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HydrologicTrends inthe Sacred Valley of the Incas

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Hydrologic Trends in the Sacred Valley of the Incas

A Water Balance Analysis of Cusco & Implications for National Water Management/Scarcity Studies in the Andean Highlands of Peru

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INTRODUCTION & BACKGROUND

Through 2018-2019, the University of Louisville International Service Learning Program sent teams of students & faculty to the Vilcanota-Urubamba basin of Peru (the Incan "Sacred Valley"), to assist with water resource management and mapping flow losses from decaying irrigation infrastructure. Additional issues with water availability were noted. Farmers in the region had reported insufficient rains towards the end of the wet season. Some also reported shifting climate with more rain than usual during planting season at colder times preventing germination in some cases, as well as traditional freeze-drying practices.

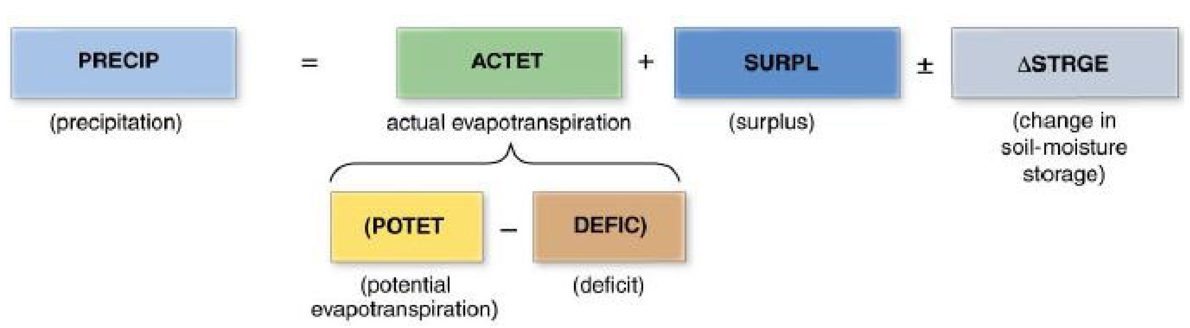
In 2019 the government of Peru (Autoridad Nacional del Agua) was provided several multi million dollar loans from the World Bank to mitigate water issues, including water resource management and establishing a monitoring system to allow data driven changes in management to prevent crop loss. The World Bank estimated the investment to avoid 281,000 tons of agricultural produce loss from the Vilcanota-Urubamba watershed in Cusco- however this estimate was likely based on wider scale data than the local level where loss would be experienced. Many steps to procure needed data to inform solutions remain unclear. Particularly, differences in trends at regional scale vs local scale in the area are in need of investigation. Regional trends within the Urubamba may prioritize study of certain watershed over others, however, management decisions are only possible at the local scale since most farms are small plots of land fed by rainfall high in the valley.

