ESTIMATING SNOW WATER EQUIVALENT AT NWS CLIMATOLOGICAL STATIONS

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ABSTRACT

Typically, National Weather Service (NWS) Climatological Stations measure snow depth but not snow water equivalent (SWE). However, SWE is generally more important than depth when used in hydrologic and wildlife studies. Typically, there are higher elevation stations that measure SWE but lower elevations stations are predominately Climatological stations that do not measure SWE. New snowfall densities are generally between 6 and 10 percent while snow packs can reach densities into the 25 to 35 percent range just prior to and during melt. As part of developing the climatic database for the core area of the Greater Yellowstone Area (GYA), daily SWE was computed for all Climatological Stations. Some of these stations have snow courses at or near the station. Also, snow measurements were made at some of these stations in conjunction with the Snow Sinking Studies on the Northern Range of Yellowstone National Park. Methods for computing daily SWE using snow depth, precipitation and temperature will be presented as well as comparisons between estimated SWE and measured SWE at ten stations. The lengths of records where both measured and estimated SWE exist vary from about 17 years up to about 75 years. Long range trends of SWE will be shown for stations with longer records. (KEYWORDS: precipitation, snow water equivalent, density, snowmelt, temperature)

INTRODUCTION

SWE is a more significant parameter for analysis than is snow depth. New fallen snow may have a density of 5 to 10 percent so that 20 cm of snow depth may contain 10-20 mm of water content. The same depth of snow later in the season may have a density of 25-35 percent. This would yield about 50 to70 mm of water content. Maximum snow depth can occur on same day as maximum SWE or up to two to three months prior to maximum SWE. A decrease in snow depth does not always indicate snow melt but may just indicate settlement within the snow pack. A decrease in SWE does indicate snow melt. Estimating snow water equivalent for NWS Climatological Stations enables analysis of all data locations and elevations and provides data comparable to that from NRCS snow courses, snow pillows at NRCS SNOTEL sites and USBR Weather Stations. Procedures used to make daily estimates of SWE at NWS Climatological Stations is presented and compared to SWE that has been measured at nearby snow courses. Also, comparison was made between SWE measured with snow pillows and with that measured at snow courses for the same locations. Manual snow measurements with the Federal snow sampler over-measure the SWE and a correction factor has been applied to adjust the SWE to near "true" SWE (Farnes et al 1983). Prior to 1977, snow sampling sets throughout the West used standard Federal cutters. These measurements have been multiplied by 0.91 to estimate the "true" SWE. In 1977, Wyoming sharpened the cutters being used for Wyoming snow courses and since then, a correction factor of 0.94 has been applied to snow courses measured in Wyoming (Farnes et al., 2000). A correction was also applied for canopy cover at the snow courses (Codd, 1959). Canopy cover was measured at most of the snow courses in this area and was reported in the printed "Summary of Snow Survey Measurements for Montana and Northern Wyoming" dated Winter 1975 under remarks for individual snow courses (Farnes, 1971). Winter precipitation measurements at NWS Climatological stations can be affected by wind and gages generally under-measure "true" precipitation. Also, in colder environments, there are sublimation losses from the snowpack through the winter and this is accounted for in the manual measurements at the snow courses. These two factors are assumed to balance so that the estimated SWE based on gage catch would be comparable to snow course measurements adjusted for over sampling error and canopy interception. Melt is dependent on exposure and may be similar or quite different within short distances. For this analysis, snow accumulation has been separated from the melt phase since the Climatological Station may have a different exposure than at the snow course.

