Quantification Of Snowmelt-induced Streamflow Within The Smith River Watershed, Montana, Using A Water Balance Analysis

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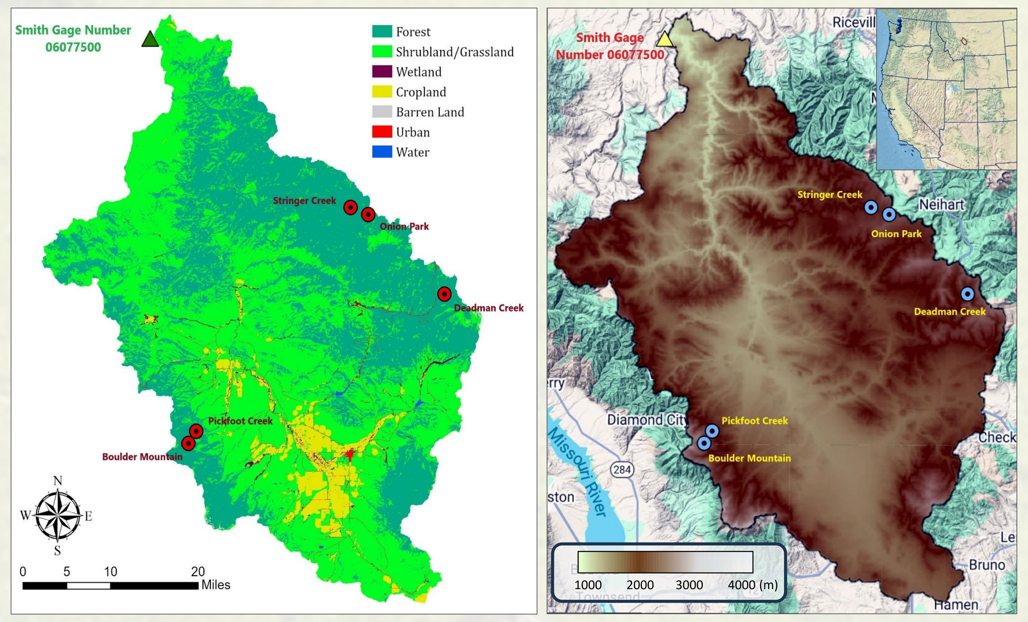
Motivation and Background

- Regional water supply in the western United States heavily relies on seasonal snowpack and meltwater.
- A better understanding of regional water balance in a snow-dominant watershed, particularly the contribution of snowmelt to streamflow, can provide valuable insights into quantifying available water resources.
- Previous studies have utilized numerous methods to quantify snow-generated streamflow. However, there is yet some uncertainty regarding the fate of solid precipitation on land. To estimate the snowmelt portion of runoff:
  - Barnett et al. (2005), and Kapnick and Delworth (2013) used Snowfall/Total Runoff.
  - Serreze et al. (1999) used SWE/ Precipitation.
  - Doesken and Judson (1996), and Kapnick and Delworth (2013) used Snowfall/Total Precipitation.
  - Mankin et al. (2015) used Snowmelt/Total Precipitation
  - Stewart et al. (2004) used Melt season runoff/ Total runoff
  - Li et al. (2017) used hydrologic model simulations and snowmelt tracking algorithms.
- To estimate the amount of snowmelt-induced streamflow, this study utilizes modeled and ground observation variables for its calculation, and addresses the following research objectives:
  - 1. Explore the water balance within the watershed
  - 2. Explore the uncertainty of snowmelt runoff using only two variables
  - 3. Quantify streamflow resulting from snowmelt using relevant variables from the water balance

Study Area



- Study Area: Conducted in the Smith River Watershed, Montana, USA, for a five-year period of October 1, 2016, to September 30, 2021 (WY2017 - WY2021)
  - The watershed was delineated based on a USGS gage (06077500) near Eden, Montana, and spans an area of 4112.6 sq. km or 1587.9 sq. miles.

