THE ANALYSIS OF MODELED AND SATELLITE GREAT LAKES SNOW WATER EQUIVALENT DATA AND INCORPORATING NEAR REAL-TIME ESTIMATES INTO WATER LEVEL FORECASTING

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Abstract: Snow water equivalent (SWE) is an important quantity contributing to the spring water level rise on each of the Great Lakes. This study analyzed modeled and satellite SWE data available for the Great Lakes basin from three primary sources: (1) the SNOw Data Assimilation System (SNODAS) created by NWS National Operational Hydrologic Remote Sensing Center (NOHRSC), (2) the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I), and (3) the Large Basin Runoff Model (LBRM) developed by NOAA Great Lakes Environmental Research Laboratory (GLERL). SWE data were evaluated for ability to estimate the absolute and relative magnitudes of annual SWE as well as the timing of snow accumulation and melt. The comparison shows that the satellite SSM/I data severely underestimates Great Lakes SWE and seems to be heavily affected by vegetation cover. Although the SNODAS SWE estimates appear reasonable, it has limited availability for the Great Lakes, with complete binational coverage dating back only to 2011. One challenge for the U.S. Army Corps of Engineers is incorporating near real-time SWE estimates into the water level forecasts for the coming months. In particular, when SWE estimates are very high or very low, the magnitude of influence on the lake's forecasted water level is poorly understood given that the water level is also influenced by other hydrologic components. Since SWE primarily enters the lake through runoff, historical runoff estimates based on measured stream discharges are also analyzed along with historical precipitation data. A useful relationship is found between observed runoff to Lake Superior and the combined total of precipitation and melted SWE across the Lake Superior watershed. A methodology is presented for how current SWE can be used to improve forecasted runoff and forecasted water levels.

INTRODUCTION

Mission: The Detroit District (LRE) of the U.S. Army Corps of Engineers (USACE) under the auspices of the International Joint Commission (IJC) and the Coordinating Committee on Basic Great Lakes Hydraulic and Hydrologic Data (CCBGLHHD) has a crucial role in water management decisions on the Great Lakes. Hydrologists and others interested in the hydrologic budget of the Great Lakes require estimates of snow water equivalent (SWE), and knowledge of the SWE statistics at various times throughout the winter. USACE has been forecasting the Great Lakes water levels as part of its operational mission since 1952. Near the beginning of each month, LRE releases the "Monthly Bulletin of Water Levels for the Great Lakes" which

includes the six-month forecast of Great Lakes water levels. An improved knowledge of SWE would enable the forecasters to determine whether the current values are above or below normal and improve the accuracy of the water level forecasts. The objective of this study is to improve Great Lakes water level forecasting based on an analysis of the available modeled and satellite SWE data for the Great Lakes Basin.

Background: The seasonal snowfall of the Great Lakes Basin is an important feature of the hydrometeorology of the region and snowmelt an important contribution to the runoff entering the Great Lakes (Norton and Bolsenga, 1993). Snowfall occurs in the Great Lakes watershed as a result of the northern latitude and "continental" climate. The Great Lakes themselves also create "lake-effect zones" where air and water temperature differentials drive enhanced snowfall downwind of the lakes. Figure 1 shows the Great Lakes and their respective basin delineations by country.

Figure 1 Binational delineation of the Great Lakes basins

The volume of water stored in the seasonal snow cover can be a significant fraction of the total annual runoff entering the lakes. For example, the volume of the annual maximum SWE in the Lake Superior watershed for the period 1979-2004 (Daly et al., 2007) ranged from 28% to 58% of the total estimated annual runoff entering the lake. The ability to estimate the volume of SWE contained in the Great Lakes watershed can lead to improvements in the forecasts of the Great Lakes water surface elevations. However, estimation of SWE volume contained in the watersheds of the Great Lakes in real or near real time is fraught with difficulties. There are three basic approaches: using ground-based and aerial observations, modeling, and satellite remote sensing.

