PREDICTING STREAMFLOW HYDROGRAPH RECESSION FROM SOIL MOISTURE LOSS AT UTAH SNOTEL SITES

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ABSTRACT

This analysis uses decreases in soil moisture (SM) at Utah SNOTEL sites during the summer months to predict discharge at nearby stream gaging locations during the recessional portion of the annual hydrograph using data from water years 2008-2012. The following characteristics were evaluated: (a) the influence of the SM loss at mid-depths (8") on hydrograph recession; (b) the influence of moisture loss from deeper portions of the soil (20") on late-season baseflow; and (c) the timing of this transition. Thirty-four pairings were used between SNOTEL sites and nearby stream gages in select locations throughout Utah, for 3-5 years each depending on data quality, to generate 143 total comparisons of soil moisture loss and stream discharge. Regressions were fairly strong ($r^2 > 0.8$) where the SNOTEL site was in a location with slow meltout rates, ample infiltration, and minimal summer precipitation. In a few cases the correlation was remarkably strong ($r^2 > 0.95$), even for SNOTEL sites located far from respective stream gages (e.g. >20 mi, >3500' elevation difference for the best pairing). At such sites, transition timing in 2013 (between hydrograph recession and baseflow, and between predominantly 8" vs. 20" SM loss) was well predicted from 2012 data given the similarity in water years, with discharges at the transition point predicted from SM loss in 2012 less than 30% different than observed values in 2013. Conversely, predictions of discharge were poor where timing was not coincident between soil moisture and discharge due to poor infiltration, intense summer precipitation, flow control structures, or other factors. An index of the robustness of each pairing was generated to attempt to develop predictive relations for where this type of analysis might be most successful for a given type of water year (normal, abnormally dry, or abnormally wet) based on watershed characteristics (e.g. average peak SWE, basin runoff production, etc.); however, results suggest that identification of high quality pairings may need to be site-by-site. (KEYWORDS: SNOTEL, soil moisture, streamflow recession, water supply forecasting, snow water equivalent, Utah)

INTRODUCTION

In the Western U.S., the vast majority of the water available for all users comes from snowmelt- in Utah snow provides 95 percent or more of the state's water needs (R. Julander, unpublished data). Peak snow accumulation typically occurs around the beginning of April and lasts until late May to mid June, depending on site and water year factors (Pagano et al., 2004; Julander, 2005; Bedford and Douglass, 2008). Reliable water supply forecasts for western states (e.g. NRCS National Water and Climate Center or National Weather Service forecast models) predict flow volume for the April-July time period and are developed during the spring (see details in Pagano et al., 2014); additional forecasts that help refine the late-season (July-September) flow volume ought to therefore be useful, even if limited to discrete locations where such analysis is successful.

Developing a late-season water supply forecast depends on hydrologic information that is both (1) available during that time period at a number of locations, and (2) integrates current and antecedent conditions to account for ongoing changes in water availability throughout the summer as well as the general annual water year pattern. One example of such hydrologic information is data provided by high-elevation soil moisture sensors. In Utah, the snowpack telemetry system operated by the NRCS (SNOTEL) has been equipped with soil moisture sensors since around 2006 (depending on the site); all SNOTEL sites in Utah have soil moisture probes at the 2", 8" and 20" depths. This results in the best resolution high-elevation soil moisture network anywhere in the Western U.S. (Bitar et al., 2012) and makes the state an ideal setting to investigate the teleconnections between upper basin hydrologic conditions and downstream response, with the goal of identifying relationships capable of predicting late-season stream volume.

For a number of locations in Utah, I compared soil moisture data from high-elevation SNOTEL sites with stream discharge from gaging stations at much lower portions of each respective watershed, called "pairings" herein (see example pairing data in Figure 1A and locations of all pairings in Figure 2). In general, the following pattern

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was observed (similar to the “characteristic soil moisture periods” described by McNamara et al. (2005) but for higher-elevation terrain): (1) during the snow meltout phase, soil water values increased at all depths as infiltrated water permeated throughout the soil complex. Streamflow increased during this period from snowmelt and from soil water pathways. (2) After the completion of snowmelt, soil moisture values remained elevated for a short period due to the slow downslope movement of water, minimal transpiration and evaporation losses given the late spring or early summer timing, and additional locally-varying topographic factors (Sutcliffe, 2014). Streamflow generally obtained peak discharge during this period. (3) The onset of soil drying occurred next, where surficial portions of the soil profile tended to decline in moisture content first (similar to Blankinship et al., 2014). Consequently, during initial portions of this stage, the difference between the soil moisture values in deeper portions of the soil (20” depth) from that of shallower soils (8” depth) tended to increase while the surficial soils provided the source for the streamflow- this phase is called the “early” period herein and corresponded (in many cases) with the period of maximum hydrograph recession in downstream locations. Very shallow soils (2” depth) followed a similar pattern but were more heavily influenced by summer precipitation, producing a highly variable time series that was generally unconducive to the analysis undertaken herein. (4) Afterwards (called the “later” portion herein), the bulk of the moisture from the shallower portion of the soil had been depleted, and much of the source of the late-recessional hydrograph and baseflow transitioned to deeper portions of the soil. The shift from stages (3) to (4) is called the “transition point” in this investigation and is seen clearly in Figures 1A and 1B.

Focusing on phases (3) and (4), this analysis uses the difference between 20” and 8” soil moisture values to assess the relative influence of each on downstream discharge for various portions of the annual hydrograph at a large number of locations throughout Utah, determines the types of settings where the analysis works, develops an objective means to qualify each pairing, and examines whether patterns exist for a given pairing and type of water year that may help improve water forecast predictions during flow recession. Figure 1B demonstrates how the magnitude of differences between soil moisture at the 20” and 8” depths may be used to reliably predict discharge- this paper explores the various factors that affect the robustness of such flow predictions. In addition, for each pairing I explore patterns in the hydrologic data for similar type water years, such as the duration of the “early” and “later” periods and the timing of the transition point and of peak stream discharge.

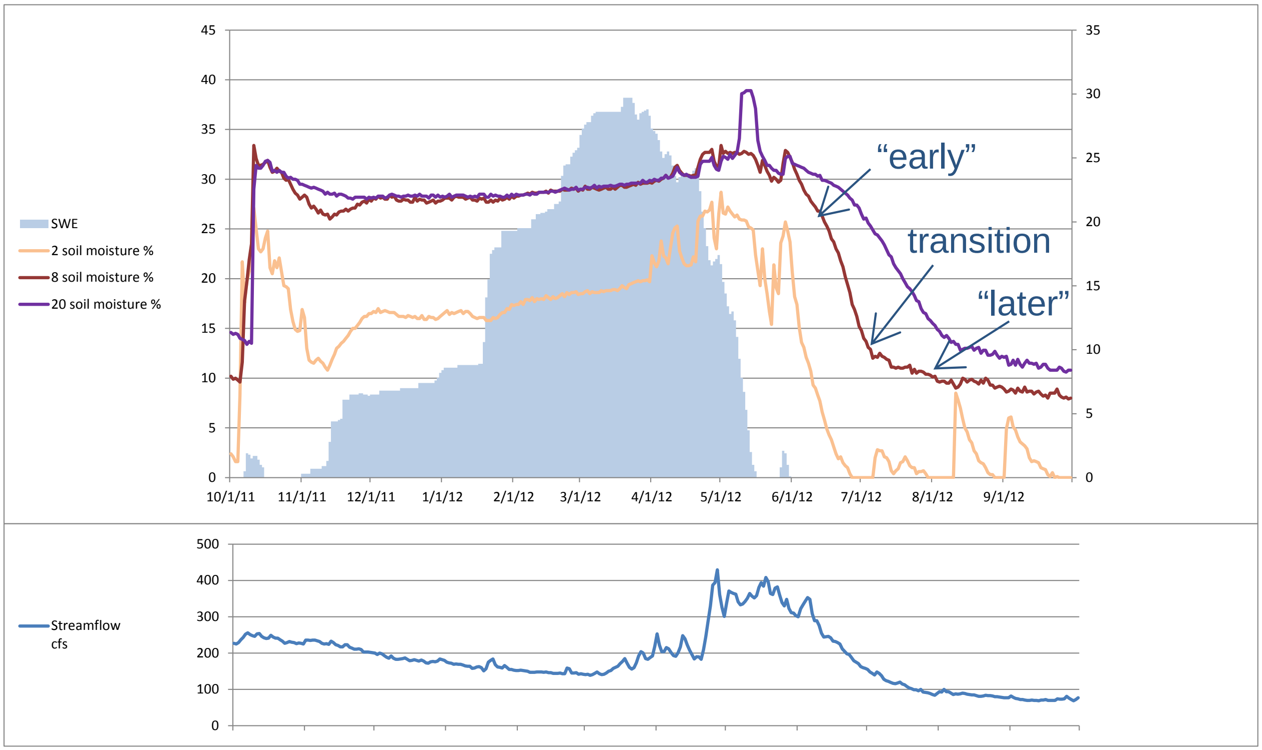

Figure 1A. Example time series of soil moisture 2” (yellow), 8” (red), and 20” (purple) sensor data and snow water equivalent (blue shaded area) at the Tony Grove SNOTEL site in 2012 (upper panel), with flow in the downstream Logan River (lower panel).