METHODS OF ANALYSIS

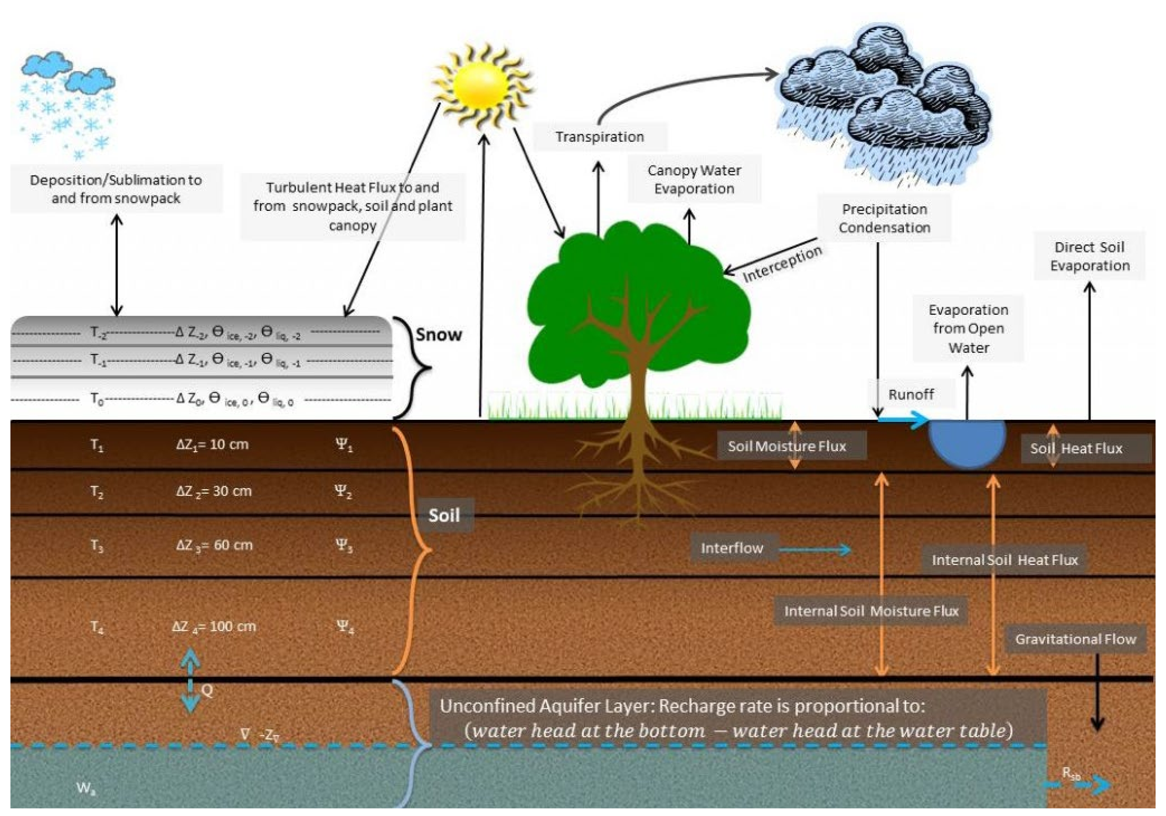
This work conducted a pilot study to identify differences between local and regional water balance trends using best-available data, and potential applications of results. Local analysis required interpolation of limited weather gage data, and estimation of total available soil water to plants (TAW). Three estimates were used based on typical total soil moisture according to literature, and also percent of total moisture typically available to plants based on soil type in the region.