Ground and aerial observations (CRREL): Geospatial interpolation of ground and aerial observations of SWE can be used to estimate the SWE volume contained in the entire watershed. Daly et al. (2007) used ground observations to estimate the time series of SWE volume for the Lake Superior basin for the period 1979-2004. This study, referred to as CRREL data from this point forward, relied exclusively on National Weather Service (NWS) first-order and cooperative stations for data in the United States and daily and weekly snow depth observations taken by the Meteorological Service of Canada and 20 other agencies for Canada. Unfortunately, the NWS changed its observation procedure in the 1990's through deployment of the Automated Surface Observing System (ASOS) at most first-order stations. ASOS does not measure snowfall or snow depth and remains ineffective for measuring SWE (Doeskin and McKee, 2000). Almost all cooperative stations snow observations are limited to snow depth. The result is that at the present time there are almost no regular observations made of SWE by the NWS throughout the Great Lakes Basin. The number of Canadian SWE observations made each winter has declined continuously starting in the 1980's (Daly et al 2007).

Satellite-based observations (SSM/I): Satellite observations of SWE are based on measuring the passive microwave signal naturally emitted from the Earth. Passive microwave signals at frequencies greater than 25 GHz are scattered as they pass through the snowpack; lower frequencies are not scattered to the same degree. The estimated SWE is proportional to the difference between the emitted signals at a low frequency that is not scattered by snow and a high frequency that is scattered. A singular advantage of satellite observations of emitted passive microwave signals is that they can be observed through cloud cover and at night.

In practice, the accuracy of SWE estimation using passive microwave signals is limited by factors that impact the emitted passive microwave signal. Sources of error in microwave SWE retrievals stem from the dynamic nature of snow and the static assumptions made in the empirical formulations concerning snow properties. Several studies have shown a significant impact of vegetation on the passive microwave signal (Chang et al 1996, Foster et al 2005, Derksen et al. 2005). Other factors that can cause errors include excessive snow depth (Dong et al., 2005, Foster et al., 2005, Clifford, 2010), liquid water in the snowpack (Matzler, 1987, Hallikainen et al., 1986, Walker and Goodison, 1993), changes in snow density and grain size (Foster et al., 1999, Hall et al., 1986; Josberger and Mognard, 2002) and topology of the ground (Matzler and Standley 2000, Dong et al., 2005, Vuyovich and Jacobs, 2011). Ongoing research, which has attempted to account for these errors and to improve results regionally and seasonally, has had varied success (Farmer et al. 2010, Tedesco and Narvekar 2010, Mizukami and Perica 2012).

Daily passive microwave SWE data from the Special Sensor Microwave/Imager (SSM/I) were used for this investigation. The SSM/I sensor was launched in 1987 on board the Defense Meteorological Satellite Program (DMSP) satellites. These data are available near real-time and have the advantage of a relatively long historical record. SWE estimates are derived from the SSM/I brightness temperatures measured at wavelengths 19 and 37 GHz, and have a spatial resolution of 69x43km (19.4 GHz) and 37x29km (37 GHz) (Armstrong and Brodzik 1995). Data are available from the National Snow and Ice Data Center (NSIDC) in an Equal-Area Scalable Earth Grid (EASE-Grid) projection at a 25 km resolution. To avoid gaps at the basin boundaries,

the passive microwave data were re-sampled to 1 km^2 grid cells using the nearest neighbor method which assigns the same value to the pixel as the data layer in that location without any interpolation. SSM/I SWE products are available twice daily; ascending passes which occur in the afternoon and descending passes which occur in the early morning. For this study, only descending SWE data was used to reduce the potential wet snow impacts in the afternoon. A gap in the satellite swath coverage can occur every 3 to 4 days, depending on the latitude of the region.