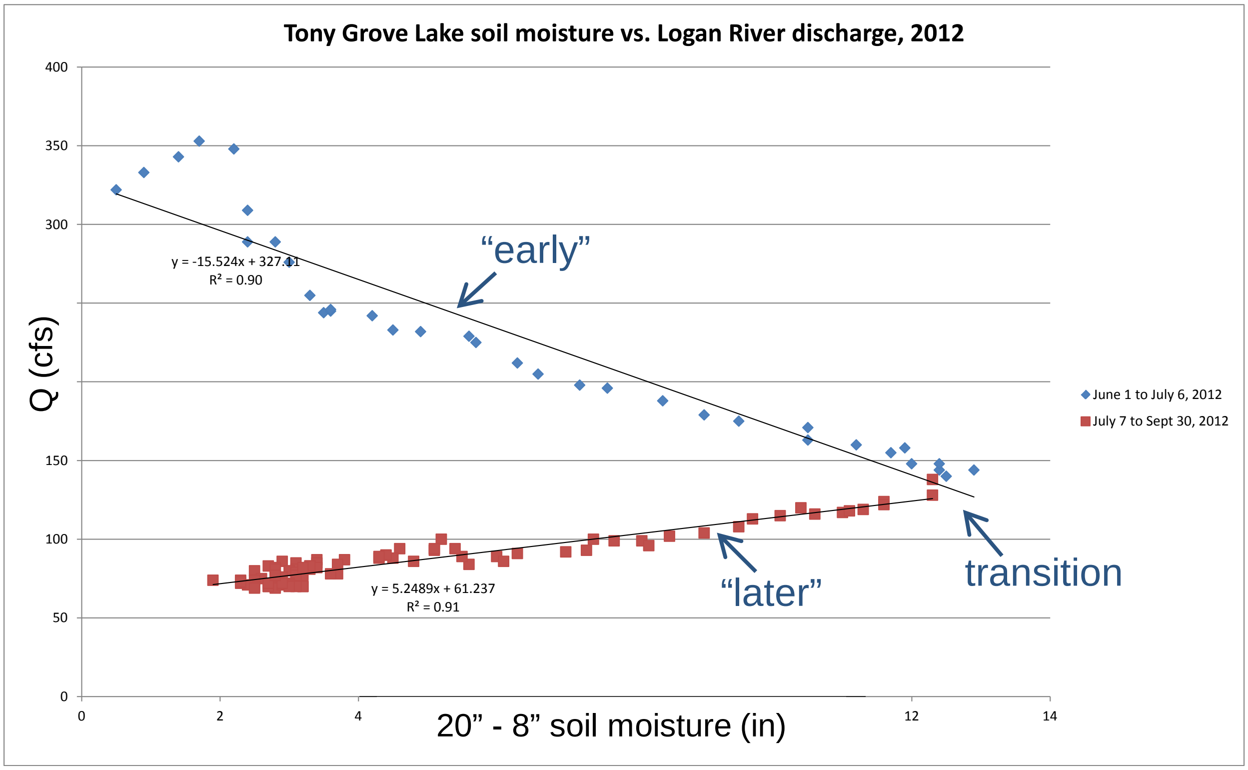

Figure 1B. Example regression analysis for 8" and 20" soil moisture data and stream discharge shown in (A). Blue and red symbols correspond to "early" and "later" portions of the time series, respectively, and black lines are regression curves using best-fit analysis. Most paired SNOTEL and stream discharge measurement site tended to exhibit this pattern, where the difference between the soil moisture values in deeper portions of the soil from that of shallower soils tended to increase while the surficial soils provided the source for the streamflow (called the "early" period herein). Afterwards (called the "later" portion herein), the bulk of the moisture from the shallower portion of the soil had been depleted, and much of the source of the late-recessional hydrograph and baseflow transitioned to deeper portions of the soil.

METHODS

Each pairing between soil moisture data at individual SNOTEL sites and nearby stream discharge was developed by the following criteria: (1) Pairings required that a SNOTEL site with a sufficiently-long record of soil moisture data existed in reasonably close proximity to a stream gage that had overlapping, daily data for the same time period. In a few cases, the closest SNOTEL site to a given stream gage was located in a different (but physiographically-similar) watershed. Google Earth© was used to aide in the co-location of SNOTEL sites and stream gaging locations.

(2) Streams needed to be either perennial or intermittent; ephemeral discharge would not be expected to correspond to high elevation soil moisture loss, such as that reported at the SNOTEL sites. As such, discharge fluctuation patterns needed to reflect an annual hydrograph. While large intensity precipitation events affected the flow at most sites, those with an indiscernible annual trend were not included.

(3) Pairings were located to represent a large range of contexts, including the following: bedrock type and geologic history, climate factors (such as a range in peak snow water equivalent, frequency and intensity of summer precipitation, typical snowmelt characteristics), soil types and drainage properties, elevations and vertical range between the SNOTEL site and the nearby stream gage, horizontal distance between the SNOTEL and stream gage, stream size, average peak discharge, and drainage area at the gage, and other factors. This produced a wide range in geographic settings for the pairings used herein (Figure 2).

(4) While all SNOTEL sites in Utah have soil moisture probes at the 2”, 8” and 20” depths, most only have good quality data from 2007 to the present. The duration of the investigation was therefore initially limited to the water years 2008 to 2012, with water year 2013 serving as a test year for the predictive capability of this analysis. Moreover, in numerous cases, missing or poor quality soil moisture or stream discharge data required the elimination of one or more water years from the investigation.

(5) Minimal external factors were allowed to affect the analysis, such as the influence of flow regulation and local factors that may impact SNOTEL soil moisture data. As such, stream gages below large dams or other regulatory structures were avoided.

In all, 44 pairings were attempted between soil moisture and streamflow. Ten pairings were eliminated early on in the investigation due to the limitations listed above, resulting in a total of 34 pairings used in the analysis - these are shown in Figure 2 and listed in Table 1. For each of the 34 pairings, 3-5 years of data were examined (2008-2012 WY), resulting in 143 total comparisons of soil moisture loss and stream discharge.