Local Analysis

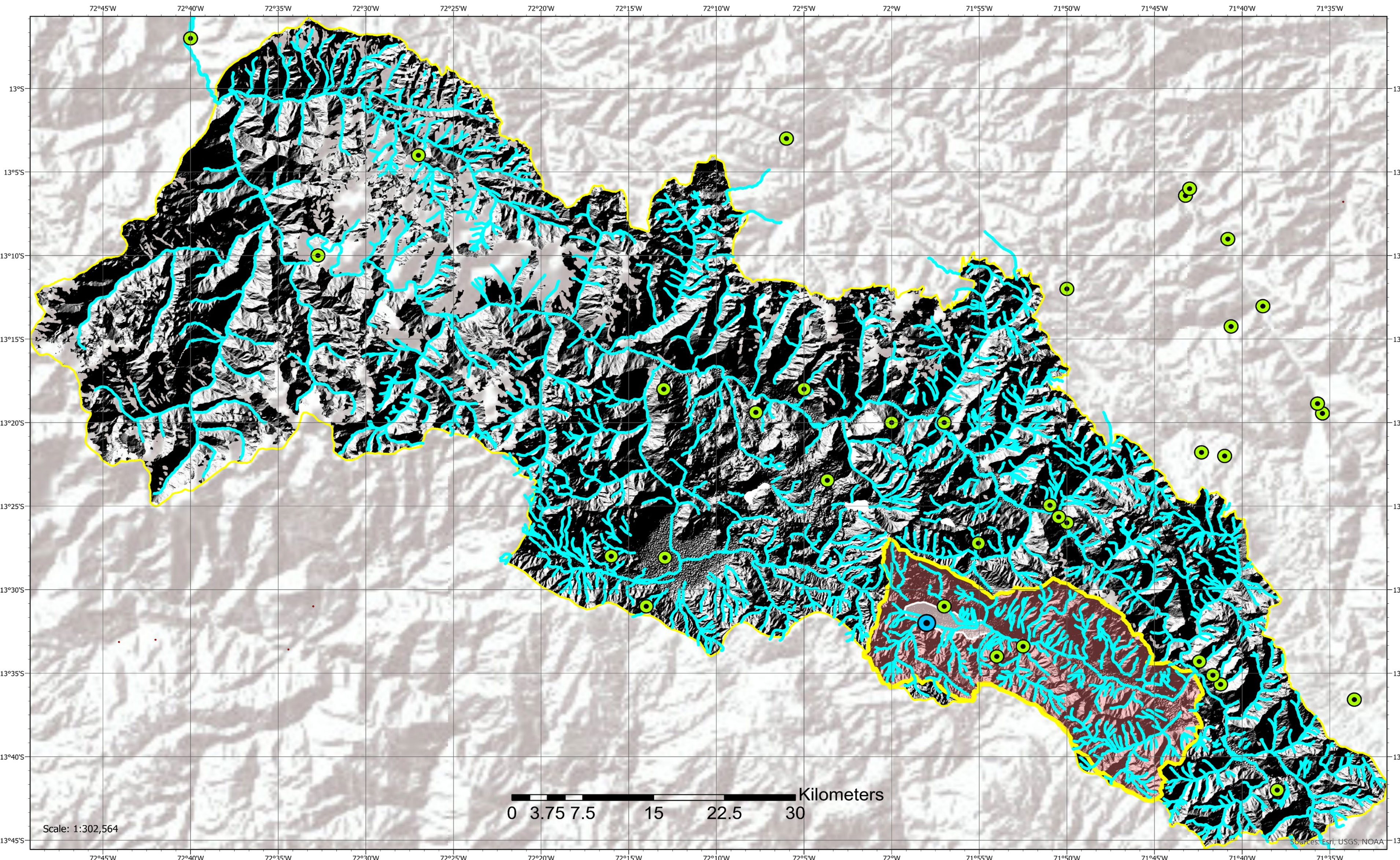
To determine any local trends, temperature and precipitation data were downloaded from the Cusco Airport weather station, accessed through NOAA, for import into the CRAN Thornthwaite Water Balance Package in R (R Core Team, 2017). The components of the water balance are shown below. Note that total available water estimates do not effect precipitation or potential evapotranspiration in the model.