SNODAS Model: Modeled estimates of SWE throughout the Great Lakes watershed are provided by the NWS National Operational Hydrologic Remote Sensing Center (NOHRSC). It offers a near real-time estimate of SWE and other snow properties for the U.S. through its SNOw Data Assimilation System (SNODAS). SNODAS is physically based, spatially distributed, energy-balance and mass-balance snow accumulation and ablation model run at a 1-km^2 resolution. SNODAS ingests data from the Rapid Update Cycle numerical weather prediction model and downscales it from 13 to 1 km^2. Multiple sources of available satellite, airborne, and ground-based snow observations are assimilated into the model and used to adjust model output by using a Newtonian nudging technique. The objective of using all of the available snow data is to produce a 'best estimate' of near real-time snow conditions for the conterminous USA and to minimize error associated with any individual method (Carroll et al., 2006). Though these data are also subject to errors, this product provides the best spatially distributed estimate of snowpack conditions throughout the U.S. and is used operationally in a number of locations. The snow model within SNODAS has been evaluated and generally shown to provide good results at a point scale (Rutter et al., 2008, Frankenstein et al., 2008, Clow et al., 2012), though over a larger scale, particularly where ground observations are sparse, additional error is introduced. The SNODAS model provides 1-km^2 estimates of snow cover and associated parameters near real-time on a 3-hourly and daily basis. SNODAS data are available from 01 October 2003 through the present from the National Snow and Ice Data Center (NSIDC). The data for Canada begins in approximately 2011. Due to this discrepancy in period of record, this study analyzed the SWE estimates of the US portion with the respective historical results, along with the watershed totals for the recent period.

Large Basin Runoff Model: Developed by NOAA's Great Lakes Environmental Research Laboratory (GLERL), the Large Basin Runoff Model (LBRM) is a lumped-parameter model of runoff for the Great Lakes Basin (Croley and He 2002). Within the LBRM framework, the daily snow pack is calculated from the previous day's snow pack, precipitation, air temperature, and a snowmelt rate parameter. In general, it is more simplified than the SNODAS model, since it only computes daily time steps and does not include any observational SWE data. However, it has the advantage of being able to simulate daily snow pack as far back as 1950, which is the available range of reliable meteorological data.

METHODOLOGY

This study analyzed time series for each of the Great Lakes watersheds of the SSM/I, SNODAS, and LBRM data over their periods of record. The evaluation compared the SSM/I and SNODAS data sets for each watershed using the estimated annual maximum SWE and the weekly maximum SWE values. The results for the Lake Superior watershed were compared to the

results of an independent study that was conducted earlier (Daly et al. 2007). The SWE statistics for each day of the year were determined.

Average basin SWE estimates from passive microwave and SNODAS SWE products were compared over the contributing watersheds to each of the Great Lakes in the north-central U.S. (Figure 1). Weekly time series of SWE and annual maximum values were evaluated over 10 years from 2004 through 2013. SNODAS data is available in the Canadian portion of the Great Lakes basins only since 2011, so the historical comparison was done only in the U.S. portions of the basins.

In order to improve the understanding of how SWE influences Great Lakes water levels, the historical record of LBRM SWE estimates were analyzed, beginning with the Lake Superior basin. Other basins could be analyzed in the future using the framework presented in this study. Statistics for the monthly LBRM SWE data were computed and compared with other historical hydrologic datasets. For the runoff component of the hydrologic cycle, the GLERL Area Ratio Method (ARM) is the most reliable historical data set. ARM includes stream flow observations within the basin, extrapolating from gauged areas to ungauged areas using an area-weighted approach. For precipitation data, the internationally coordinated over-basin precipitation data set is used. This precipitation data set begins with NOAA GLERL's Thiessen Method, is reviewed by NOAA Center for Operational Oceanographic Products and Services (CO-OPS), and is agreed upon between USACE and Environment Canada. Currently, the coordinated precipitation data set spans 1900 through 2010.

