-crop irrigation	1.00
249	Industrial processing	0.25	290	Major crop irrigation	1.00
251	Construction (non-dewatering)	1.00	296	Wild rice irrigation	1.00

Figure 1: Geographic location of the 90 USGS stream gages used in the analysis with major watershed delineated.

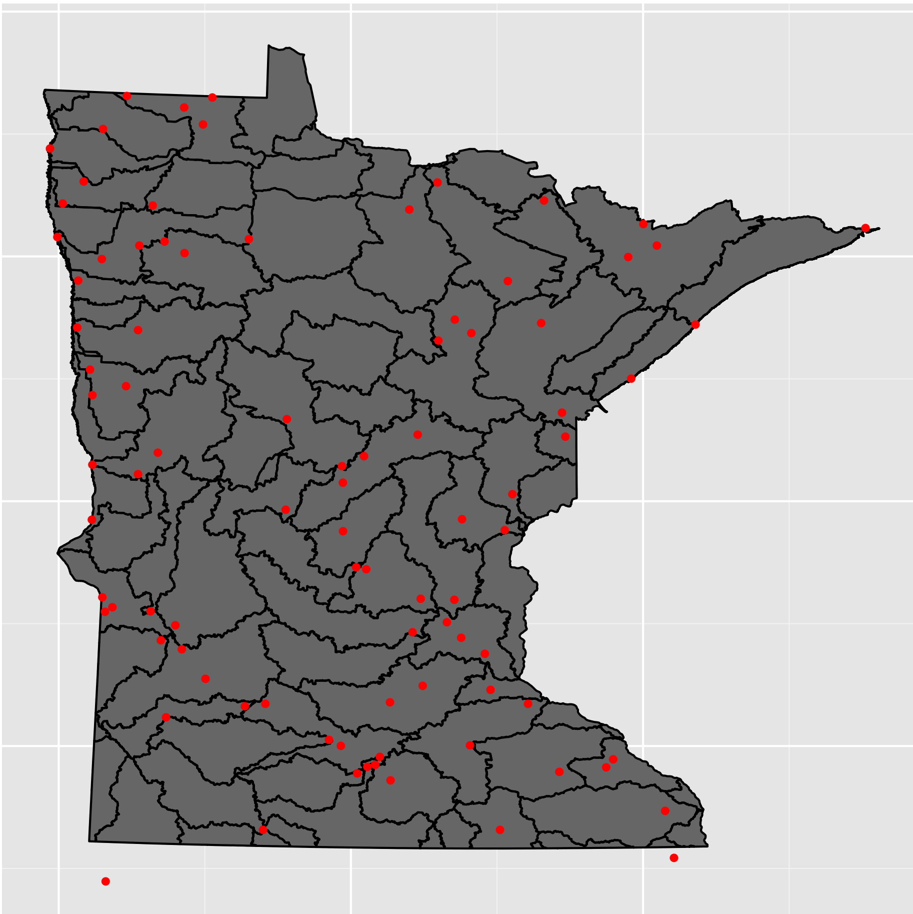

Figure 2: Comparison of observed and predicted runoff.