Regional Analysis



To determine trends at the regional scale, remotely sensed data were acquired from the ESRI Water Balance App, with the indicated location for data retrieval directly above the Cusco Airport weather station used for local analysis. ESRI data are derived from pixels of NASA's GLDAS – 2.1 dataset, and have a maximum resolution area at 30km ^2. The basin in Cusco captured by this area is plotted the remotely sensed watershed in the adjacent map. For water balance calculation, the NOAH land surface model (above) is used to estimate what amount of sensed precipitation becomes runoff, evaporation, or infiltrates soil.



VILCANOTA - URUBAMBA WATERSHED

SACRED VALLEY REGION . NORTH OF SICUANI SUBBASIN

CUSCO . PERU

N

Legend

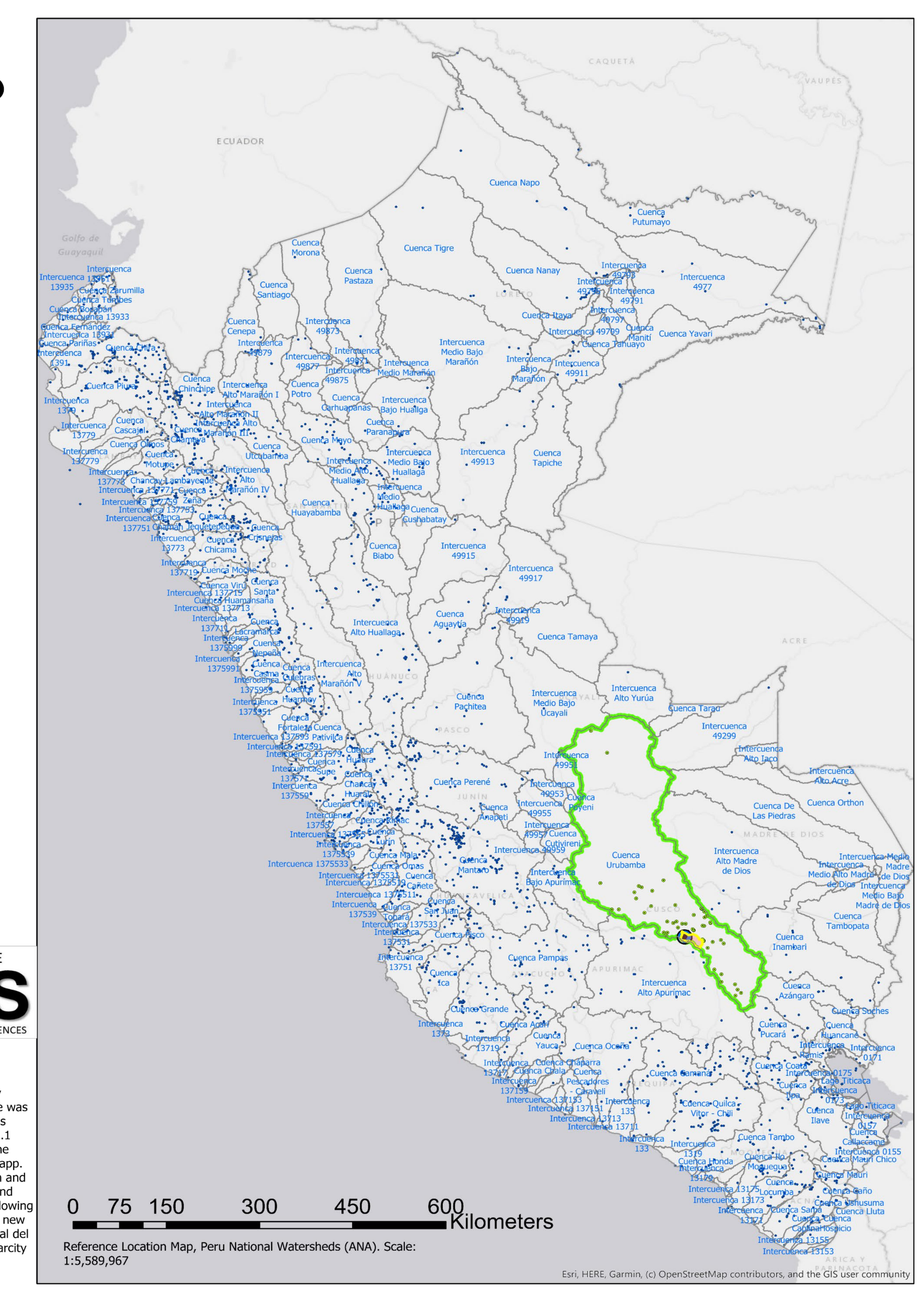
Cusco Remotely Sensed Basin (ESRI)
0
Cusco Local Rain Gage
0
Cusco Hydrometeorological Station
Other Hydrometeorological Stations in the Urubamba (ANA)
Sacred Valley/Vilcanota-Urubamba Sub-basin
Streams
Urubamba Watershed
Other Hydrometeorological Stations in Peru (ANA)
Peru National Watersheds

Spatial Reference
Name: GCS WGS 1984
GCS: GCS WGS 1984
Datum: WGS 1984
Page units Degree

Cartography by Samuel C. Kessler. Feature data source obtained via 'Geo GPS Peru' database at geogpsperu.com, derived from the Peru National Water Authority.

Description:

The above Vilcanota - Urubamba watershed (VAB) was delineated by tracing a digital elevation model in GoogleEarth, whereafter a kml file was exported into ESRI ArcGISPro. The Cusco Remotely Sensed Basin was identified by delineating the smallest basin within the NASA GLDAS-2.1 imagery over the Alejandro Velasco Astete airport weather station, the primary datasource for the computations of the ESRI Water Balance app. The VAB is located in the Urubamba watershed, between the Eastern and Central Andes in the region of Cusco, and has complex topography and hydroclimatology. The basin elevation range is 1180-5443 asl, river flowing northward. This region has been identified for the implementaiton of new water resource management plans by the Peruvian Autoridad Nacional del Agua in order to mitigate the effects of shifting climate and water scarcity with prolonged drought. Much of the area is depent on rain-fed and irrigated agriculture.