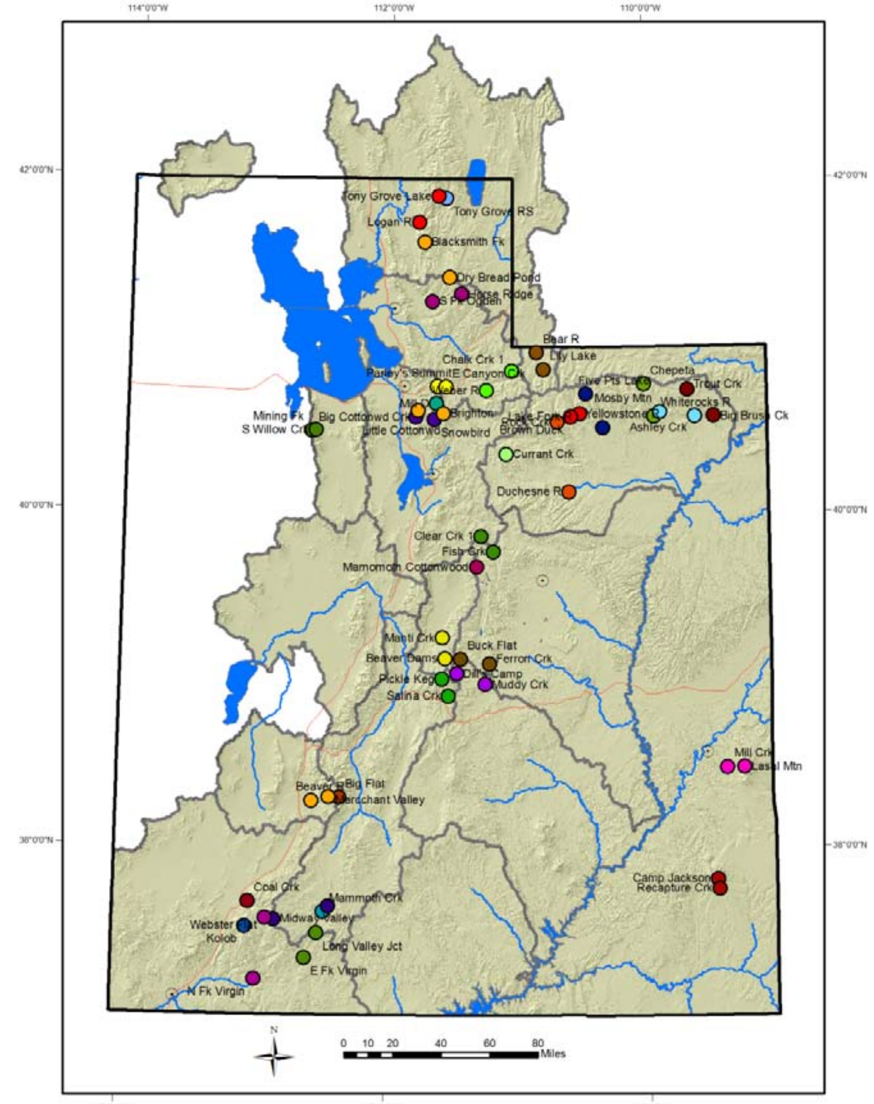

Figure 2. Locations of each pairing, where each are displayed as a single color. Table 1 also gives geographic information for each pairing. All sites are in Utah.

			SNOTEL		Qgage		elevation (ft)		area at	historic avg. peak	
SNOTEL	Qgage	Qgage ID	latitude	longitude	latitude	longitude	SNOTEL	Qgage	gage (mi^2)	SWE (in)	Q (ft^3/s)
Beaver Dams	Manti Creek blw Dugway Crk, nr Manti	USGS 10215900	39.137	-111.558	39.256	-111.574	7970	6500	26.4	12.1	361
Big Flat	Beaver River nr Beaver	USGS 10234500	38.302	-112.357	38.275	-112.567	10292	6200	91.0	22.0	414
Brighton	Big Cottonwood Creek at Canyon Mouth	Salt Lake County 320	40.599	-111.583	40.618	-111.775	8761	5017	na	25.1	310
Brown Duck	Lake Fork River ab Moon Lake, nr Mtn Home	USGS 09289500	40.581	-110.586	40.604	-110.523	10569	8180	77.9	22.0	1458
Buck Flat	Ferron Creek (Upper Station) nr Ferron	USGS 09326500	39.134	-111.437	39.103	-111.210	9403	6210	138.0	19.3	983
Camp Jackson	Recapture Creek nr Blanding	USGS 09378630	37.813	-109.487	37.753	-109.472	8832	7200	3.8	15.2	23
Chalk Creek #1	Weber River nr Oakley	USGS 10128500	40.855	-111.048	40.736	-111.242	9159	6640	162.0	26.7	1906
Chepeta	Whiterocks River nr Whiterocks	USGS 09299500	40.775	-110.011	40.590	-109.926	10492	7200	109.0	16.6	1249
Clear Creek #1	Fish Creek above reservoir, nr Scofield	USGS 09310500	39.867	-111.284	39.771	-111.254	8958	7670	60.1	20.3	744
Currant Creek	Duchesne River nr Tabiona	USGS 09277500	40.358	-111.090	40.300	-110.601	7936	6190	353.0	11.1	1359
Dill's Camp	Muddy Creek nr Emery	USGS 09330500	39.046	-111.469	38.977	-111.250	9239	6400	105.0	14.8	759
Dry Bread Pond	Blacksmith Fk ab Up & L Co's Dam, nr Hyrum	USGS 10113500	41.413	-111.538	41.621	-111.736	8299	5021	263.0	21.1	540
Five Points Lake	Yellowstone River nr Altonah	USGS 09292500	40.718	-110.467	40.507	-110.338	10924	7430	132.0	19.9	1214
Horse Ridge	S Fk Ogden River nr Huntsville	USGS 10137500	41.314	-111.446	41.268	-111.671	8205	5190	137.0	23.2	818
Kolob	N Fk Virgin River nr Springdale	USGS 09405500	37.526	-113.054	37.206	-112.973	9266	3970	344.0	25.2	2245
Lasal Mtn	Mill Creek at Sheley Tunnel, nr Moab	USGS 09183500	38.482	-109.272	38.477	-109.402	9575	5500	26.8	14.2	354
Lily Lake	Bear River nr UT-WY state line	USGS 10011500	40.865	-110.798	40.959	-110.852	9116	7965	172.0	14.8	1914
Long Valley Junction	E Fk Virgin River nr Glendale	USGS 09404450	37.488	-112.515	37.337	-112.602	7453	5900	74.2	6.9	169
Mammoth Cottonwood	Fish Creek above reservoir, nr Scofield	USGS 09310500	39.867	-111.284	39.771	-111.254	8701	7670	60.1	22.0	744
Merchant Valley	Beaver River nr Beaver	USGS 10234500	38.302	-112.357	38.275	-112.567	8724	6200	91.0	14.5	414
Midway Valley	Coal Creek nr Cedar City	USGS 10242000	37.569	-112.838	37.670	-113.034	9827	6000	80.9	27.2	1099
Midway Valley	Mammoth Creek abv W Hatch Ditch, nr Hatch	USGS 10173450	37.569	-112.838	37.620	-112.510	9827	7300	105.0	27.2	459
Midway Valley	Sevier River at Hatch	USGS 10174500	37.569	-112.838	37.651	-112.424	9827	6870	340.0	27.2	637
Mill D	Big Cottonwood Creek at Canyon Mouth	Salt Lake County 320	40.599	-111.583	40.618	-111.775	8927	5017	na	27.1	310
Mining Fork	S Willow Creek nr Grantsville	USGS 10172800	40.494	-112.611	40.491	-112.571	8312	6360	4.2	20.3	40
Mosby	Ashley Creek nr Vernal	USGS 09266500	40.608	-109.888	40.573	-109.620	9546	6231	101.0	15.0	1192
Parleys Summit	E Canyon Creek nr Jeremy Ranch	USGS 10133800	40.762	-111.629	40.756	-111.558	7566	6240	57.2	17.4	283
Pickle Keg	Salina Creek nr Emery	USGS 10205030	39.012	-111.583	38.907	-111.525	9023	7000	51.8	18.2	205
Rock Creek	Duchesne River nr Tabiona	USGS 09277500	40.358	-111.090	40.300	-110.601	7884	6190	353.0	9.3	1359
Snowbird	Little Cottonwood Crk at Jordan Riv nr SLC	USGS 10168000	40.564	-111.655	40.658	-111.901	9595	4255	46.0	45.8	577
Tony Grove Lake	Logan River abv State Dam, nr Logan	USGS 10109000	41.898	-111.630	41.739	-111.776	8449	4680	214.0	37.6	977
Tony Grove RS	Logan River abv State Dam, nr Logan	USGS 10109000	41.898	-111.630	41.739	-111.776	6321	4680	214.0	9.2	977
Trout Creek	Big Brush Creek abv Red Fleet Res, nr Vernal	USGS 09261700	40.739	-109.673	40.587	-109.459	9437	5625	77.2	12.4	245
Webster Flat	N Fk Virgin River nr Springdale	USGS 09405500	37.526	-113.054	37.206	-112.973	9165	3970	344.0	17.4	2215

Table 1. Site information for SNOTEL sites and stream gages used in this analysis.

For each water year, soil moisture and snow water equivalent data were obtained from each SNOTEL site (http://www.nrcs.usda.gov/wps/portal/nrcs/main/ut/snow/) and stream discharge data were obtained from the USGS (http://waterdata.usgs.gov/ut/nwis/rt) or Salt Lake County, Utah, webpages (http://www.pweng.slco.org/flood/streamFlow/history/index20.cfm). Data were selected from the onset of soil moisture depletion to either the end of the water year or the date after which the soil moisture data were disproportionately affected by precipitation events or other factors unrelated to this analysis. As stream discharge was, effectively, the dependent variable in this analysis, those data were not screened and therefore may have been affected by these or other factors. The onset of soil moisture depletion was determined qualitatively by graphing all of the water year data and evaluating when the minor fluctuations in soil moisture during snowmelt transitioned to a continuous decrease in moisture content (i.e. the shift from phases (2) to (3) identified in the Introduction)- in all cases, these assessments were confirmed by examining the daily values. Similarly, the transition point between "early" and "later" portions of the analysis was determined from visual inspection of the graph at first, and then confirmed by examining the daily data. In most cases the transition point corresponded to the maximum difference between the 8" and 20" soil moisture values during the soil drying period.