Data

Dataset	Resolution	Variables used	Relevant information
Western Land Data Assimilation System (**WLDAS**)	1 x 1 km	Precipitation, Groundwater storage, Soil Moisture, Evapotranspiration	Noah-MP forced by NLDAS-2
Snow Data Assimilation System (**SNODAS**)	1 x 1 km	SWE, Sublimation	Modeling data assimilation system developed by NOHRSC
United States Geological Survey gage (**USGS**)	-	Streamflow	Ground observation gages
Landsat-based irrigation reanalysis dataset (**LANID**)	HUC12	Irrigation water usage	Utilizes OpenET/SSEBop to calculate Eta, Eto, irrigated areas, consumptive use, and effective precipitation

Result 1: Regional Water Balance

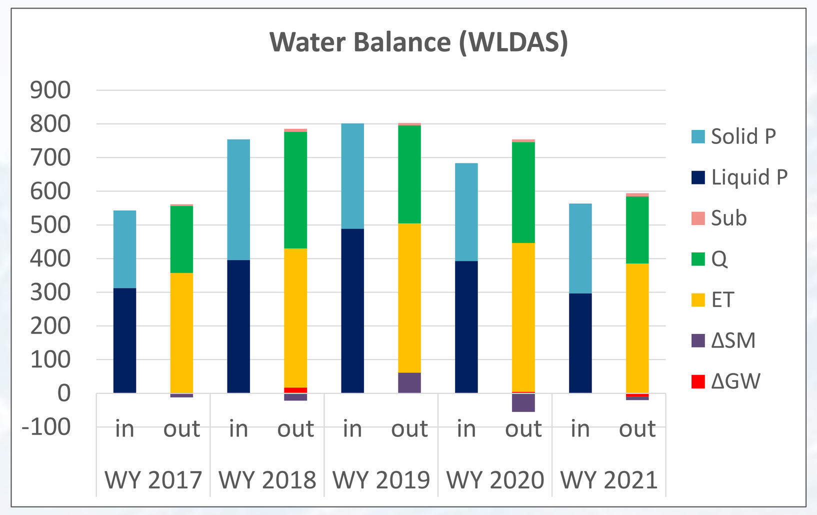
- We generated a water balance table comparing the values of modelled and ground observation variables, namely Precipitation (*P*), Evapotranspiration (*ET*), Sublimation (*Sub*), Groundwater Storage (*ΔGW*), Soil Moisture (*ΔSM*), and Streamflow (*Q*)

1. **WLDAS watershed-averaged water balance**

- **Method:** The following formula was used for the water balance: *P (in) = ET + Sub + ΔGW + ΔSM + Q (out)*

WY	Solid P	Liquid P	Total P	ET	Sub	ΔGW	ΔSM	Q	Difference (in - out)
WY 2017	230	312	543	356	5	2	-12	199	-7
WY 2018	359	395	754	413	9	17	-22	346	-9
WY 2019	313	489	802	443	7	0	61	291	0
WY 2020	291	393	684	443	8	4	-55	300	-16
WY 2021	267	297	564	385	10	-11	-9	199	-10

(All values in mm)



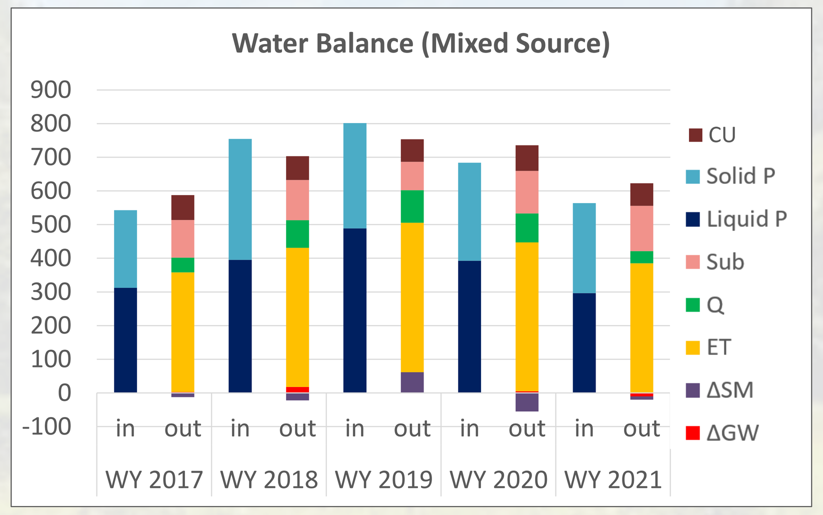
2. Mixed Source and Consumptive Use watershed-averaged water balance

