2009

The Water Balance of the Okanogan River Watershed

Basin analysis

Abstract

I calculated the water balance for each sub-basin in the US portion of the Okanogan River watershed using a Thornthwaite-type model. I used average temperature and precipitation for Okanogan County from 1971 to 2000 obtained from the PRISM climate mapping project and soil water holding capacity from the NRCS soil database. I summarized annual potential evapotranspiration, annual actual evapotranspiration, annual climatic water deficit, and annual water surplus. I also provided monthly summaries of these data in Excel spreadsheets suitable for import to a geographic information system.

Prepared for
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The Water Balance of the Okanogan River Watershed in the United States

INTRODUCTION

The annual water balance of a site – the flows of water throughout the year – determines vegetation type and abundance, indicates conditions favourable and unfavourable to trees and other vegetation, and can serve as a proxy for irrigation demand. Water availability to plants at a site represents a non-linear combination of water supply, soil water storage, and water demand. The amount of precipitation, the proportion falling as snow, and the timing of the snow melt determine water supply at a site (Figure 1). The prolonged summer dry season in the Okanogan River watershed decreases the availability of water when plants need it for photosynthesis.

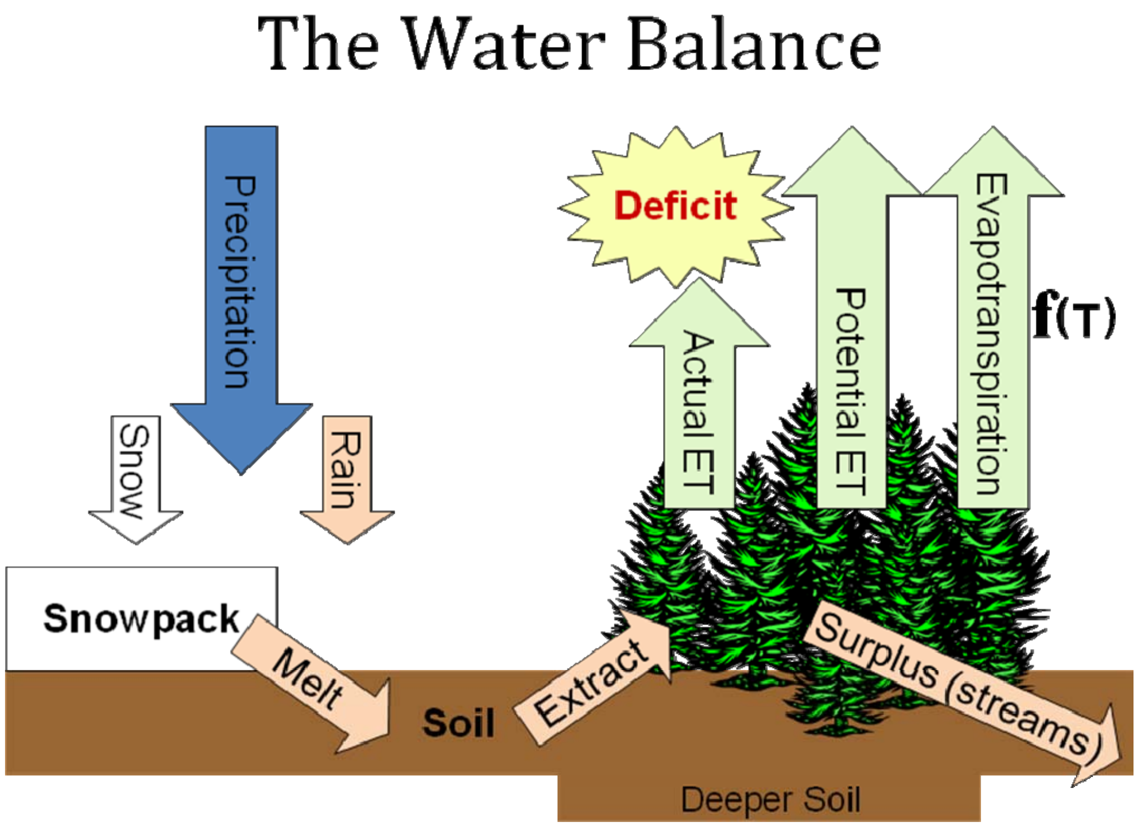


Figure 1. Diagram of the water balance for a site. Precipitation falls as either rain or snow. Rain enters the soil immediately, and snow is stored in the snowpack until it melts, when it also enters the soil. Vegetation extracts water from the soil, and when water supply exceeds evapotranspiration the surplus makes its way to streams through surface or sub-surface flow. When soil contains the maximum possible amount of water, vegetation can extract that water easily and transpire it; this rate of water use is defined as potential evapotranspiration. As soil becomes drier, it becomes progressively more difficult for vegetation to extract that water and the actual amount of water that vegetation uses declines; this is defined as actual evapotranspiration. The difference between potential evapotranspiration and actual evapotranspiration is the climatic water deficit. Values are customarily expressed per unit area.

Water balance models based on temperature and precipitation were first developed in the 1940s by Thornthwaite. Since then, models have been continually refined to include wind speed, short-wave and long-wave radiation, and cloudiness. However, unless very detailed meteorological information is available (and this is rarely the case over large areas of complex terrain), the simple Thornthwaite-type methods still give the best results (Vörösmarty et al. 1998). Following Thornthwaite and Mather (1955) and Stephenson (1990, 1998), the definitions of the constituents of the water balance are:

Potential evapotranspiration (PET): PET is the evaporative water loss from a site covered by a hypothetical standard crop, when the soil is fully recharged with water. In this definition, PET includes evaporation from the soil surface and transpiration by plants. The "standard crop" was originally taken to be corn, but the relationship is robust across vegetation types from herbaceous cover to forests. PET increases exponentially with increasing mean daily temperature and linearly with increasing day length.

Actual evapotranspiration (AET): AET is the evaporative water loss from a site covered by a hypothetical standard crop, constrained by the current water availability. AET can be considered a proxy for site net primary productivity because AET represents the simultaneous availability of biologically-useable energy and water.

Climatic water deficit (Deficit): Deficit is the difference between PET and AET. It is the unmet water demand at a site, and can be considered a metric for drought. Deficit as defined here is positively correlated with vapour pressure deficit and negatively correlated with pre-dawn water potential. Each plant has a level of Deficit above which it cannot survive. Deficit is a property of a site and does not reflect the differing water demand that is associated with different levels of vegetation. Plant species can be considered as falling on sites within a given range of annual productivity (AET) and a given range of drought (Deficit). These two variables can be used to predict vegetation presence and growth rates.

Soil water extraction: The amount of water removed from the soil either by direct evaporation or by plants. Soil water extraction increases with PET, but decreases based on the proportion of water already extracted from the soil – it is easier for plants to extract water from soil that is near maximum water capacity (field capacity) than when soils are dry.

Surplus: The difference between the liquid water available at a site and the amount that plants use or that goes to soil water recharge. Soil water recharge is assumed to be complete (no time delays), and surplus is assumed to all flow immediately into streams with no further use. It includes both surface and sub-surface flow.

As soil depth and type are often correlated with landscape position, spatially explicit data for air temperature, precipitation, and soil water-holding capacity allow calculation of seasonal soil water balance in a manner that follows topography. Landscapes have heterogeneous terrain, and sites within a few kilometres of each other may have very different water balances because of differing soil conditions, precipitation, or temperature. Increases in Deficit are correlated with increasing tree mortality (and of course higher Deficit increases irrigation demand). Earlier snowmelt could increase Deficit on sites with shallow soils; evapotranspiration would start earlier in the season, and the evapotranspiration would deplete soil water sooner, thereby decreasing growing periods. Conversely, more summer precipitation could alleviate drought stress considerably.