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METHODS

Snow Water Equivalent

NWS does not measure SWE at Climatological Stations. SWE was calculated at climatological stations using snow depth, precipitation and temperature (Farnes, 2012). A copy of this data is available from the NPS web site (see section on Data Bases). SWE was assumed to be zero if the snow depth was zero. If the average daily temperature (Tavg) was below 0 ^{0}C (32 ^{0} F) and snow depth was greater than zero, precipitation was accumulated and reported as SWE. The density was calculated as the SWE divided by the snow depth. If the density exceeded 35 percent, the SWE was adjusted since it is unlikely that undisturbed snow will exceed this level of density. In some cases, where it was apparent that the depth was recorded incorrectly, the snow depth was adjusted. This was common in the melt phase where there was a melt-out around the snow stake and the observer reported the depth at the bottom of the well rather than the depth of the surrounding snow. When Tavg exceeded 0 ^{0}C (32 ^{0} F), the melting degree-day was calculated as Tavg minus 0 ^{0}C (32 ^{0} F). Negative values were changed to zero. Melt rates based on SNOTEL stations in the area (Figure 1) can be calculated and this value used to determine daily melt which is then subtracted from the accumulated SWE (Farnes et al., 1999 and 2000). Melt rate can also be determined by using the maximum SWE plus any precipitation between the day of maximum SWE and melt-out divided by sum of degree-days above 0 ^{0}C (32 ^{0} F). Snowmelt-temperature relationships have been determined for some areas and this can also be used to estimate daily melt. In some cases where the snow depth was observed at the depression on the snow stake rather than at the true snow depth of the snowpack, it may be necessary to adjust snow depth observations or melt rates. When the snow depth becomes zero, the SWE was assumed to be zero. Wind at some sites can cause decreased precipitation catch, particularly if it is in the form of snow.

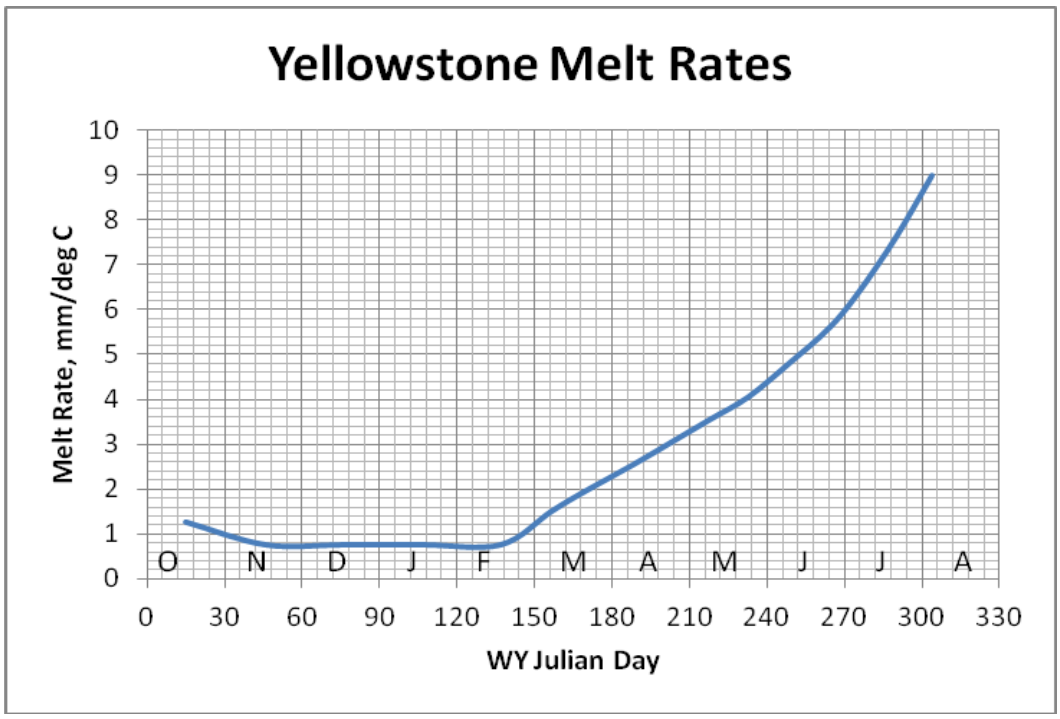

Figure 1. Temperature based snow melt rates derived from melt-temperature data at SNOTEL Stations in the Yellowstone National Park area.