- We used modeled SNODAS sublimation (*Sub*), USGS gage streamflow (*Q*), and LANID irrigation consumptive use (*CU*) values for this water balance version. The rest of the variables were derived from WLDAS

- **Method**: Mixed source formula: *P (in) = ET + Sub + ΔGW + ΔSM + Q + CU (out)*

WY	Solid P	Liquid P	Total P	ET	Sub	ΔGW	ΔSM	Q	CU	Difference (in - out)
WY 2017	230	312	543	356	112	2	-12	44	75	-33
WY 2018	359	395	754	413	119	17	-22	82	71	74
WY 2019	313	489	802	443	84	0	61	97	67	49
WY 2020	291	393	684	443	126	4	-55	86	75	4
WY 2021	267	297	564	385	134	-11	-9	36	67	-39

(All values in mm)



Sources: WLDAS - Precipitation, ET, ΔGroundwater Storage, Δ Soil Moisture;
SNODAS – Sublimation;
USGS,- Streamflow;
LANID: Irrigation use

3. Sublimation value uncertainty

- WLDAS and SNODAS sublimation values vary significantly over the analysis period. So, we compared annually accumulated SWE values to sublimation values for each dataset.
- The amount of snow sublimated from the snowpack averaged at 5% per year for WLDAS, while SNODAS sublimation averaged at 38% per year during WY2017- 2021

WY	WLDAS SWE	WLDAS sublimation	% Sublimated
WY 2017	112	5	5%
WY 2018	210	9	4%
WY 2019	208	7	3%
WY 2020	193	8	4%
WY 2021	165	10	6%

WY	SNODAS SWE	SNODAS sublimation	% Sublimated
WY 2017	301	112	37%
WY 2018	476	119	25%
WY 2019	313	84	27%
WY 2020	270	126	47%
WY 2021	237	134	56%

(All values in mm)

Result 2: Snowmelt Runoff Estimation Using Prior Methods

- We used methods employed by researchers mentioned in the background section, to get an estimate of the amount of snow-driven streamflow in the watershed.
- The results are based on watershed-averaged values of the variables used in each calculation
- Method:

Used by	Method	Result (avg WY2017-21)
Mankin et al. (2015)	Snowmelt/Total Precipitation	31%
Doesken and Judson (1996), and Kapnick and Delworth (2013)	Snowfall/Total Precipitation	44%
Serreze et al. (1999)	SWE/ Precipitation	48%
Stewart et al. (2004)	Melt Season Runoff/Total Runoff	68%
Barnett et al. (2005), Kapnick and Delworth (2013)	Snowfall/Total Runoff	472% *

* The result reflects extremely high values for each year due to WLDAS snowfall output being consistently larger than USGS streamflow values