After dividing the soil moisture data into "early" and "later" periods, regression analysis was performed on the difference between the 20" and 8" soil moisture values versus the stream discharge for each water year. In a few cases where soils that tended to exhibit much higher annual soil moisture values, the analysis was conducted for the 8" and 2" soil moisture data. For each case, I recorded: (1) the corresponding r^2 values, (2) the dates of the onset of soil drying, the transition point, and the end of that year's analysis, (3) the discharge at the transition point, at peak flow, at the transition from recession to baseflow (estimated from the break in slope on the annual hydrograph), and the minimum flow during the analysis, and (4) the duration of the analysis. Some of these factors were used in the development of the "pairing index" to assess the robustness and predictive power of each pairing- details regarding this index are given in the next section.

RESULTS

Regression analysis for each pairing resulted in a wide range of results, depending on site features and the characteristics of each water year. Details regarding the length of analysis and some comments for each pairing are given in Table 2. In general, regressions for the "early" portion of the soil drying and streamflow recession period were excellent (produced the highest r^2 values) where the SNOTEL site had (1) a tendency for a slow meltout of each year's snowpack, (2) good infiltration, (3) minimal high-intensity summer precipitation, and (4) coincident timing of soil moisture drying with declines in the annual hydrograph. In some cases a nonlinear relationship provided the best regression r^2 for the "early" period (Table 2). The type of regression was allowed to vary for the "early" period as the best-fit curve ought to reflect particulars related to each pairings' physical setting and drainage characteristics and would not necessarily be linear in all cases.

Conversely, regressions for the "early" portion of the soil drying and streamflow recession period were fair to poor (produced the lowest r^2 values) where: (1) timing was not coincident between soil moisture declines and discharge recession, (2) the SNOTEL site was located in a topographic low that produced elevated soil moisture levels, (3) infiltration tended to be low at the SNOTEL site and in the drainage basin, (4) the water holding capacity of the soils was too low to allow for teleconnections between the high elevation SNOTEL and a downstream gaging site, (5) intense summer precipitation was common, and (6) flow control structures and/or tributaries affected the discharge at downstream gaging sites.

As such, the quality of each regression varied both per pairing and by water year. In some cases, almost all regressions provided an excellent fit (e.g. "early" $r^2 > 0.9$ for four out of five water years for Tony Grove Lake SNOTEL vs Logan River discharge, or $r^2 > 0.77$ for all water years for Chalk Creek SNOTEL vs Weber River discharge and Parley's Summit SNOTEL vs E. Canyon Creek discharge). Most other pairings worked best only during normal, wet, or dry years (see comments in Table 2), and several pairings provided poor results for all water years for reasons listed above. Detailed regression results for all cases are too numerous to provide here and are available upon request. Regression results for six example pairings are provided in Figure 3, ranging from excellent to fair or poor in quality.

SNOTEL	Q gage	length of analysis	relation	Comments
Beaver Dams	Manti Creek	2008-2012	power	8"-2" used as Q precedes SM loss due to wet meadow soils
Big Flat	Beaver	2008-2012	linear	"later" period not available too frequently, omitted from pairing
Brighton	Big Cottonwood	2009-2012	linear	8"-2" used as 2" dries out sooner. Q data suspect for portions of 2011
Brown Duck	Lake Fork	2008-2012	linear	short "early"
Buck Flat	Ferron Creek	2008-2010	power	2011: SM data plateau, too wet; 2012: SM data go bad
Camp Jackson	Recapture Creek	2008-2009, 2011-2012	linear	Q are very small values, missing 2010
Chalk Creek #1	Weber	2008-2012	power	20"-2" used. Frequent storms in late summer
Chepeta	Whiterocks	2008-2012	linear	poor relation
Clear Creek #1	Fish Creek	2008-2012	exponential	Good relation. May only work for normal-dry WY
Currant Creek	Duchesne	2008-2010, 2012	linear	Q pk comes after SM starts to drop, but decent relation in dry WY
Dill's Camp	Muddy Creek	2008-2012	linear	linear & exp trendlines very similar
Dry Bread Pond	Blacksmith Fork	2008-2011	exponential	"early" freq comes after Qpk, 2012 SM data are bad
Five Points Lake	Yellowstone	2008-2012	power	8"-2" used, "early" only, works best in dry years
Horse Ridge	S Fk Ogden	2008-2012	exponential	relation works best for wet years
Kolob	N Fk Virgin	2008-2010, 2012	linear	Poor relation, persistent pattern due to sandy soils
Lasal Mtn	Mill Creek	2008, 2010-2011	linear	"early" affected by storms, Q postdates SM decrease a bit
Lily Lake	Bear	2008-2012	exponential	SM sometimes dries before Q reacts
Long Valley Junction	E Fk Virgin	2008-2012	linear	20" SM only (8 & 20 are similar, 2" are bad). Does not work in v dry year.
Mammoth Cottonwood	Fish Creek	2008-2012	linear	nonlinear, scattered "early" trend, fairly clean "later"
Merchant Valley	Beaver	2008-2012	linear	lots of fluctuation in all 3 SM sensors, no clear transition point
Midway Valley	Coal Creek	2008-2010	power	smooth Q, 20" SM affected by eqn issues
Midway Valley	Mammoth Creek	2008-2010	power	smooth Q, 20" SM affected by eqn issues
Midway Valley	Sevier River at Hatch	2008-2010	power	smooth Q, 20" SM affected by eqn issues
Mill D	Big Cottonwood	2009-2012	exponential	Q low flow data are suspect. Some storm spikes during recession
Mining Fork	S Willow Creek	2008-2012	linear	v low Q at all times at this location
Mosby	Ashley Creek	2008-2012	linear	2"-8" used. 20" SM bad for all WY
Parleys Summit	E Canyon Creek	2008-2012	linear	excellent fit, some storm disruption esp. during dry year
Pickle Keg	Salina Creek	2008-2012	linear	20"-2" used, not good for wet yr
Rock Creek	Duchesne	2008-2010, 2012	linear	Q pk comes after SM starts to drop, timing is off
Snowbird	Little Cottonwood Creek	2009-2012	linear	short "early"
Tony Grove Lake	Logan	2008-2012	linear	excellent fit, smooth Q
Tony Grove RS	Logan	2008-2012	linear	8" plots above 20". Good fit
Trout Creek	Big Brush Creek	2008-2010, 2012	linear	8"-2" used. Lots of scatter in SM, hard to pick transition pt
Webster Flat	N Fk Virgin	2008-2010, 2012	linear	no "later" as 8 & 20" SM act v similarly, 2" is too spiky to use. Poor relation

Table 2. Details regarding analysis conducted for each pairing of soil moisture data from SNOTEL sites and stream discharge at gaging locations (labeled “Q gage”). Variation in the length of analysis per pairing resulted from missing or unreliable data during portions of the time series, interruption in soil moisture data due to precipitation, use of recently-installed SNOTEL sites, and other factors. Additional information regarding the quality of each pairing can be supplied by the author upon request.