Adjustments to Snow Course Data

Snow course measurements may be affected by type of snow sampling equipment used and the local environment at the snow course location. Standard Federal cutters were use in all of the Western states early in the Snow Survey Program. When snow pillows were first installed, they reported less SWE than was measured with the manual snow sampling equipment. The initial asumption was that the snow pillows were bridging and that the snow tube measurement had no error. However, field tests using snow pits showed the Federal Snow Sampler over-meaured the SWE. Further studies associated with the directive to switch to metric units quantified the measurement

accuracy of various kinds of snow tubes and cutters. (Farnes et al., 1983). Prior to 1977, snow sampling sets throughout the West used Standard Federal cutters. These measurements have been multiplied by 0.91 to estimate the "true" SWE. In 1977, Wyoming sharpened the cutters being used for Wyoming snow courses and since then, a correction factor of 0.94 has been applied to snow courses measured in Wyoming (Farnes et al., 2000). Montana continued to use the original version with the assumption that the corrections would be applied when measurements were changed to metric and cutters modified to measure "true" SWE. Presidential orders stopped the change to metric units.

A correction was also applied for canopy cover at the snow courses (Codd, 1959). Canopy cover was measured at most of the snow courses in this area and was reported in the printed "Summary of Snow Survey Measurements for Montana and Northern Wyoming" dated Winter 1975 under remarks for individual snow courses (Farnes, 1971). Typically, sampling points having tree canopy within a 30 degree cone from the vertical will have some interception of snow before it reaches the snow surface. Also, some snow courses are located on a slope. It is possible to adjust snow measurements for slope and aspect using Figure 2. The center represents level and flat areas. Lines represent correction factor. For example, the SWE at a site with a 20 degree slope and aspect of due south would have only 0.7 times (70%) the SWE of a flat level site in the same area. Sites used in this analysis were all located in relatively flat areas.

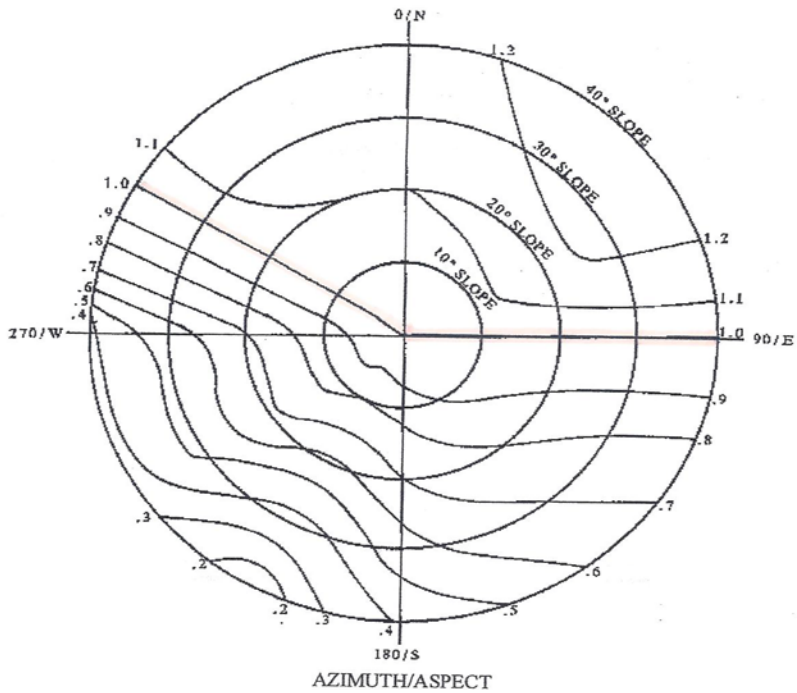

Figure 2. Adjustment for data sites that are not in level areas. Contour lines represent the ratio of SWE at an area with a given slope (represented by circles) and aspect (compass points) to SWE at a level location (center of the graph).