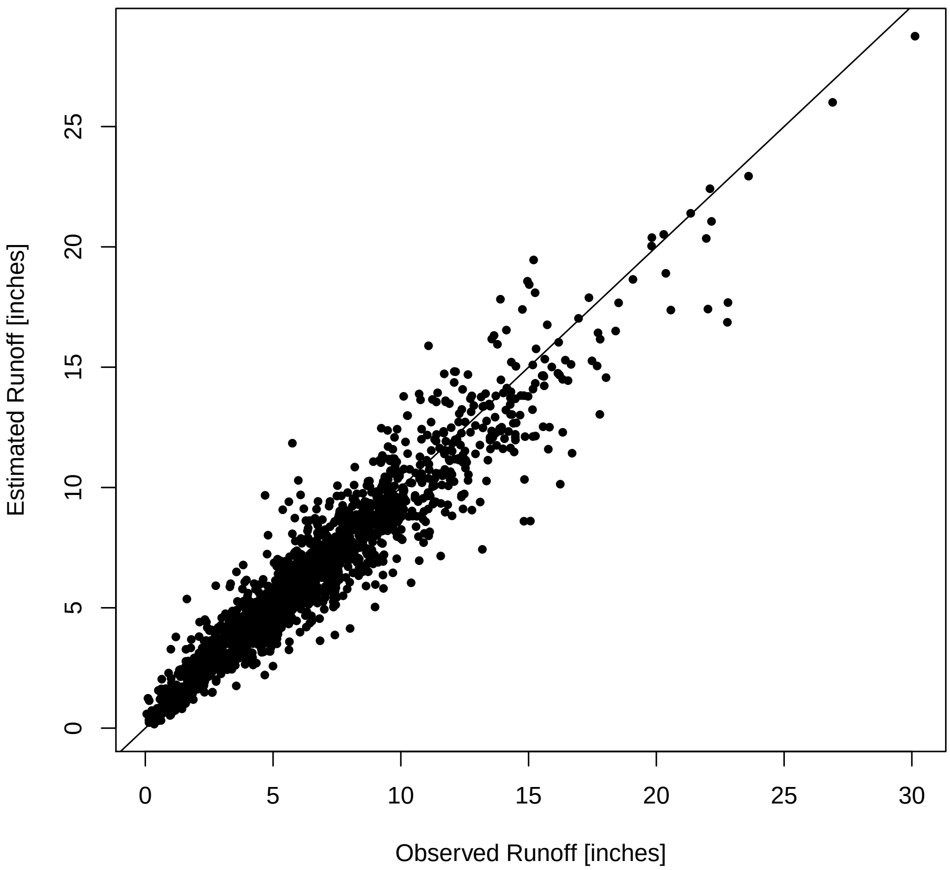

Figure 3: Distribution of water use intensity index values. Values for the major watersheds are on the top graph and DNR Level 08 catchments on the bottom graph. Note the differences in scales between graphs, and on the lower graph the first bar (for water use intensity between 0 and 5% is not displayed due to the large value (9374).