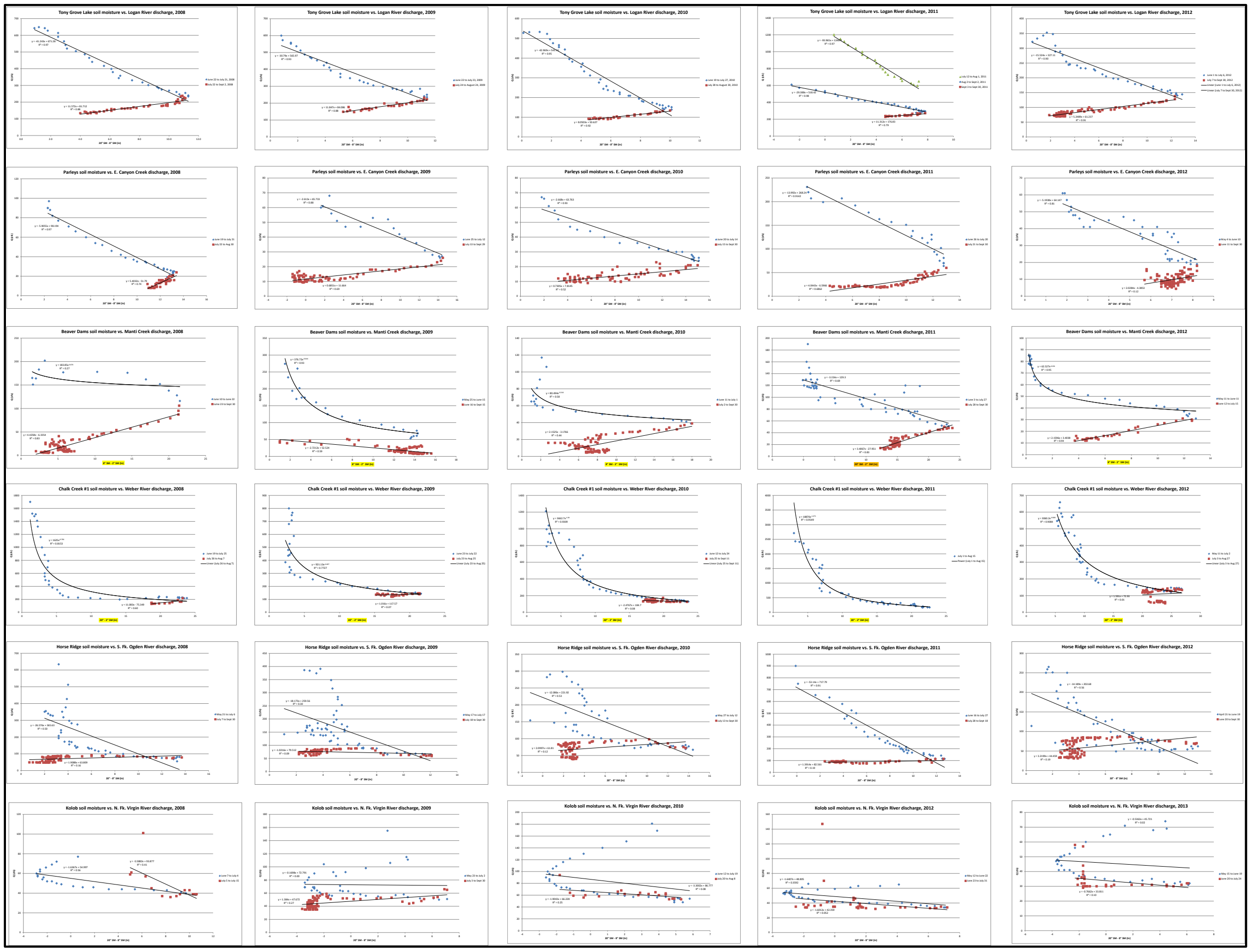

Figure 3. Example pairings of 20”-8” soil moisture values at SNOTEL site (x-axis) versus nearby stream discharge (y-axis) for water years 2008 to 2012 (left to right). Symbology is the same as for Figure 1B: blue and red symbols correspond to “early” and “later” portions of the time series, respectively, and black lines are regression curves using best-fit analysis. From top to bottom, the pairings shown above are: Tony Grove Lake SNOTEL vs Logan River discharge, Parley’s Canyon SNOTEL vs East Canyon Creek discharge, Beaver Dams SNOTEL vs Manti Creek discharge, Chalk Creek #1 SNOTEL vs Weber River discharge, Horse Ridge SNOTEL vs South Fork Ogden River discharge, and Kolob SNOTEL vs North Fork Virgin River discharge. The author acknowledges that individual data on these graphs and corresponding r^2 values are too small to discern- the intention of Figure 3 is mainly to provide characteristic patterns that resulted from the analysis. These example pairings were selected to illustrate the difference between those with an excellent relationship and high predictive power (*top two rows*), those where the “early” portion of the analysis was nonlinear (*middle two rows*), and those where the analysis did not work (*bottom two rows*) for reasons explored in the text. This type of analysis was undertaken for all 34 pairings, for 3 to 5 water years each. See Figure 2 and Table 1 for locations of all pairings.

To synthesize the results from each pairing of SNOTEL soil moisture and nearby streamflow data, I developed a “pairing index”, an objective index designed to quantify the quality and the predictive capability of each pairing. The pairing index is based on the following: a weighted r^2 of the “early” and “later” regressions (both linear and nonlinear r^2 included), the percent of the discharge and number of days captured during the annual recessional flow, the absence of missing WY data, the length of the analysis per year, and (in some cases) the exclusion of anomalously wet or dry years. Specifically, the pairing index score for each WY was determined from:

$$score_\mathrm{i} = \sum(r_e, r_l, n, d) \qquad (1)$$

where $score_\mathrm{i}$ is the score for an individual water year, r_e is the cumulative score based on the strength of the “early” regression, given by:

$$r_e = \sum\{(+1 \text{ if early } r^2 > 0.89), (+1 \text{ if early } r^2 > 0.79), (+1 \text{ if early } r^2 > 0.69), (+1 \text{ if early } r^2 > 0.59), (+1 \text{ if early } r^2 > 0.49)\},$$

r_l is the cumulative score based on the strength of the "later" regression, given by:

$$r_l = \sum\{(+1 \text{ if later } r^2 > 0.89), (+1 \text{ if later } r^2 > 0.69), (+1 \text{ if later } r^2 > 0.49)\},$$

n accounts for missing data or opposing trends, given by:

$$n = \sum\{(-1 \text{ for early slope in wrong direction}), (-1 \text{ for missing later portion of regression})\},$$

and d is the cumulative score based on the length of analysis and proportion of flow hydrograph captured, given as:

$$d = \sum\{(+1 \text{ for early period} > 25 \text{ days}), (-1 \text{ for early period} < 15 \text{ days}), (+1 \text{ for} > 79\% \text{ of flow captured until transition point}), (+1 \text{ for} > 89\% \text{ of days captured during recession}), (+1 \text{ for} > 69\% \text{ of days captured during recession})\}.$$

The scoring was intentionally designed to give the most weight to: (1) strong correlations for the "early" period, and (2) longer duration analyses as a goal of this research was to provide a tool to improve late season water supply forecasting. From that perspective, the greater the volume of stream water that could be predicted from the soil moisture loss at SNOTEL sites, the better. Still, additional quality control was accomplished by accounting for the quality of the regression during the "later", mainly baseflow, period of the hydrograph, r_l, and the potential for missing data or inappropriate trends, n.

The pairing index was then determined as an average of each WY score, not counting anomalously wet or dry years:

$$Pairing\ index = \sum \frac{score_i}{n} \tag{2}$$

where n is the number of water years included in the analysis per pairing. Table 3 lists the results for each pairing. Index values ranged from 9.2 (best) to -1.67 (worst).

Of particular interest was whether certain site or basin factors tended to improve or degrade the index values. Some geographic clustering was found (see Figure 4), which was attributable, in part, to large-scale bedrock geologic and climatic patterns and their effect on surficial soil properties and drainage routing (Kelson and Wells, 1989). In Figure 4, for northern Utah (Logan-Huntsville region), predominantly limestone and other sedimentary bedrock produced excellent pathways and connectivity between upland soil water and downstream channels, as reflected by the very high pairing index values. Soils tend to be deep in this region, and while high-intensity summer storms are not uncommon, they tend to be of lower influence on the annual hydrograph. Central Utah (Salt Lake-Coalville region in inset map) and areas farther west (Western Utah in inset map) pairing index values were also high but were more mixed, due in part to the complex faulting and the combination of mainly sedimentary and metamorphic lithologies in the region. Northeastern Utah (Uinta Mountains in inset map) pairing index values were of medium quality, reflecting in part the predominant igneous and metamorphic bedrock and shallow soils. South-central portions of the state (Central Utah in inset map) are underlain by various sedimentary lithologies and resulting pairing index values were high but were also affected by the increasing influence of intense summer precipitation that disrupted soil moisture depletion patterns. In the southeastern corner of the state (Southeastern Utah in inset map), sedimentary rock types are prevalent but streams are generally small and high intensity summer precipitation is common, resulting in average pairing index values. Southwestern Utah produced the lowest average pairing index; volcanic bedrock and ubiquitous sandstone produces sandy soils with low moisture retention capacity and therefore poor connectivity to downstream portions of the basin. In other portions of southwestern Utah, very thin soils produce a flashy runoff response- particularly considering the frequent high-intensity summer precipitation.