METHODS

Climate data

Climate data were obtained from the PRISM climate mapping project. PRISM uses established meteorological stations to develop relationships between stations that are in turn used to predict the climate variables between stations. I used PRISM grids for monthly precipitation, monthly mean maximum temperature, and monthly mean minimum temperature for the entire area. PRISM considers meteorological phenomena relevant to mountainous terrain (e.g., temperature inversions, topographic barriers, the effects of air flow through terrain, and cold air drainages), and may offer improvements over other models (such as WorldClim and Daymet) that interpolate climate over the conterminous United States (Daly *et al.* 2008).

Soil data

Recent soil maps and data were obtained from the Natural Resources Conservation Service. NRCS data have different resolutions. Near developed areas, spatial resolution can be as good as 0.4 ha (1 acre), but in remote areas, resolution is no better than 16 ha (40 acres). For each soil polygon, the soil water-holding capacity in the top 150 cm (60 inches) of the soil profile was extracted (NRCS variable: AWS150). Each 800 m × 800 m PRISM grid was then overlaid on the soil map. The average soil water-holding capacity of that grid cell was determined as an area-weighted average of the soil polygons within that grid cell. Average soil water-holding capacity ranged from 0 mm (on areas of rock, or on areas of permanent standing water where soil is not defined) to 370 mm. Because soil water-holding capacity was determined in this way, grid cells including both land and permanent water will have calculated Deficit higher than the true value, and calculated AET lower than the true value. *Soil water-holding capacity data extraction was provided by Andrew Phay of the Whatcom Conservation District.*

Data reduction and analysis

I used a Thornthwaite-type water balance model, as modified by Hamon (1963). Thornthwaite-type methods are most appropriate when data are limited to temperature and precipitation (many references available on request). I used the equations in the appendix for each grid cell in the portion of the Okanogan River watershed lying within the United States, assuming flat topography. Flat topography tends to understate PET on south-facing slopes by about 10% and overstate PET on north-facing slopes. The overestimate of PET on north facing slopes depends on slope, aspect, and cloudiness and ranges from about 10% to 50%. The basins in the Okanogan River watershed are large enough that slope and aspect should not affect the results, because each basin has relatively equivalent distributions of aspect.

This analysis used snowpack modelled from temperature and precipitation. While the absolute values of snowpack may differ from the snowpack modelling, relative values between basins in the Okanogan River watershed are consistent.

Climate sensitivity

I used results from the recently concluded Washington State Climate Impacts Assessment to examine increases in Deficit on USDA forest service monitoring plots throughout Eastern Washington. Under the climate change scenarios modelled by the University of Washington Climate Impacts Group, forested areas in the Okanogan watershed appear to have projected increases in climatic water deficit that are among the highest in the state. The executive summary of the Washington State Climate Impacts Assessment is available on-line at http://cses.washington.edu/cig/res/ia/waccia.shtml and the full report is scheduled to be published in June 2009.

RESULTS

Figures 2 – 6 illustrate the patterns of water balance parameters in Okanogan County (a continuous area including the US portions of the Okanogan River watershed). Table 1 summarizes the annual water balance (in mm) in each sub-basin of the Okanogan River watershed, with totals for the larger hydrological units. Table 2 summarizes the annual water balance in acre-feet (units converted from Table 1). Figure 7 shows the month-by-month constituents of the water balance for the watersheds of Antoine Creek, Bonaparte Creek, Salmon Creek, and the Okanogan Mainstem.