DATA BASE

Data for about 67 climate sites in the core of the Greater Yellowstone Area (GYA) have been made available to the public via NPS's IRMA web site (https://irma.nps.gov/App/reference/Profile/2192237). This includes NWS Climatological stations, NRCS SNOTEL sites and snow courses, USBR Weather Stations, and NPS recreation monitoring sites. Data was cleaned up and missing values estimated (Farnes 2012). Daily snow water equivalent (Table 1) was estimated for NWS Climatological Stations and was compared to manual snow measurements at the same locations. Stations with snow courses and Climatological Stations in this area are Lake Camp/Lake Yellowstone, Old Faithful, Moran/Moran 5WNW, Snake River Station/Snake River, West Yellowstone, Hebgen Dam, and Northeast Entrance. At four of these sites, snow pillows were established in the later years of the

record period. These were at Jackson Dam, Snake River Station, Northeast Entrance, and West Yellowstone. In addition, there were three locations where SWE was measured at Climatological Stations for the Snow Sinking Study (Farnes, 2008). These were at Lamar RS, Tower Falls, and Yellowstone Park (Mammoth), all in Yellowstone National Park.

Table 1. Daily data format used for all stations on Excel worksheet in GYA database available on the NPS website shown under the Data Base section.

Site Name: Yellowstone Park (Mammoth)

station id	mo	da	wy	wyd*	Tmin	tmax	tavg*
WY9905	03	12	2012	164	27	51	39
WY9905	03	13	2012	165	32	47	40
WY9905	03	14	2012	166	36	48	42
WY9905	03	15	2012	167	36	45	41
WY9905	03	16	2012	168	38	47	43

ppt	swe**	snwd	dens*	kbdi*	gdd*	agdd gra*	agdd tre*
0.03	2.3	8	29				
0.00	2.1	8	26				
0.02	1.5	5	30		1		
0.04	0.6	2	30				
0.08	0.0	0			2		

Note: All 16 columns of data are entered on one line on Excel spreadsheet (one day's data). *Value Added Data. **Value added data for Climatological Station but measured data for SNOTEL and USBR Stations.

SUMMARY

Comparison of snow depth at Climatological Stations and snow courses for three locations in the GYA is shown in Table 2. The average multiple correlation coefficient was 0.55 for 672 observations. Use of snow depths was a poor indicator of SWE. Estimated SWE at NWS Climatological Stations provided a better index of SWE that was measured at the snow courses than did the snow depth observations. The multiple correlation for 1412 observation at ten locations shows an R^2 of 0.87 for periods when snow was accumulating and an R^2 of 0.67 for 321 observations during melting periods (Table 3). West Yellowstone's lower correlation than the other stations may be partially the result of the Climatological Station being moved about six times over the period of record. SWE measured by snow pillows had the best correlation with adjusted SWE measured at snow courses. For 493 observations during accumulation and129 observations during melt, the R^2 was 0.94 (Table 4).

Trends for the past 113 years for Yellowstone Park (Mammoth), WY Climatological Station for the day that the snowpack started to accumulate, the day the accumulated snow pack melted, the maximum estimated SWE and the day the SWE was maximum for that year are shown in the four graphs in Figure 3. The snow has started to accumulate about four days later and has melted out about 21 days earlier over the past century. The maximum SWE has trended down from about 100 mm to about 55 mm since 1900. The day of maximum SWE has remained at about the same date for the past century. The elevation of this site is 1899 m.

Table 2. Comparison of snow depth observed at NWS Climatological Stations to the adjusted SWE measured at adjacent snow courses for the snow accumulation periods for three stations in the GYA.

Site Name	Number Obs.	R2 Accum.	Years			
Hebgen Dam MT	**275**	**0.41**	**1937-2012**			
Lake Yellowstone WY	**283**	**0.61**	**1936-2012**			
West Yellowstone MT	**114**	**0.62**	**1935-1966**			
TOTAL SNWD	**672**					
AVERAGE SNWD		**0.55**				

Table 3. Comparison of SWE estimated from NWS Climatological Station data to adjusted SWE measured at nearby snow courses and observations made during the Snow Sinking Study in the GYA.