Reference Location Map, Peru National Watersheds (ANA). Scale: 1:5,589,967

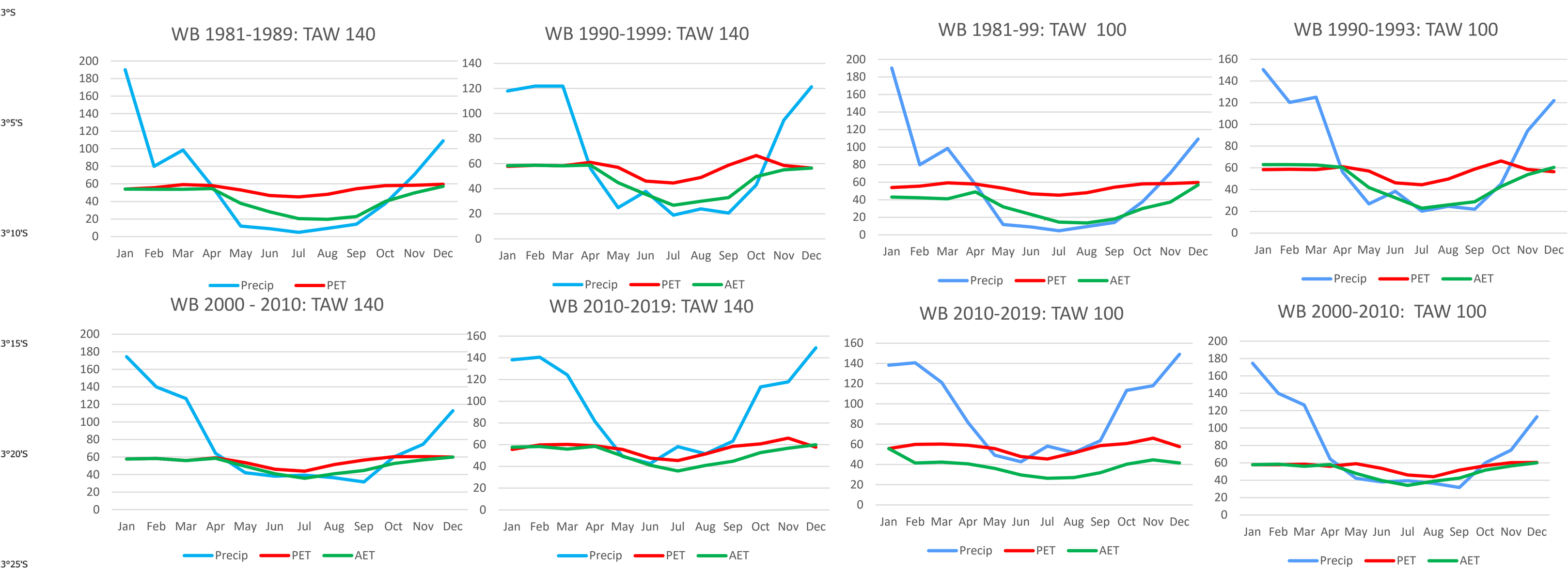
Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community

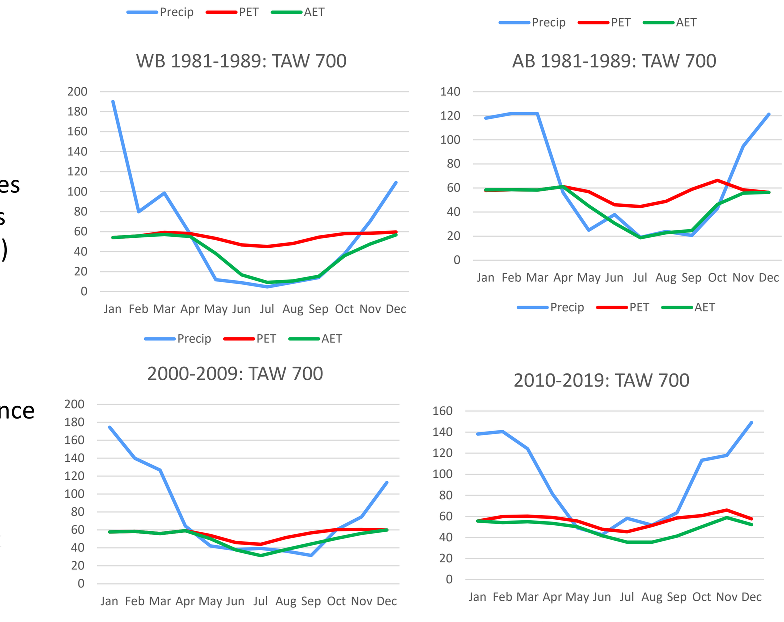
Tables 1: Mann Kendall Trend Analysis (RStudio):
Cusco Remotely Sensed Basin (Left/Below), Cusco Hydrometeorological Station (Right)- values for TAW 140 water balance are highlighted as this exhibited the greatest amount of significant values (bolded).