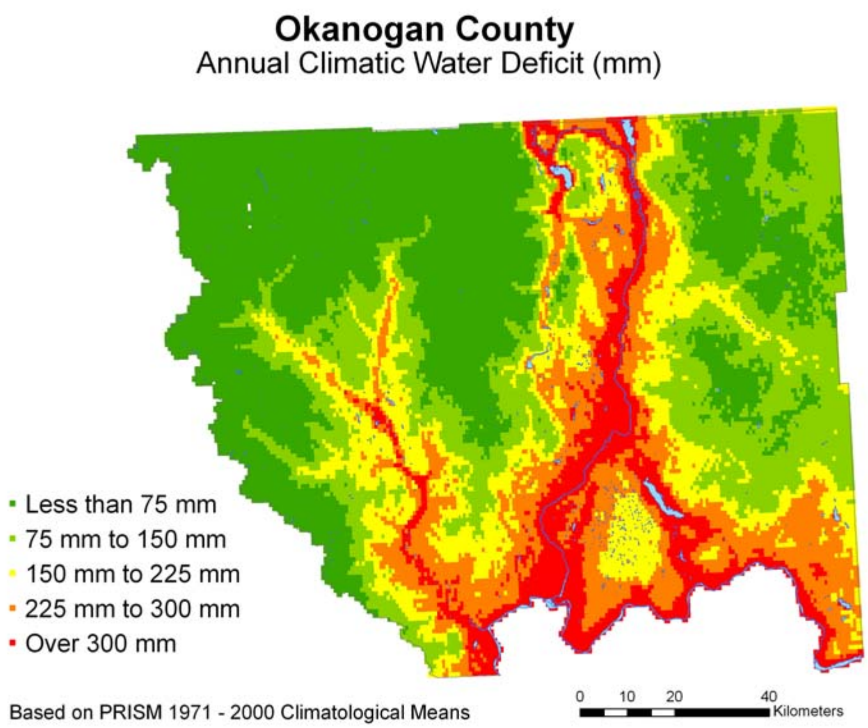


Figure 2. Modelled annual climatic water deficit for Okanogan County based on temperature and precipitation from PRISM climatological averages (1971 – 2000) and Thornthwaite-type evapotranspiration.