RESULTS

Gridded daily SWE data from SSM/I and SNODAS were obtained for ten water years when both datasets were available, 2004 – 2013. For both datasets, the gridded data were aggregated by basin region to produce a daily time series of average-basin SWE. Weekly time series were also developed for each basin using the maximum weekly values in order to accommodate the satellite overpass cycle which results in some days without satellite observations. Annual maximum SWE values for each of the ten water years were extracted from the weekly time series. Daily maximums, minimums, and averages were calculated from the daily time series. Data for the Superior, Michigan, Erie, and Ontario basins are shown in Figure 2 through Figure 5.

The SSM/I data is clearly underestimating the SWE in the Great Lakes. The passive microwave results seem to be heavily affected by the significant vegetation in the region considering the U.S. portion of the Lake Erie basin has a 14.9% forest fraction while the Superior, Michigan, Huron, and Ontario basins all have greater than 30% forest fraction according to the Vegetation Continuous Field collection from the University of Maryland (Hansen et al. 2006). Azar et al (2008) evaluated the SSM/I SWE products in the Great Lakes region using the SNODAS data and found poor results using the original passive microwave algorithm. They were able to improve the SSM/I results around the Great Lakes by developing an algorithm that uses a Normalized Difference Vegetation Index (NDVI) to classify the mixed use forest in the region. Figure 6 shows the SWE for the U.S. portion of the Lake Superior basin during the winter of 2003-2004, the only winter in common between the SSM/I, SNODAS, and CRREL data sets. In

the winter of 2003-2004, the SNODAS and CRREL data are well correlated ($R^2 = 0.91$) as might be expected since both the SNODAS and CRREL estimates likely use the same ground observations. This provides some confidence in the SNODAS SWE.