While the variation in pairing index values appeared to relate to both broad-scale geologic and climatic patterns, additional regression analysis was used to determine that no correlation existed for any of the following parameters: (1) the elevation of the SNOTEL site or the difference in elevation between the SNOTEL site and the stream gage, (2) the drainage area at the stream gage, (3) the basin runoff production (peak discharge/drainage area), (4) the average peak snow water equivalent from the historical record, or (5) the average peak discharge from the historical record. It is likely that a significant correspondence exists between pairing index values and the texture and/or depth of surficial soils but statewide soil data were insufficient to resolve at the scale needed for this analysis and site-specific data were not available at all SNOTEL sites (this effort is ongoing).

SNOTEL	Q_gage	Pairing index	% dif b/w pred. & obs. 2013 Q
Tony Grove Lake	Logan	9.20	11.7
Chalk Creek #1	Weber	8.40	61.8
Dill's Camp	Muddy Creek	8.25	12.2
Parleys Summit	E Canyon Creek	7.25	28.2
Brighton	Big Cottonwood	7.00	17.3
Lily Lake	Bear	6.40	33.5
Mining Fork	S Willow Creek	6.40	10.6
Dry Bread Pond	Blacksmith Fork	6.25	75.0
Buck Flat	Ferron Creek	6.00	na
Beaver Dams	Manti Creek	5.75	33.2
Brown Duck	Lake Fork	5.75	13.7
Tony Grove RS	Logan	5.67	46.9
Mill D	Big Cottonwood	5.25	31.5
Clear Creek #1	Fish Creek	5.00	24.4
Mosby	Ashley Creek	4.80	55.6
Lasal Mtn	Mill Creek	4.67	375.7
Horse Ridge	S Fk Ogden	4.50	20.7
Trout Creek	Big Brush Creek	4.50	41.4
Five Points Lake	Yellowstone	4.00	3.9
Camp Jackson	Recapture Creek	3.75	270.1
Pickle Keg	Salina Creek	3.75	9.8
Currant Creek	Duchesne	3.50	21.6
Midway Valley	Mammoth Creek	3.33	na
Midway Valley	Coal Creek	2.67	na
Midway Valley	Sevier River at Hatch	2.67	na
Chepeta	Whiterocks	2.60	32.4
Long Valley Junction	E Fk Virgin	2.00	na
Rock Creek	Duchesne	2.00	29.8
Snowbird	Little Cottonwood Creek	2.00	73.0
Merchant Valley	Beaver	1.60	29.4
Big Flat	Beaver	1.40	36.3
Mammoth Cottonwood	Fish Creek	0.75	na
Kolob	N Fk Virgin	0.25	128.8
Webster Flat	N Fk Virgin	-1.67	750.9

Table 3. Pairing index and predictive power (percent difference between predicted and observed 2013 flow) for each pairing used in analysis. Pairings are ordered according to pairing index value. Numbers marked in red correspond to the five pairings with the best predictive power for the 2013 water year. See text for details regarding the calculations.

The next step was to determine whether the pairings investigated above for water years 2008-2012 could be used to predict stream discharge in 2013. This was accomplished by: (1) determining which of these water years was likely to be most-similar to 2013 and could serve as an analog, (2) using the soil moisture pattern and relationship to stream discharge from the analog water year to predict discharge in 2013, and (3) comparing the predictions with the observed 2013 flow values. For (1), the similarity in peak snow water equivalent between 2012 and 2013 for most parts of Utah (from SNOTEL observations) prompted its usage as the water year analog. In general, both were anomalously dry years with below-average snowpacks and early melt timing. However, not yet determined is an objective methodology by which a given water year can be designated as a suitable analog. A large part of the predictive success discussed below regarding the use of 2012 data to forecast 2013 flow is owed to their striking similarity; in order for this type of analysis to be applied as a forecasting tool, future work must determine how and when a given water year can be compared to other WY during the period of record, such as at the time of peak snow accumulation or at the onset of widespread snowmelt. Additional work is needed to resolve this uncertainty.

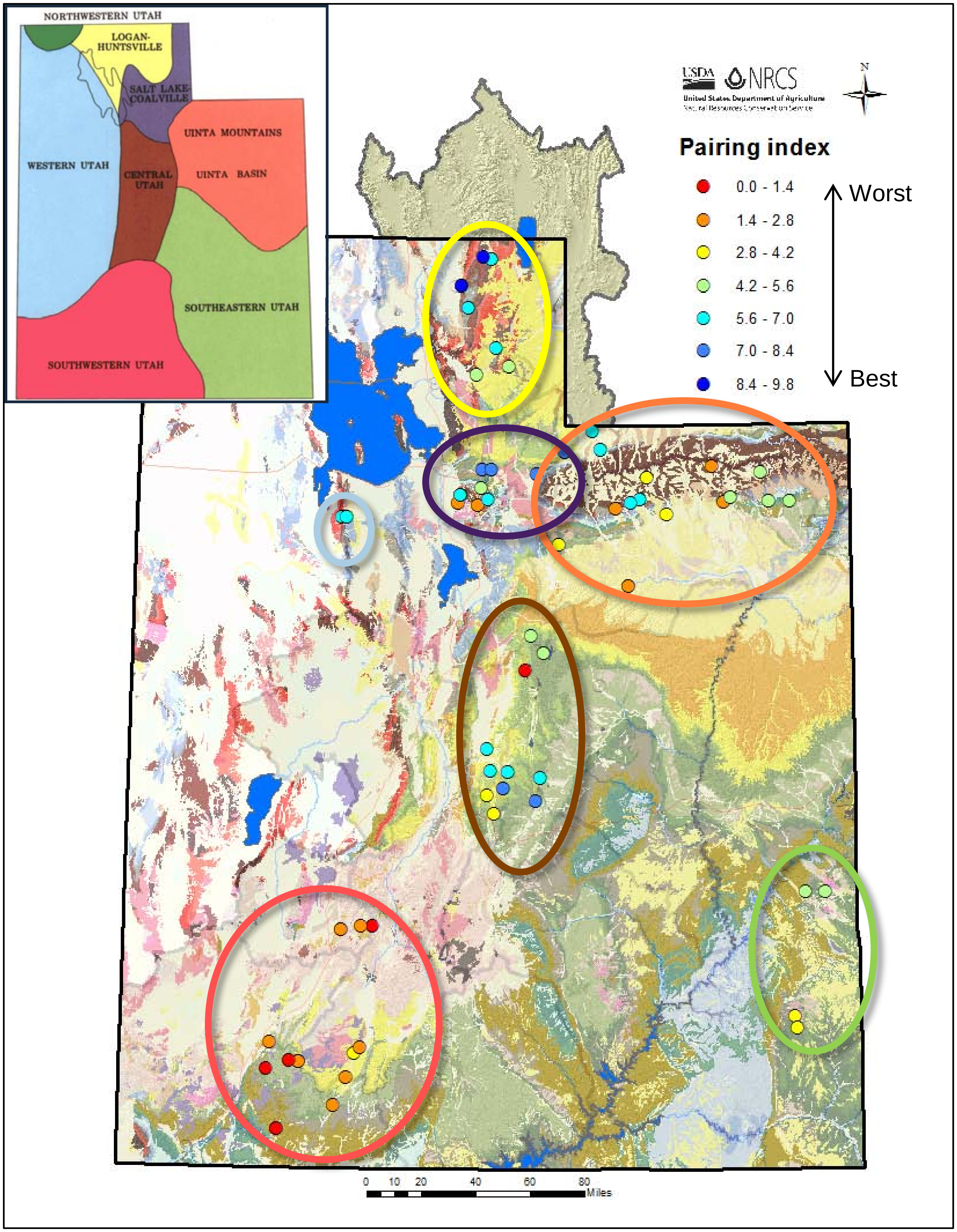

Figure 4. Quality of pairing index and association with general geology of Utah, where symbol colors are scaled according to the index value per pairing. Ovals define broad geologic regions of the state (see text for details) and are colored similarly to the inset map. Inset map and background GIS layer courtesy of Utah Geological Survey. ArcMap© was used for this figure.