Mann Kendall – ESRI Data	January	February	March	April	May	June	July	August	September	October	November	December
Runoff (p)	0.097994	0.074048	0.010374	0.006396	0.0033359	0.0014052	0.00056989	0.003673	0.0062408	0.00046544	0.0052435	0.43594
tau	-0.274	-0.296	**-0.421**	-0.449	-0.488	-0.531	-0.58	-0.494	-0.587	-0.587	-0.459	-0.132
Storage	0.82034	1	0.25614	0.059733	0.82015	0.0793	0.81997	0.62528	0.31299	0.21673	0.091413	0.89658
	0.0421	0	-0.189	0.311	0.0423	-0.292	-0.0426	-0.0856	-0.171	-0.207	0.28	0.0265
Soil Moisture	0.04757	0.068699	0.006396	0.0034489	0.0016304	0.0010369	0.0025502	0.0013028	0.0037957	0.00014706	0.0013182	0.2984
	-0.328	-0.302	**-0.449,**	**-0.483**	**-0.519**	**-0.54**	**-0.495**	**-0.529**	**-0.479**	**-0.621**	**-0.526**	-0.175
Evaporation	0.069887	0.22948	0.29772	0.36289	0.71928	0.36221	0.60209	0.57952	0.8705	0.87054	0.19162	0.21689
	0.308	0.201	0.176	0.154	0.0649	-0.155	-0.0912	-0.0968	-0.0323	0.0323	0.221	0.207
Precipitation	0.11189	0.20575	0.0010496	0.20575	0.04757	0.0093319	0.054993	0.04053	0.044156	0.0094067	0.69688	0.77005
	-0.263	-0.211	**-0.537**	**-0.211**	**-0.328**	**-0.43**	*-0.319*	**-0.34**	**-0.332**	**-0.427**	-0.0686	-0.0529