Site Name	Number Obs.	R^2 Accum.	Years	Number Obs.	R^2 Melt	Years
NWS STATIONS						
Hebgen Dam MT	275	.84	1937-2012	102	.645	1937-2012
Lake Yellowstone WY	283	.89	1936-2012	68	.49	1936-2012
Moran 5WNW WY	154	.86	1949-1989	12	.86	1949-2012
Northeast Entrance MT	68	.85	1949-1966	21	.53	1949-1966
Old Faithful WY	99	.88	1979-2012	62	.65	1979-2012
Snake River Station WY	232	.92	1933-1989	17	.82	1933-1989
West Yellowstone MT	117	.73	1935-1966	39	.70	1935-1966
TOTAL NWS	1228			321		
AVERAGE NWS		.85			.67	
SNOW SINKING STUDY						
Lamar RS WY	51	.90	1992-2008			
Tower Falls WY	50	.88	1992-2008			
Yellowstone Park (Mammoth) WY	83	.91	1992-2008			
TOTAL SSS	184					
AVERAGE SSS		.90				
TOTAL CLIM vs SC	1412			321		
AVERAGE CLIM vs SC		.87			.67	

Trends for the past 109 years for LakeYellowstone, WY Climatological Station for estimated SWE and day snowpack started to accumulate, the day the accumulated snow pack melted, and the day the SWE was maximum for that year are shown in the four graphs in Figure 4. The snow has started to accumulate about nine days earlier and has melted out about 3 days earlier over the past century. The maximum SWE and the day of maximum SWE have remained about the same for the past century. The elevation of this site is 2368 m.

Table 4. Comparison of SWE observed at NRCS SNOTEL stations to adjusted SWE measured at adjacent snow courses in GYA.

Site Name	Number Obs.	R^2 Accum.	Years	Number Obs.	R^2 Melt	Years
Moran WY 10 ft Pillow	74	.93	1990-2012	17	.83	1990-2012
Northeast Entrance MT 6 ft Pillow	125	.90	1967-1996	43	.94	1937-1996
Northeast Entrance MT 10 ft Pillow	35	.94	1997-2012	8	.96	1997-2012
Snake River Station WY 10 ft Pillow	88	.98	1990-2012	3	.99	1990-2012
West Yellowstone MT 6 ft Pillow	114	.95	1967-1997	42	.92	1967-1997
West Yellowstone MT 10 ft Pillow	57	.94	1998-2012	16	.98	1998-2012
TOTAL PILLOWS	493			129		
AVERAGE PILLOWS		.94			.94	