To predict 2013 late-season streamflow (2), I created artificial "early" and "later" periods from the 2012 soil moisture-discharge pairings (Figure 5). This was accomplished by: (a) using the streamflow data from the beginning to the end dates of the 2012 analysis (see previous section for criteria for the onset and end dates of each year's analysis), (b) using the intersection of the best-fit regression lines for the "early" and "later" periods in 2012 to find the discharge at the transition point from predominantly recessional flow to baseflow. For the majority of cases where both regressions were linear, this was accomplished from the equation for the intersection of two lines (e.g. Fig 1B). For nonlinear cases, the intersection point was determined from graphical estimation. (c) Treating the flow recession portion of the hydrograph as the area of two triangles (for recession and baseflow), combining with the underlying baseflow (area of two rectangles), and integrating over time to calculate a flow volume (Figure 5). In essence, this allows for the prediction of flow volume from three data points: the discharge at the onset of the analysis, at the transition point, and at the end of a given water year's analysis. This greatly oversimplifies the recessional portion of the annual hydrograph but may provide a reasonable approximation of flow in many areas of the western U.S. where streams are most heavily influenced by the annual snowmelt pattern (as opposed to a less-predictable rainfall-generated pattern).

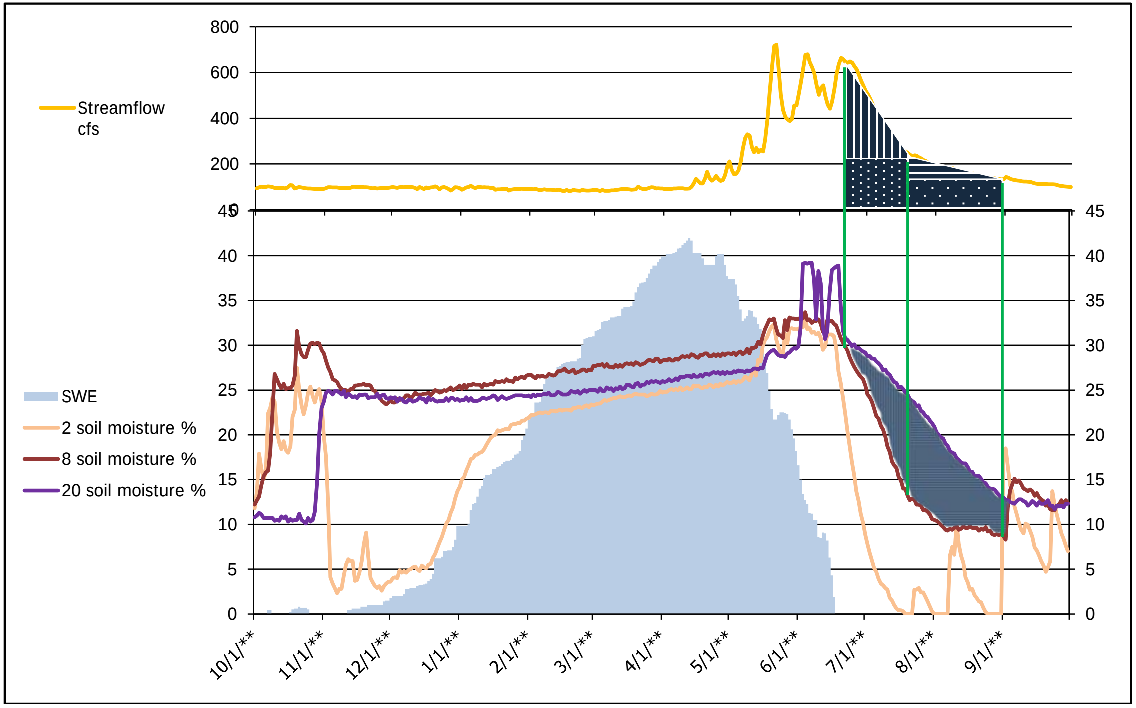

Figure 5. Example analog pairing data used to predict flow in similar water year. As for Figure 1A, soil moisture 2" data are given by the yellow curve, 8" data are the red curve, and 20" sensor data are the purple curve. Snow water equivalent data are represented by the light blue shaded area, and corresponding downstream flow are given in the upper panel. The dark blue shaded area represents the difference between the 20" and 8" soil moisture data and provides the bounds for the analysis. The onset, transition point, and end date for the analysis for these example data are shown with the vertical green lines. In the upper panel, the recessional flow and baseflow are quantified by using the triangles with vertical and horizontal lines, respectively, and the area represented by the underlying rectangles gives the remaining baseflow.

Comparison of predictions with the observed 2013 flow values (3) was straight-forward: observed daily discharge values were summed to obtain a flow volume from the time of peak discharge to the same end date as used in the analog water year (2012 in this case). Recessional flow and baseflow were differentiated from the observed break in slope in the annual hydrograph.

Figure 6 and Table 3 summarize the results of the attempt to predict 2013 flow from observed 2012 soil moisture and stream discharge data for all pairings. Of the 14 "good" pairings (pairing index ≥ 5.0, see Table 3), the mean percent difference between the predicted and observed 2013 flow was 30.8%, with a minimum, maximum, and standard deviation of 10.6%, 75.0%, and 20.1%, respectively. For the 20 "fair" to "poor" pairings (pairing index < 5.0), the mean percent difference between the predicted and observed 2013 flow was much higher (125.3%), with a minimum, maximum, and standard deviation of 3.9%, 751.0%, and 202.6%, respectively. The best-predicted pairings were: Five Points Lake SNOTEL vs Yellowstone River, Pickle Keg SNOTEL vs Salina Creek, Tony Grove Lake SNOTEL vs Logan River, Mining Fk SNOTEL vs S. Willow Creek, Dill's Camp SNOTEL vs Muddy Creek, and Brown Duck SNOTEL vs Lake Fork River. The least-reliable predictions were all in southeastern or southwestern Utah: Kolob SNOTEL vs N. Fk. Virgin River, Webster Flat SNOTEL vs. N. Fk. Virgin River, Lasal Mtn SNOTEL vs Mill Creek, and Camp Jackson SNOTEL vs Recapture Creek.

It follows that the same factors that improved the pairing index would be expected to allow for the most robust predictions of flow between water years for a given pairing. Figure 7 illustrates that, in general, as pairing index values increase, the predictive capability for a site's recession and baseflow improves, though this relationship is not statistically significant. Some of the variability shown in Fig. 7 is due to the fact that some pairings work best for normal water years, and others work best for wet or dry years; the test case used herein was for two anomalously dry years and therefore would not necessarily be expected to match all high-quality pairings.

In addition to predictions of flow volume, I also investigated whether other hydrological similarities existed between the 2012 and 2013 water years for all pairings. Most striking was the remarkable consistency in the timing of the soil moisture transition (in numbers of days) for the two water years (Figure 8). While this underscores the similarity between the 2012 and 2013 water years, it is worth noting that other comparisons in timing proved to be much less consistent, such as the timing of the peak discharge between the two water years (Figure 9). By the time of the soil moisture transition, however, discharge values were somewhat consistent between water years (Figure 10), reflecting the hydrologically-integrative effect of the soil moisture data. These graphs exclude tiny streams (e.g. Recapture Creek) where the percent change in flow between water years was too greatly exaggerated to be of value as well as several sites with bad 2013 soils data (Table 3).

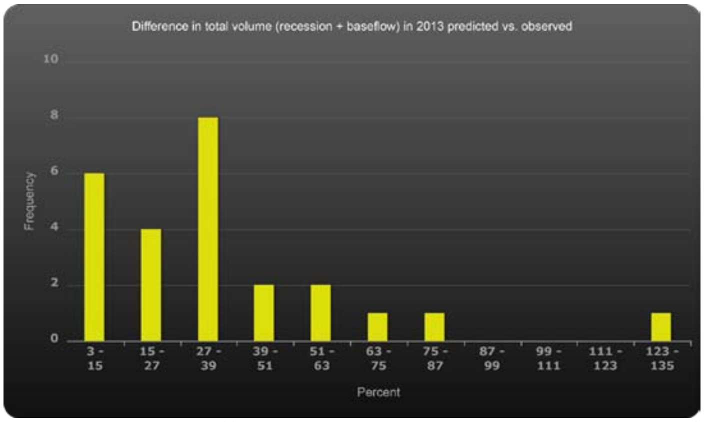

Figure 6. Percent difference in total volume (recession and baseflow) in 2013, predicted vs. observed.