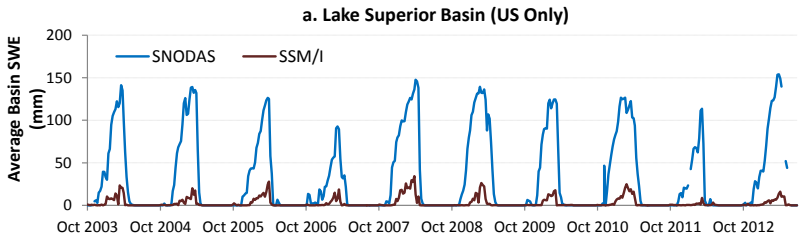

Figure 2 Lake Superior basin (US only) SWE estimates since 2003

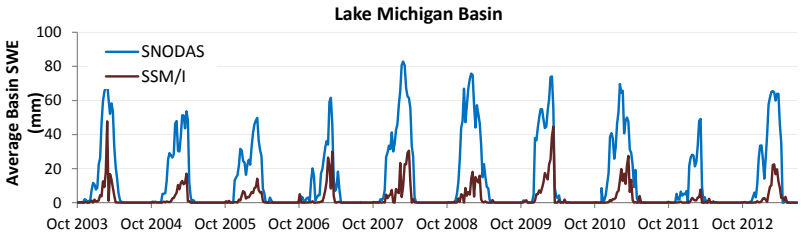

Figure 3 Lake Michigan basin SWE estimates since 2003

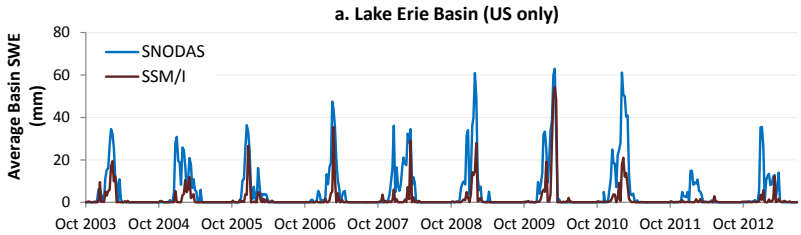

Figure 4 Lake Erie basin (US only) SWE estimates since 2003

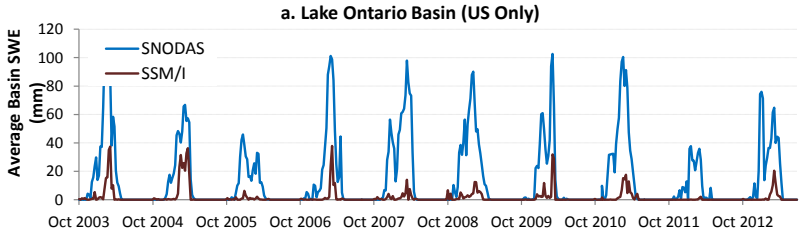

Figure 5 Lake Ontario basin (US only) SWE estimates since 2003

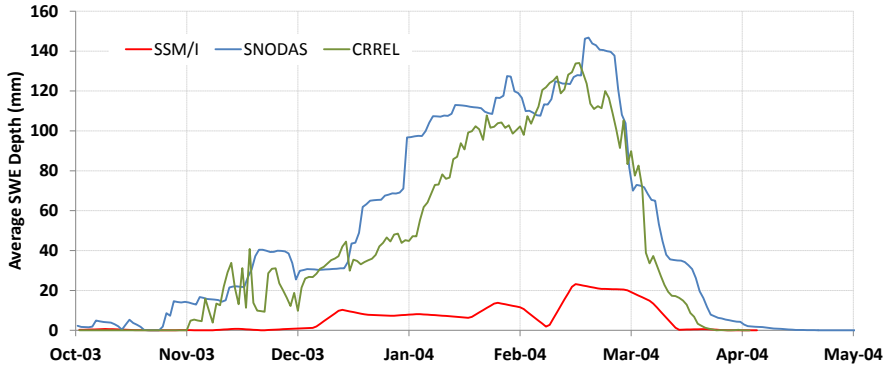

Figure 6 CRREL (daily), SNODAS (daily), and SSM/I (weekly) SWE estimation for Lake Superior (US only) for the winter of 2003-04

The LBRM Lake Superior SWE statistics were calculated using end-of-month data and are shown in the box and whisker plot of Figure 7. For Lake Superior, the snow pack generally begins to develop in November, peaks in March, and lasts until May. A further analysis is to look at the decline of SWE through each month, as shown in Figure 8, which shows the amount of water which is made available to runoff (when positive) or the amount of precipitation which enters snow pack (when negative). This figure clearly shows that SWE typically gives a boost to runoff, and hence the Lake Superior water level, during the months of April and May.

To further understand the influence of SWE within Lake Superior's hydrology, the statistics for historical runoff and historical precipitation were also analyzed, as shown in Figure 9 and Figure 10, respectively. The runoff component has been converted to depth units of mm over land, in order to match the units of SWE. The precipitation data set represents units of mm averaged over the entire basin, and this study will assume that the depth is constant over each part (land area and lake area). When comparing Figure 8 with Figure 9, one can clearly see an influence of SWE on runoff. However, Figure 10 shows that there is also an increase in precipitation at this time of the year as well.