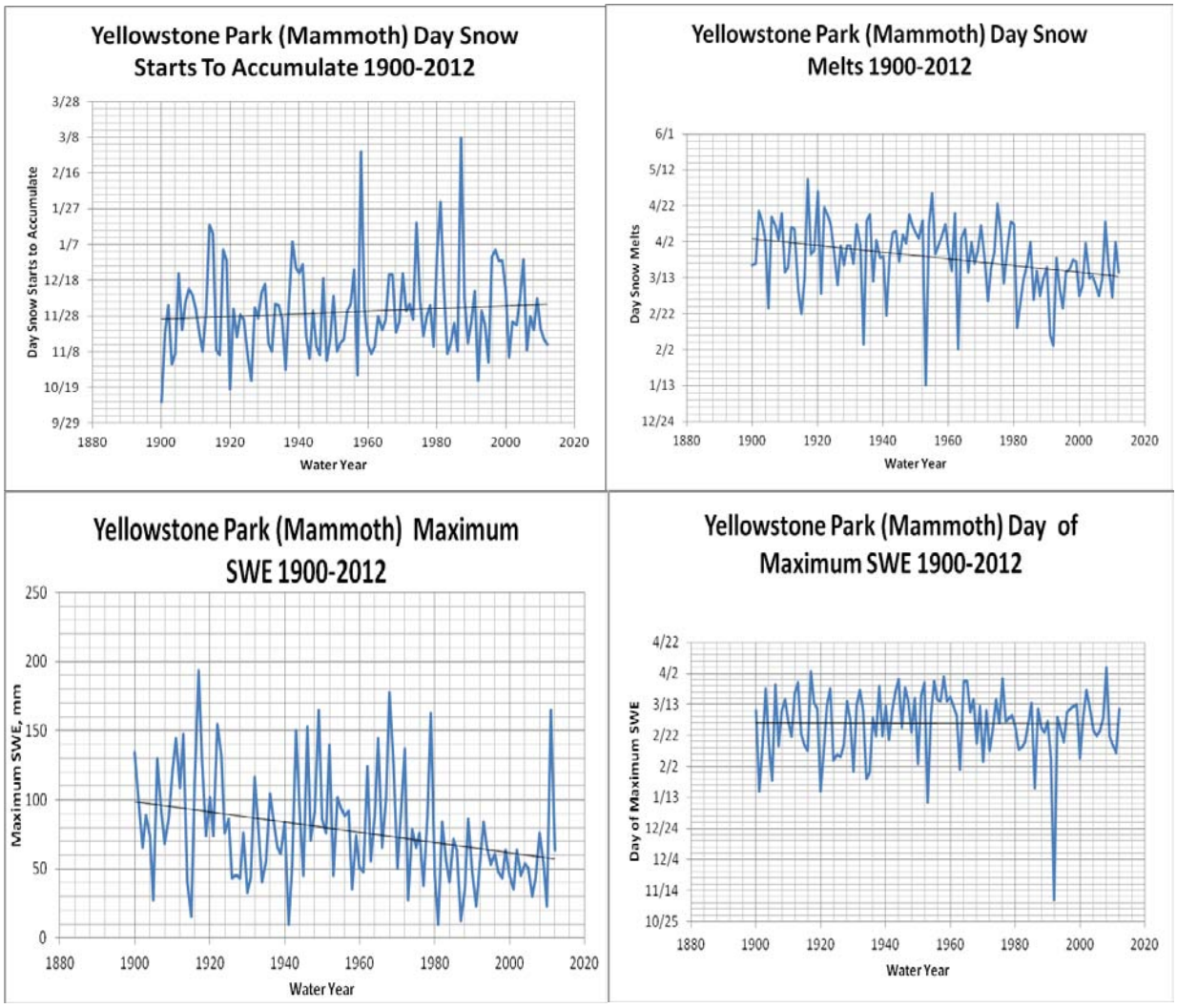

Figure 3. Long-term trends of the day snow starts, when the snow ends, the maximum estimated SWE and the day of maximum estimated SWE for the Yellowstone Park (Mammoth), WY Climatological Station.