Mann Kendall Thornthwaite	January	February	March	April	May	June	July	August	September	October	November	December
Surplus100 (p)	0.1049	0.37404	0.081468	0.49797	0.080224	0.031456	0.12148	0.064355	0.00041425	0.0025585	0.00027668	0.0087431
(tau)	0.183	0.104	0.216	0.0885	0.225	0.278	0.208	0.248	0.465	0.377	0.429	-.356
Surplus140	0.1049	0.37404	0.081468	0.49797	0.080224	0.031456	0.12148	0.064355	0.00041425	0.0025585	0.00027668	0.0087431
	0.183	0.104	0.216	0.0885	0.225	**0.278**	0.208	0.248	**0.465**	**0.377**	**0.429**	**-0.356**
Surplus700	0.75676	0.88447	0.75213	1	1	0.37296	0.37296	0.37296	0.074766	0.15525	0.035609	1
	0.0428	-0.0211	-0.0453	1	1	0.123	0.123	0.123	0.242	0.192	0.28	1
Deficit100	0.16845	0.0033605	0.014764	0.0011842	0.00078512	0.0027076	0.00050475	0.0046207	0.0029917	0.0011793	0.12237	0.056239
	-0.191	-0.389	-0.312	-0.387	-0.385	-0.347	-0.402	-0.322	-0.335	-0.38	-0.196	-0.259
Deficit140	1	0.015464	0.0033605	0.0043411	0.00038759	0.0022063	0.00016911	0.0032613	0.00040029	0.0043576	0.33503	0.064959
	1	**-0.324**	**-0.398**	**-0.347**	**-0.414**	**-0.354**	**-0.435**	**-0.335**	**-0.4**	**-0.336**	-0.124	-0.25
Deficit700	1	1	0.19762	0.035721	0.020312	0.00094041	0.0043837	0.0031621	0.00034399	0.0037532	0.39271	0.23033
	1	1	-0.179	-0.284	-0.298	-0.403	-0.342	-0.348	-0.416	-0.344	-0.110	-0.167
AET100	0.96139	0.7075	0.52904	0.42433	0.24529	0.23559	0.14633	0.085734	0.12431	0.11849	0.0374	0.98068
	-0.00678	0.0434	0.0719	-0.0909	0.131	0.134	0.164	0.194	0.173	0.176	0.234	-0.00408
AET140	0.7622	0.032165	0.24037	0.72562	0.00027061	0.0067103	0.00037432	8.4281e-05	8.8573e-05	0.014037	0.00011349	0.56129
	0.0353	**0.241**	0.133	0.0406	**0.408**	**0.305**	**0.399**	**0.44**	**0.439**	**0.276**	**0.433**	0.0664
AET700	0.7622	0.12729	0.65427	0.66305	0.079313	0.016049	0.015001	0.012259	.0020329	0.059108	0.0011852	0.66305
	0.0353	0.172	0.0515	-0.0501	0.198	0.27	0.274	0.281	0.346	0.212	0.364	0.0501
Storage100	0.031749	0.0028932	0.020037	0.001772	0.0015005	0.00050128	0.00022376	0.00053132	0.00018156	3.0398e-05	0.0018669	0.002522
	0.268	0.395	0.295	0.371	0.364	0.399	0.421	0.39	0.422	0.471	0.358	0.373
Storage140	0.011847	0.0069416	0.02173	0.001772	0.0015005	0.00050128	0.00021303	0.00069439	0.00020039	2.6345e-05	0.00086522	0.0023928
	0.33	**0.356**	**0.291**	**0.371**	**0.364**	**0.399**	**0.423**	**0.382**	**0.419**	**0.473**	**0.383**	**0.368**
Storage700	0.10719	0.0055411	0.0027734	0.0017996	0.0011852	0.00028265	0.00024211	0.00020039	0.00026047	0.00037885	0.014061	0.0047939
	0.182	**0.313**	**0.337**	**0.35**	**0.364**	**0.408**	**0.419**	**0.437**	**0.436**	**0.419**	**0.28**	**0.317**
PETTW	0.7622	0.058984	1	0.74375	0.52122	0.98069	0.99034	0.0062337	0.13031	0.52926	0.00013018	0.89408
	0.0353	*0.213*	-0.00136	-0.038	0.0732	0.00406	-0.00271	**0.308**	0.171	0.0716	**0.431**	0.0163
PrecipTW (p)	0.69864	0.01032	0.065916	0.034251	0.0010859	0.011749	0.00056696	0.00095046	0.00018537	0.00061667	0.19551	0.018321
(tau)	-0.0446	**0.288**	0.207	**0.238**	**0.367**	**0.284**	**0.393**	**0.372**	**0.419**	**0.384**	0.146	**0.265**