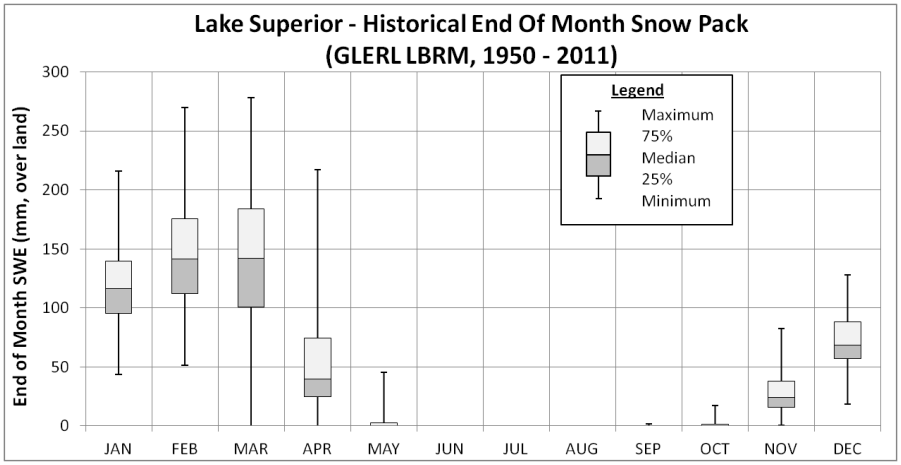

Figure 7 Lake Superior LBRM historical snow pack

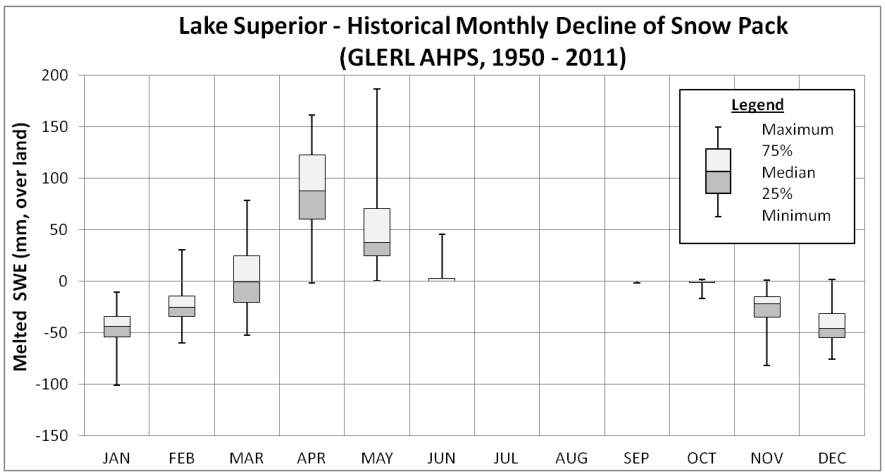

Figure 8 Lake Superior LBRM historical average decline of snow pack

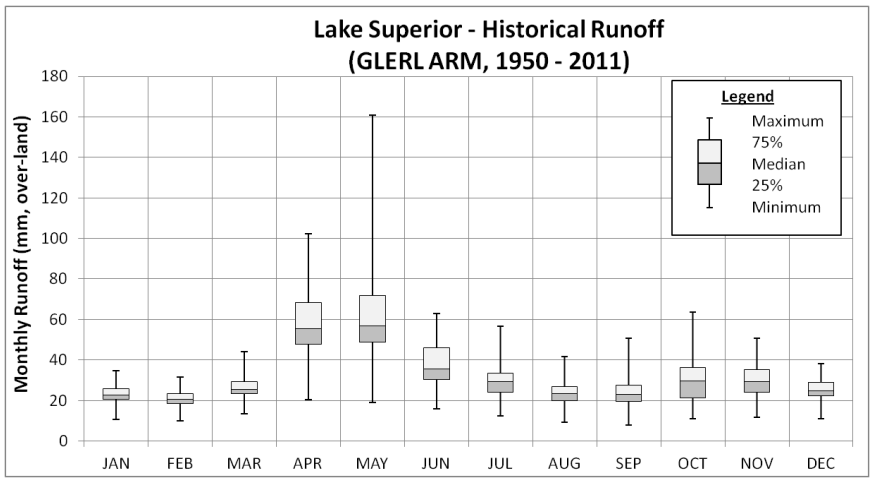

Figure 9 Lake Superior ARM historical runoff

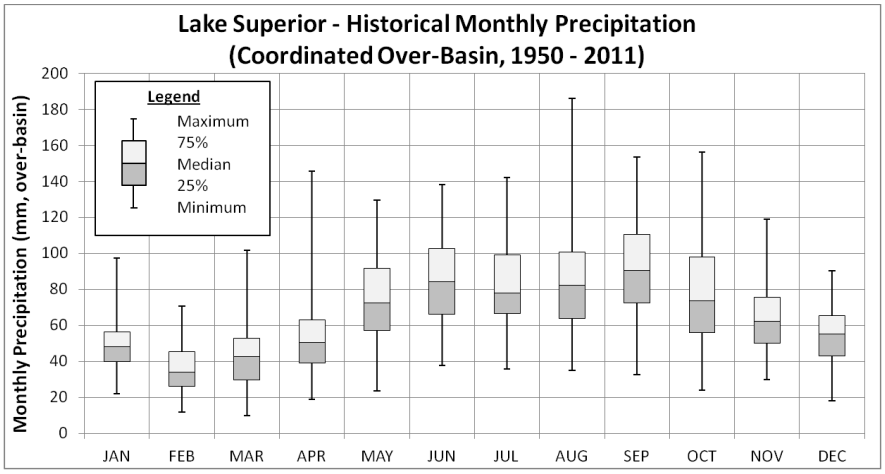

Figure 10 Lake Superior historical coordinated precipitation

Water which is available for spring's seasonal runoff to Lake Superior comes from two sources: melted SWE and spring over-land precipitation. This study found that developing a relationship

between only one of these components and runoff was not as strong as including both components. Figure 11a shows the historical data for Lake Superior during April of runoff on the vertical axis and the combined total of melted SWE and over-land precipitation on the horizontal axis. Figure 11b shows the historical data for the month of May. Other months exhibited much weaker relationships.

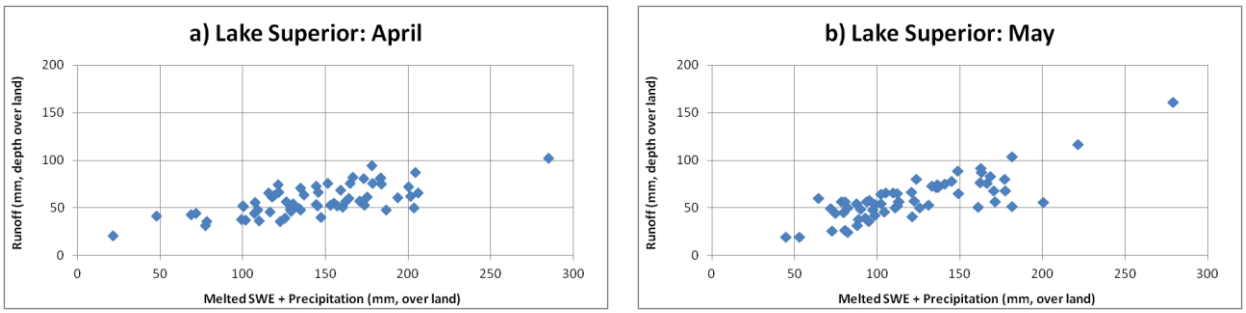

Figure 11 Relationship between Lake Superior runoff and the combined total of melted SWE and over-land precipitation for the months of (a) April and (b) May

As shown in the above figures, the total amount of available water is significantly greater than what arrives to the lake since much of the water infiltrates into the ground or is taken up by vegetation. For example, during the month of April the historical average amount of melted SWE in the Lake Superior drainage basin is 11.24 km^3 and the average over-land precipitation is 6.91 km^3 for a total of 18.15 km^3, while the average runoff during April is only 7.41 km^3. Assuming the two sources of water behave equally, 62% of Lake Superior's April runoff typically comes from melted SWE and 38% comes from over-land precipitation. For the month of May, 39% of Lake Superior's runoff typically comes from melted SWE while 61% comes from over-land precipitation.

APPLICATION: WATER LEVEL FORECASTING

A challenge in forecasting the Great Lakes water levels is determining how much of an adjustment to implement in the predicted water supply when viewing the near real-time SWE estimates within the basin. The analysis in the previous section demonstrated a clear relationship between the April and May runoff and the available water from melted SWE and over-land precipitation during each month. These relationships can be used in the water level forecast for the months of April and May.