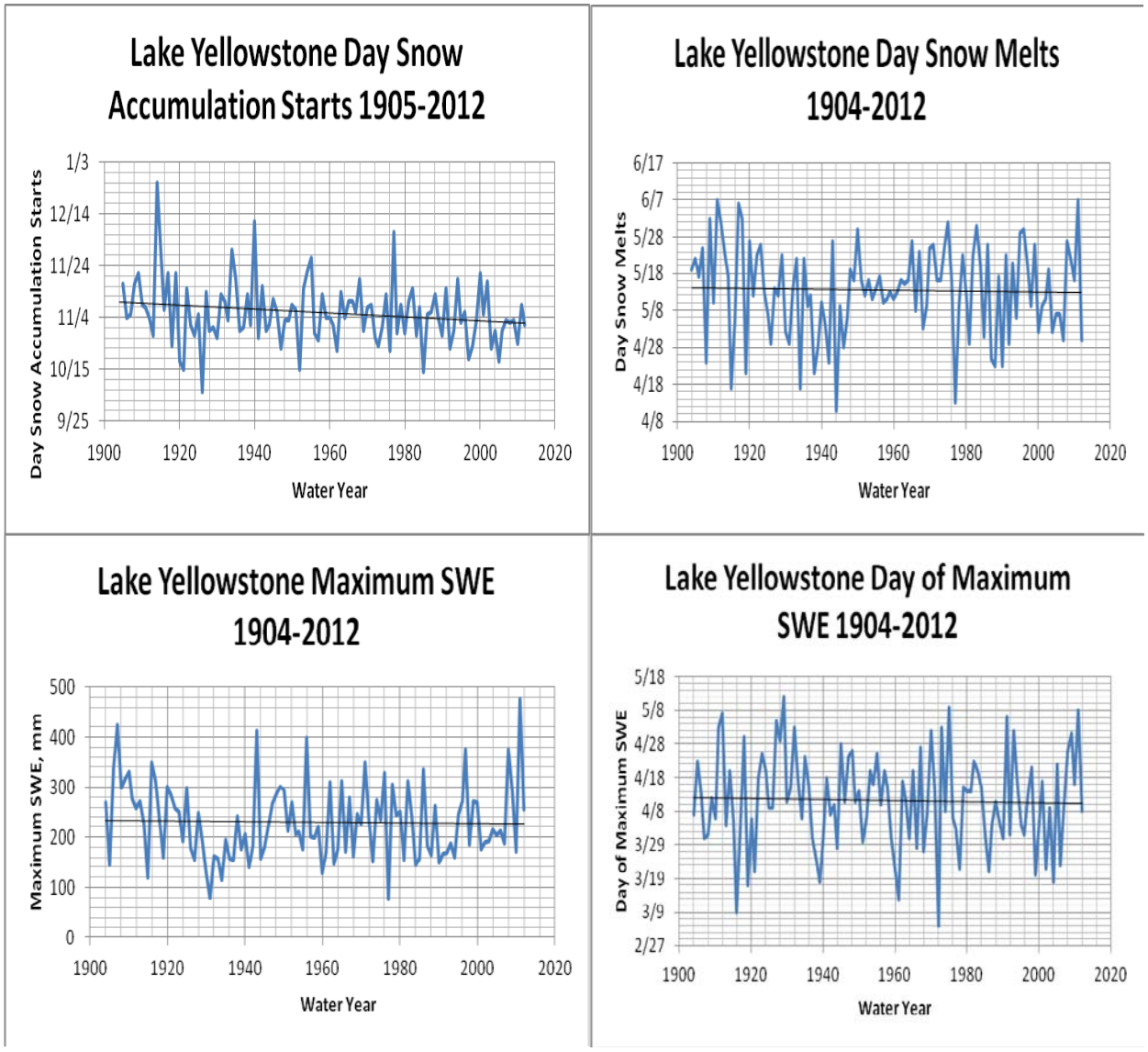

Figure 4. Long-term trends of the day snow starts, when the snow ends, the maximum estimated SWE and the day of maximum SWE for the estimated SWE at the Lake Yellowstone, WY Climatological Station.

Figure 5 shows graphs of the long-term trends of estimated maximum SWE at four Climatological Stations in the GYA. The Moran 5WNW Station shows a slight decrease in SWE over the past 60 years. The station is at elevation 2072 m. At the Snake River Station, SWE has increased about 9 percent over 80 years. Elevation of the Snake River Station is 2109 m. Hebgen Dam shows about a 40 percent increase in SWE over nearly a century. The station is at elevation 1978 m. The West Yellowstone Climatological Station shows about 40 percent increase in SWE over the past 87 years. The West Yellowstone Climatological Station is at elevation 2029 m.