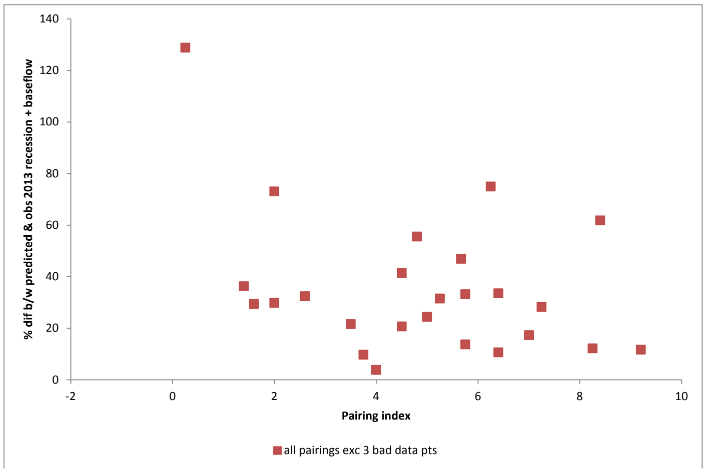

Figure 7. Pairing index versus percent difference between predicted and observed 2013 flow.

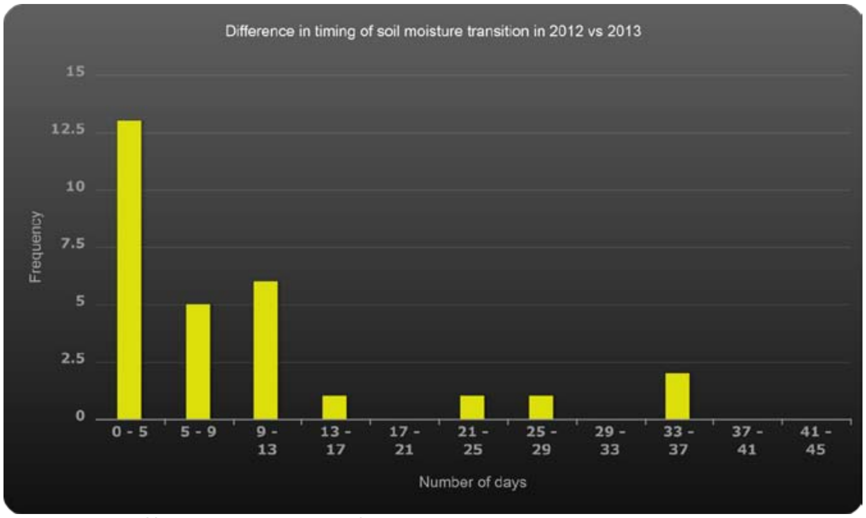

Figure 8. Difference in timing of soil moisture transition in 2012 vs 2013, in numbers of days.

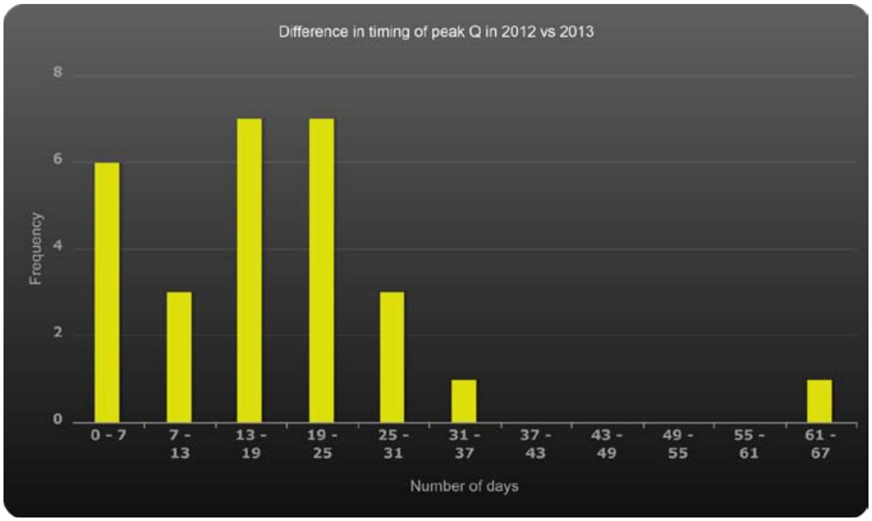

Figure 9. Difference in timing of peak discharge in 2012 vs 2013, in numbers of days.

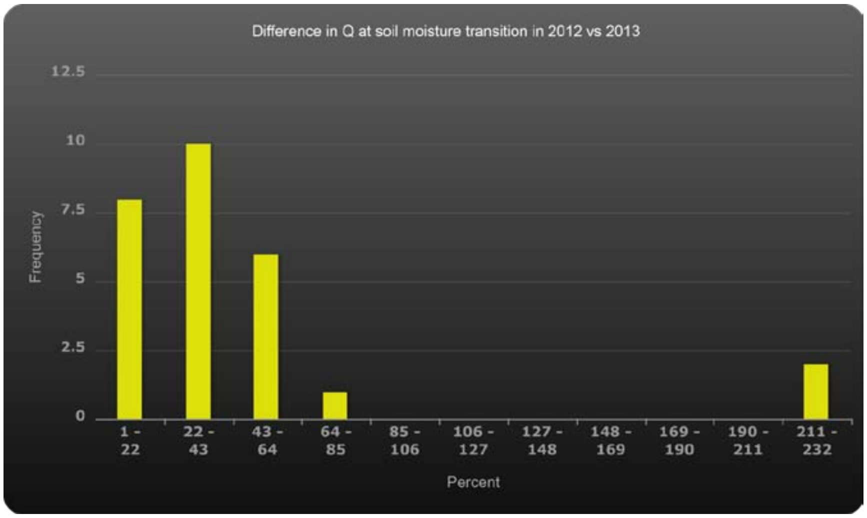

Figure 10. Percent difference in discharge at the time of the soil moisture transition at the SNOTEL site in 2012 vs 2013. Histograms generated using easycalculation.com.

CONCLUSIONS

This paper describes an effort to evaluate the teleconnections between high-elevation soil moisture and downstream discharge in Utah drainage basins, and to employ these relationships to develop predictions about late-season flow from analog water years. The main findings of this investigation can be summarized as follows:

(1) In most mountainous areas of Utah, the source of water for streams transitions from shallow (8") to deep (20") portions of upstream soils at a predictable time for a given type of water year, particularly for deeper soils with decent water holding ability. In some cases, the relationship between the soil moisture decline and downstream flow was very robust ($r^2 > 0.9$) - even for SNOTEL sites located far from respective stream gages (e.g. >20 mi, >3500' elevation difference for the best pairing). This analysis assumed that the majority of snowmelt enters into the soil instead of running off over the surface as overland flow, which is reasonable in these settings (Huth et al., 2004).

(2) In general, teleconnections were strongest (highest pairing index) where basins were underlain by sedimentary bedrock with fairly simple structural history, had deep soils with good infiltration potential and water holding capacity, and had streams that were perennial with minimal flow control structures and an annual hydrograph chiefly influenced by snowmelt.

(3) Recessional flow and baseflow volume can be predicted where soil moisture data are known. For "good" quality pairings, volumetric predictions were, on average, only around 30% different that observed values. This may aid in the development of water supply forecasts beyond the normal April-July timeframe, which has thus far been poorly predicted by widely-used models such as the Soil and Water Assessment Tool, or SWAT (Ahl et al., 2008).

(4) The timing of the soil moisture transition from predominant declines in near-surface soils (the "early" period) to declines in moisture from deeper portions of the soil profile (the "later period) occurs with remarkable consistency for similar water years. This underscores the value of using soil moisture data to characterize hydrologic conditions in the western U.S.

Future work should determine how far in advance one can sufficiently assess the similarity in water years in order to predict future recessional flow. It may be possible to combine snow water equivalent data from around the time of peak snowpacks (e.g. April 1) with antecedent soil moisture conditions (see Blankinship et al., 2014) at each SNOTEL site and seasonal climate predictions from the National Weather Service to develop a hydrologic index for this purpose. Another area of future work would be to apply this type of analysis to other western states, though for the time being this is made more challenging given the comparative lack of soil moisture data infrastructure in most other states. Alternatively, where pairings are robust (high pairing index, small difference between predicted and observed flow), it may be possible to extend this type of analysis to predict flow in nearby, ungaged watersheds in Utah, which, given the complexity of mountain terrains, would otherwise be challenging to model (Hartman et al., 1999; Fontaine et al., 2002). Finally, where soil moisture information exists but snow water equivalent data do not, it may be possible to use this or similar types of analysis to back-calculate snowpack conditions, similar to Brocca et al. (2013).

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