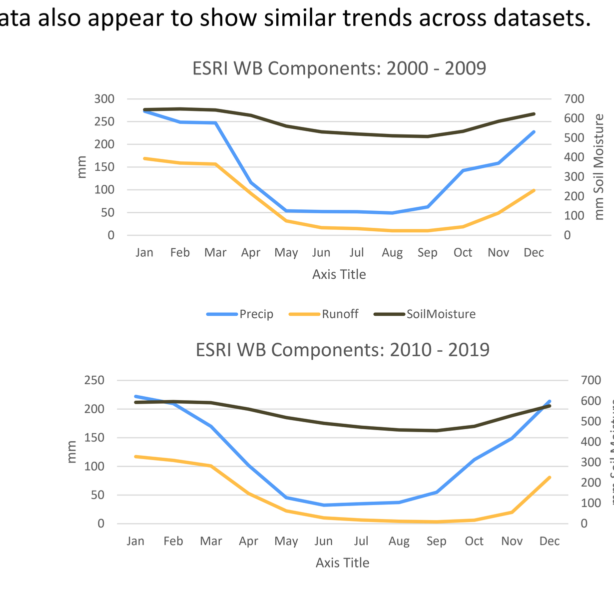
SELECTED RESULTS

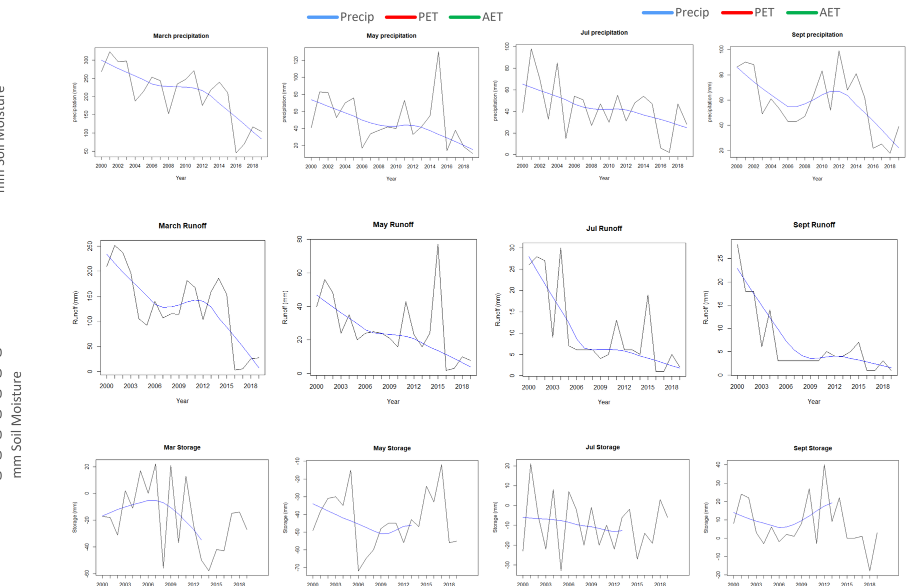




Figures: Thornthwaite Decadal Water Balance, across varied TAW estimates at total estimated soil moisture (700mm), 20% (140mm), and 14% (100mm).

Description: Mann Kendall results for displayed Thornthwaite variables were significant across most months in the year. Significant tau values are positive indicating increasing trend. Decadal graphs (Above, Right) also show this trend is consistent, where more precipitation increase between the decades is observed in the second half of the calendar year. In analyzing graphs with multiple TAW values for trends it is particularly notable that TAW 140 had the most significant values compared to others.) Displayed figures from regional ESRI water balance data (Below, Right) only observed significance for soil moisture and precipitation due to limited data. Monthly trends in evaporation and storage did appear to have seasonal alignment, however. Significant decrease in precipitation and soil moisture were indicated, with most decrease of precipitation occurring in the second half of the year. Mann Kendall data also appear to show similar trends across datasets.





Figures: ESRI Decadal Water Balance (left) ; selected significant Mann Kendall graphs (right).

CONCLUSIONS

Several conclusions may be drawn from comparing local & regional trends. Critically, given conflicting increasing vs decreasing trends between both scales, it is clear that immediate use of regional trends for local analysis may yield improper conclusions and is inadequate for local scale management. New gage infrastructure is also needed to allow needed confidence for local management especially in the Andes- significant gaps were present in gage data which required a high degree of interpolation and introduced uncertainty. There is also need for remotely sensed data at a more regional scale to be interpolated with limited error for a longer time period, which may yield more confidence behind seasonal trends than what limited local gage data alone can provide. With these conclusions in mind, both datasets may still be considered to obtain practical insight between local and regional levels:

- Local increasing trend in precipitation is occurring below the average total monthly precipitation for the region. Considering the regional sensed watershed as an average implies that some other local watersheds in the region (potentially at or above the regional average for monthly precipitation) must have a decreasing trend. These could be prioritized be monitoring, with others excluded by process of elimination.

-Regional Mann Kendall data *may* indicate a new cycle of generally decreasing water availability around 2016 and thereafter in the Cusco/Urubamba region. This is not certain, additional data must be observed.

-Data support suggestions of a potentially shortening dry season. The amount of local significant increase in precipitation appears more consolidated at the end of planting season/second half of the calendar year (planting & early wet season), while significant regional decrease is distributed more towards the beginning of the calendar year (mid-late wet season).

-Considering reported germination issues in light of these observed trends, water authorities may find it advantageous to identify local watersheds within regions of known trends that have a desirable base level of soil moisture conducive to crop germination (without decreasing trend) and local decreasing or stabilized trend of precipitation specifically in late dry season/early wet season months. These watersheds may prove ideal for investigating the irrigation and growth of crops which may otherwise struggle to germinate in local areas. This may entail irrigation in more rain-shadowed areas, or identifying microclimates.

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