Implementing the relationships of Figure 11 into operational forecasting is suggested in two basic steps: assess the current SWE and then adjust the forecasted runoff. First, the near real-time SWE estimates are compared with the average SWE for that time of the year. For example, a current end-of-March SNODAS SWE estimate is divided by the historical average end-of-March LBRM SWE. At the current time, this comparison has uncertainty since the best SWE estimates are from the SNODAS model while the relationships developed in the previous section used the LBRM data set. The SNODAS model only has full basin coverage since 2011, and although the two model results seem to agree relatively well in the recent overlapping years, this method should improve as more years of data become available.

Once the current relative SWE is determined, as a percentage of the typical SWE, the forecasted runoff can be adjusted using the typical proportion of melted SWE for that month. For the month of April, the average runoff volume for Lake Superior is 7.41 km^3, 62% of which (or 4.59 km^3) comes from melted SWE and the rest (2.82 km^3) from over-land precipitation. Since the relationship between runoff and available water was linear in Figure 11, the runoff adjustment is made by directly multiplying the SWE portion of runoff (4.59 km^3) by the current relative SWE. This text explained the connection in terms of water volume, but in general the USACE forecasts use units of flow rate for the runoff component. For runoff in units of flow rate, the same logic can apply by calculating the proportion (62%) of the flow coming from melted SWE and adjusting it based on the current relative SWE. As an example, if the current end-of-March SWE was 150% of average and the typical runoff for April was 2,560 m^3/s, the adjusted runoff for the forecast would be 3,350 m^3/s. An improvement to the forecasted runoff will also improve the Great Lakes water level forecast.

CONCLUSION

Available historic SWE data from passive microwave SSM/I and NOAA NOHRSC SNODAS were compared for the Great Lakes basin. Since the Canadian coverage of the SNODAS model is only available since 2011, figures present the 10 available years (since 2003) of U.S. coverage of SWE. Results indicate that SSM/I data severely underestimates Great Lakes SWE, likely due to the significant forest fraction within the basin. Historical LBRM snow pack, ARM runoff, and coordinated precipitation were analyzed for the Lake Superior basin in order to quantify the influence of SWE on the Lake Superior water level. A linear relationship was found between runoff and the combined total of melted SWE and over-land precipitation during the months of April and May. A method of adjusting the forecasted April and May runoff is suggested which uses near real-time SWE and the historical proportions of runoff which originate from melted SWE and over-land precipitation. As more years of SNODAS become available, the understanding of SWE behavior and its incorporation into the Great Lakes water level forecasts will continue to improve, as will the uncertainty in the proposed method.

LIST OF ABBREVIATIONS

ARM:	Area Ratio Method (of GLERL)
ASOS:	Automated Surface Observing System
CCBGLHHD:	Coordinating Committee on Basic Great Lakes Hydraulic and Hydrologic Data
CO-OPS:	Center for Operational Oceanographic Products and Services (of NOAA)
CRREL:	Cold Regions Research and Engineering Laboratory (of USACE)
DMSP:	Defense Meteorological Satellite Program
EASE-Grid:	Equal-Area Scalable Earth Grid
ERDC:	Engineer Research and Development Center (of USACE)
GLERL:	Great Lakes Environmental Research Laboratory (of NOAA)
IJC:	International Joint Commission
LBRM:	Large Basin Runoff Model (of GLERL)
LRE:	Detroit District (of USACE)
NDVI:	Normalized Difference Vegetation Index
NOAA:	National Oceanic and Atmospheric Administration

NOHRSC: National Operational Remote Sensing Center (of NOAA)
NSIDC: National Snow and Ice Data Center
NWS: National Weather Service (of NOAA)
SNODAS: SNOw Data Assimilation System (of NOHRSC)
SSM/I: Special Sensor Microwave/Imager (of DMSP)
SWE: Snow-water equivalent (usually units of depth over the land surface)
USACE: U.S. Army Corps of Engineers

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