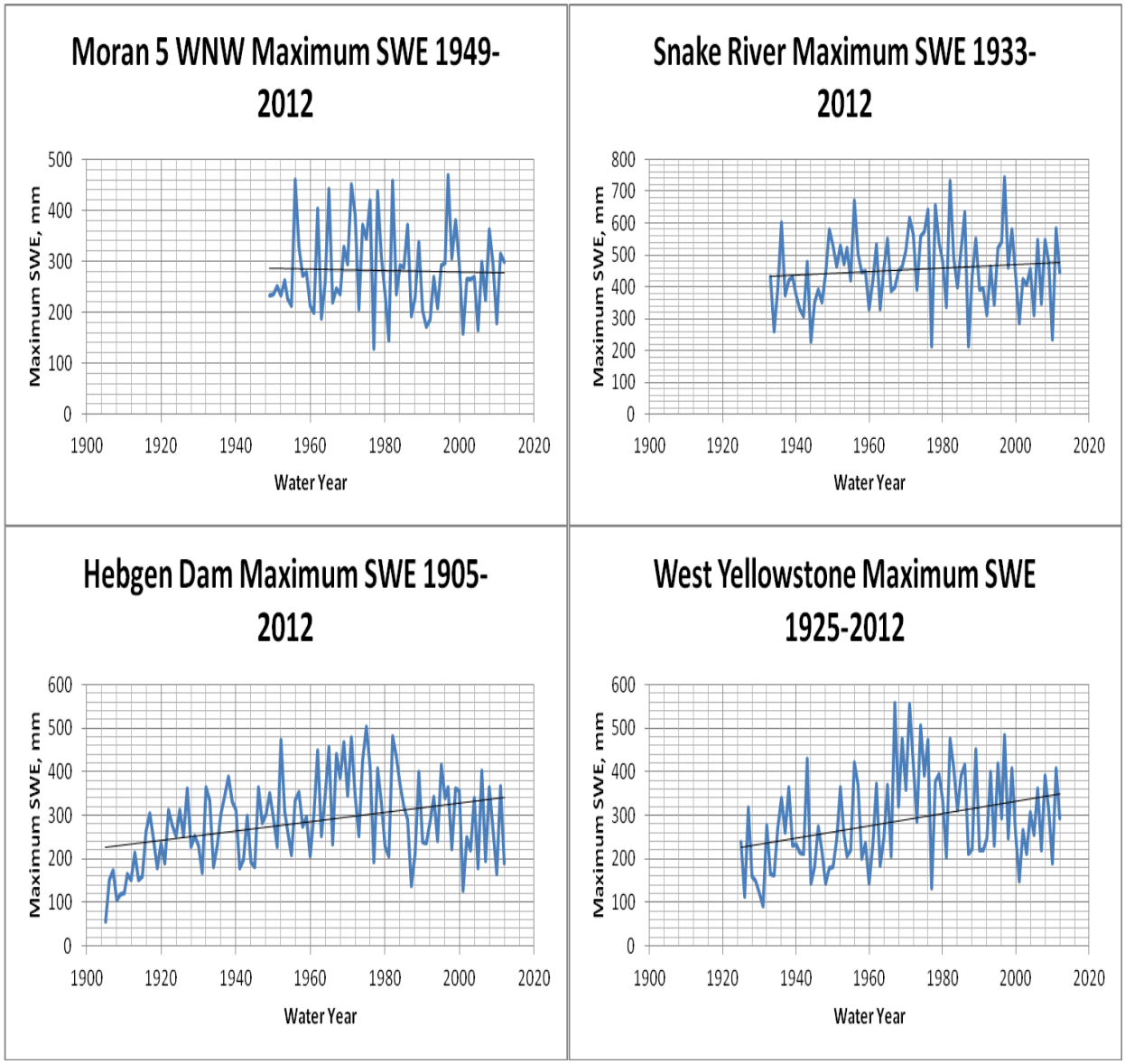

Figure 5. Long-term trends of maximum SWE for four of the Climatological Stations in greater Yellowstone Area where SWE was estimated using daily snow depth, temperature, and precipitation data.

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