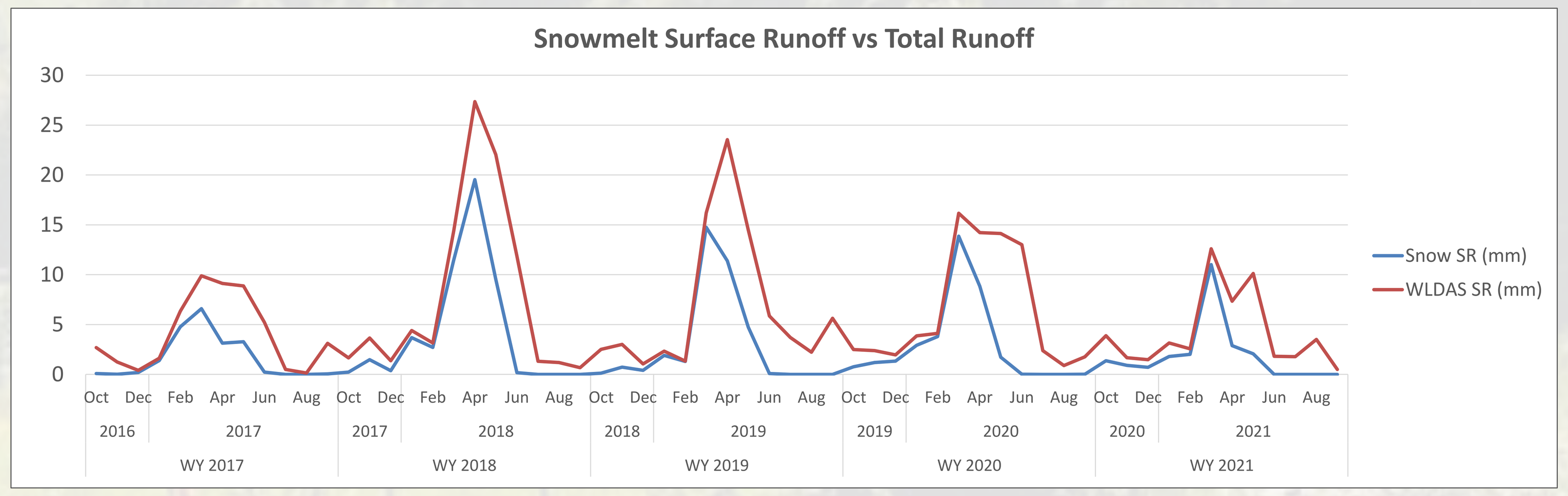
Source
SNODAS: SWE
WLDAS: solid and liquid precipitation, snowmelt, streamflow
Eden gage: streamflow

Result 3: Estimating Snow-Generated Surface Runoff

- We followed the methodology of Li et al. (2017) to partition snowmelt-induced surface runoff (**SR**) and subsurface runoff (**SubSR**) from rain-generated runoff.

Method:
- Formula to estimate snow contribution to total runoff: $\frac{Snow\ SR + Snow\ SubR}{SR + SubSR}$
- To calculate snow surface runoff per pixel, we calculated total infiltration *(i)* for each pixel in the watershed using $i = Melt + Rain - SR$
- Assuming that snowmelt and rain exhibit identical infiltration and runoff ratios, we calculate the fraction of snowmelt infiltration using the ratio of $melt$ to the total water available: $f_{snow} = \frac{Melt}{Melt + Rain}$
- We then calculate snow-generated surface runoff ($Snow\ SR$) per pixel in the watershed by subtracting snow infiltration from melt: $Snow\ SR = Melt - (i * f_{snow})$
- On average, snow surface runoff was estimated to be 32 mm per year, accounting for roughly 45% of total surface runoff per year. Calculations for snow subsurface runoff are yet to be completed

WY	Snow SR (mm)
WY 2017	20
WY 2018	49
WY 2019	35
WY 2020	35
WY 2021	23



Key Takeaways:

Result 1: Sublimation, Δ groundwater, and Δ soil moisture change, along with irrigation water use, are important variables required to track the water balance and fate of snow. WLDAS sublimation and streamflow values vary significantly compared to those of SNODAS sublimation and USGS streamflow

Result 2:. The contribution of snowpack to streamflow reasonably ranges from 31% to 68% in this watershed, displaying the uncertainty of using only two variables for snowmelt runoff calculation

Result 3: Snowmelt accounts for roughly 45% for surface runoff within the Smith River Watershed for the analysis period of WY2017- WY2021

Future Scope

- We will quantify snowmelt-driven subsurface runoff values per pixel within the watershed, based on the calculations provided by Li et al. (2017)
- SnowModel output variables (references) will be compared with SWE, sublimation, and snowmelt variables generated by WLDAS (Noah-MP) to verify their reliability.
- A separate analysis comparing SWE outputs from WLDAS, SNODAS, University of Arizona (UA), Western United States Snow Reanalysis (WUS-SR), and Snow Telemetry (SNOTEL) datasets will be done to assess model performance within the watershed.

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