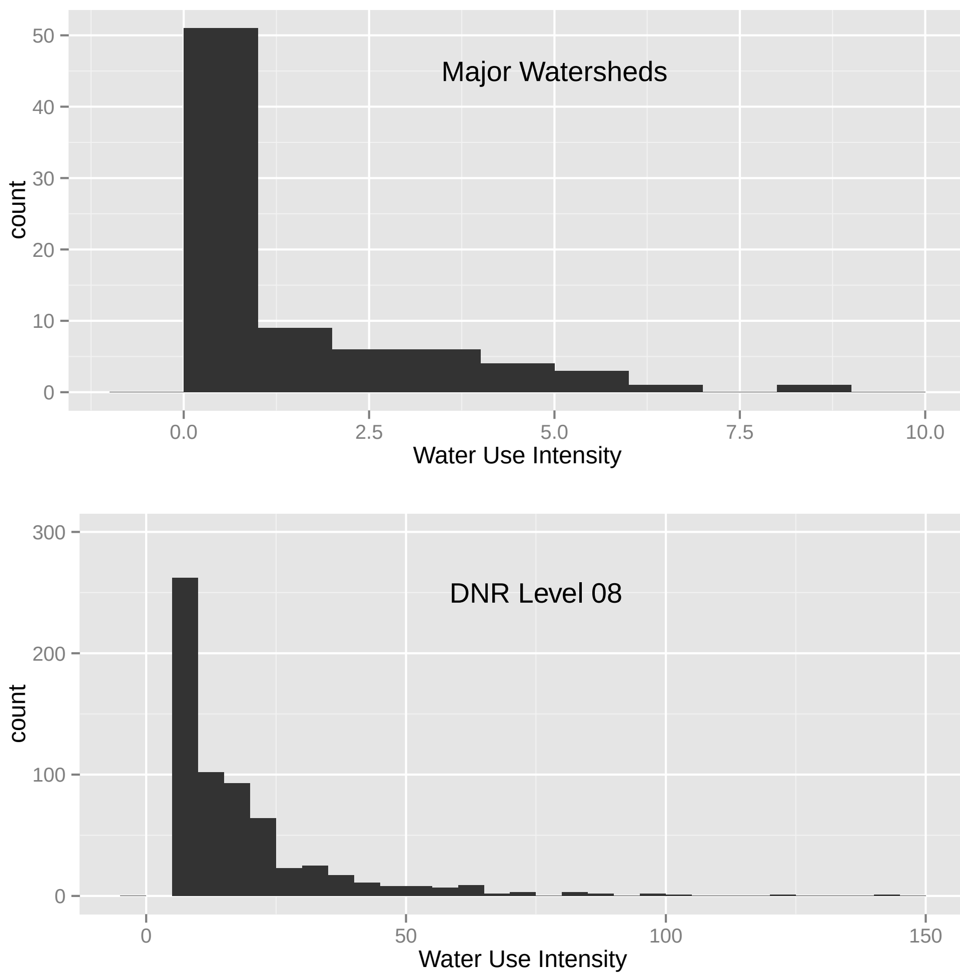

Figure 4: Water use intensity (i.e., percent of available water used) index at the major watershed scale.

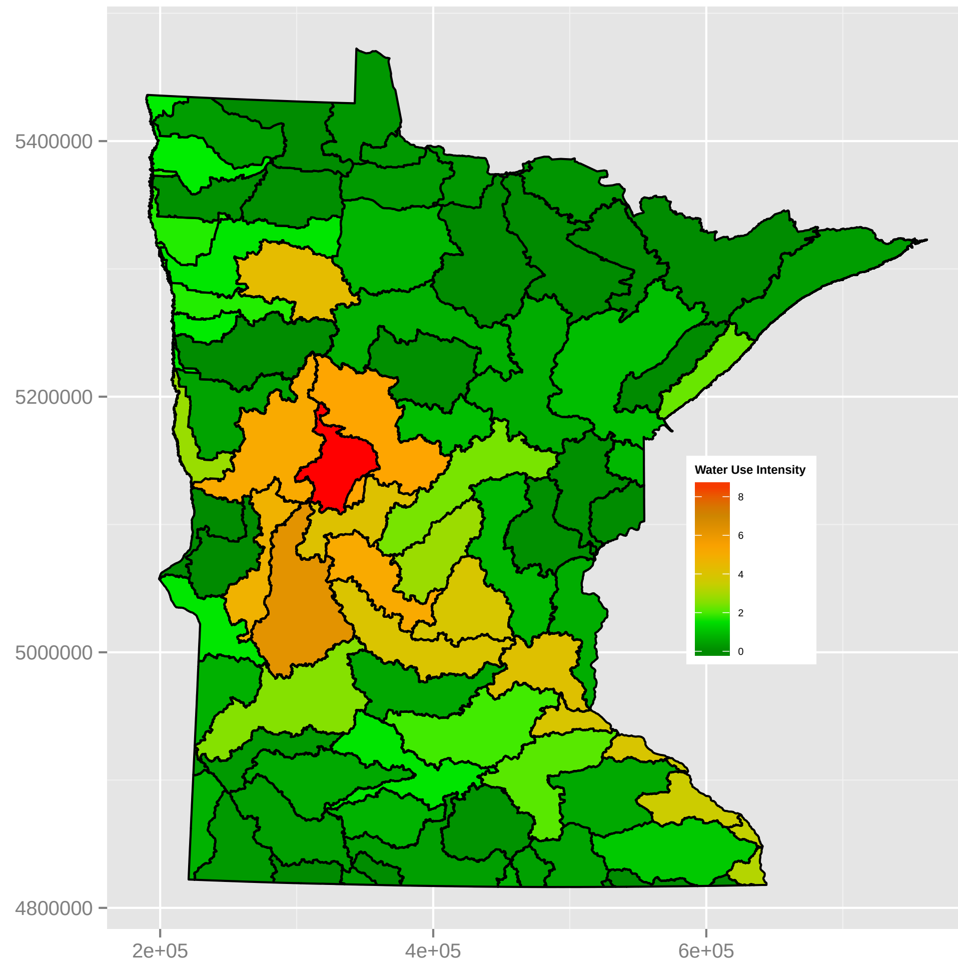

Figure 5: Water use intensity (i.e., percent of available water used) index at the DNR level 08 scale.