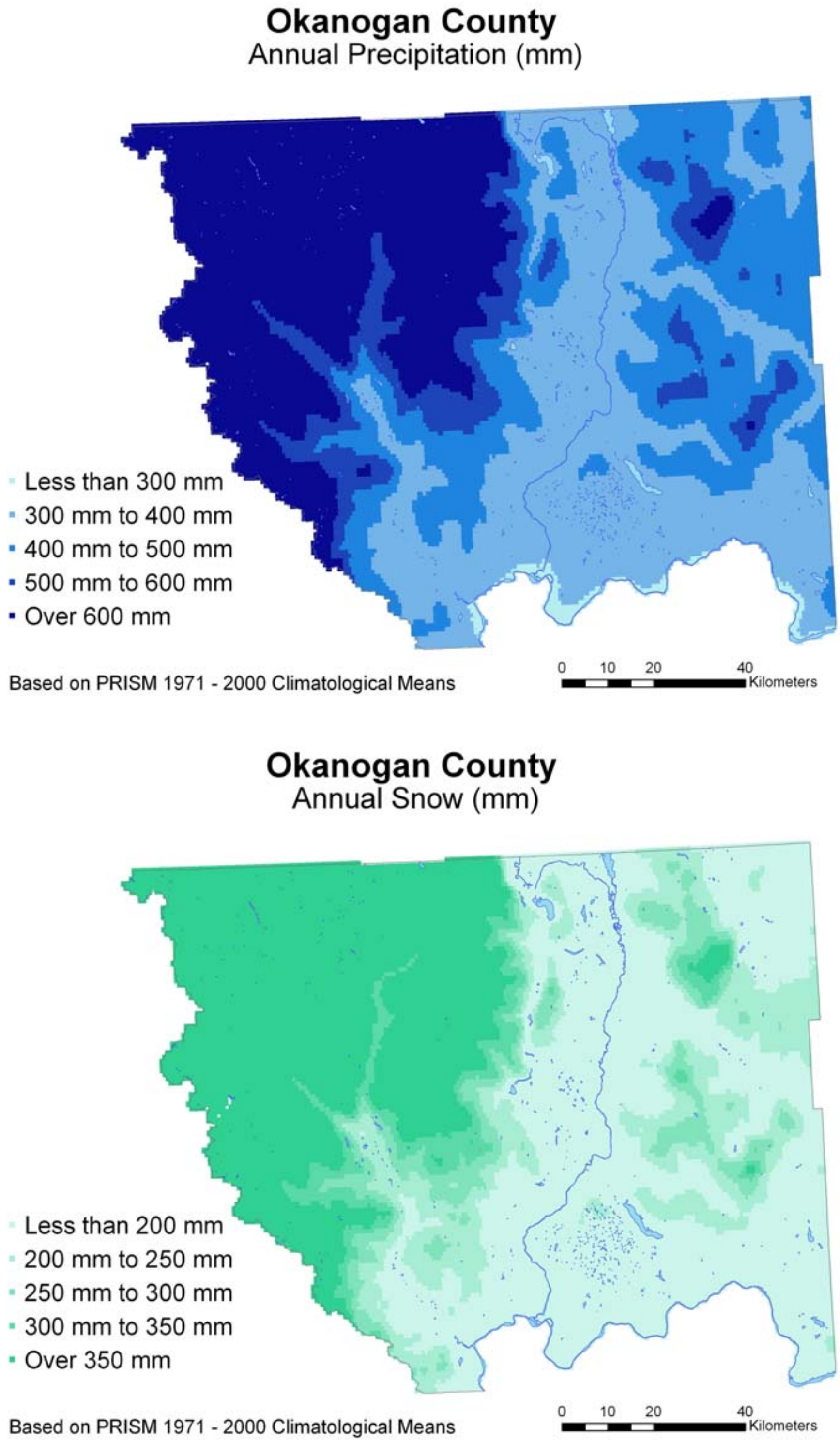
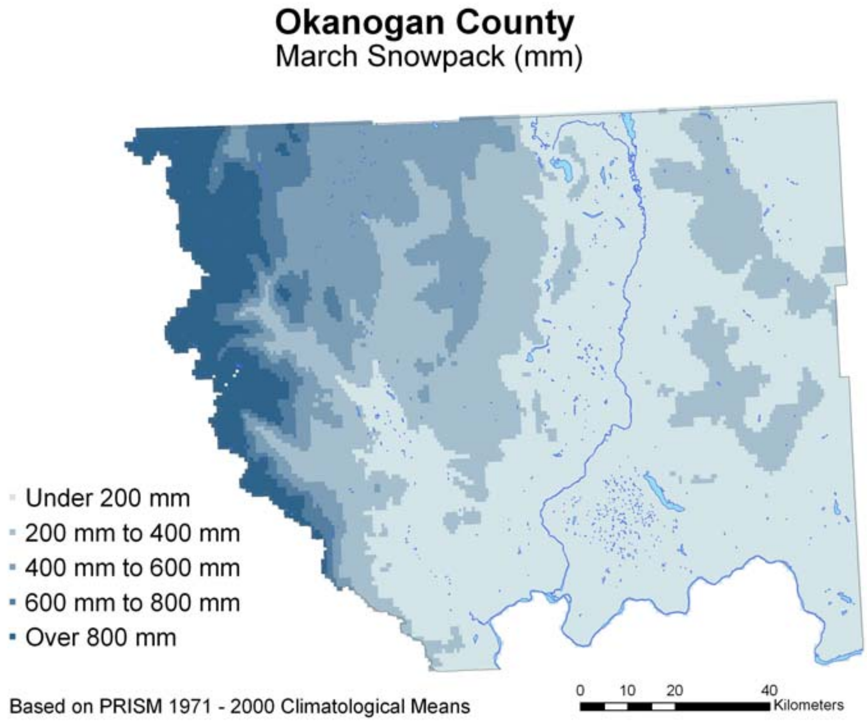


Figure 3. Modelled precipitation (above) for Okanogan County based on PRISM climatological means (1971 – 2000) and the amount of precipitation that falls as snow (below) based on the Thornthwaite-type model approximations for snow accumulation and melt.



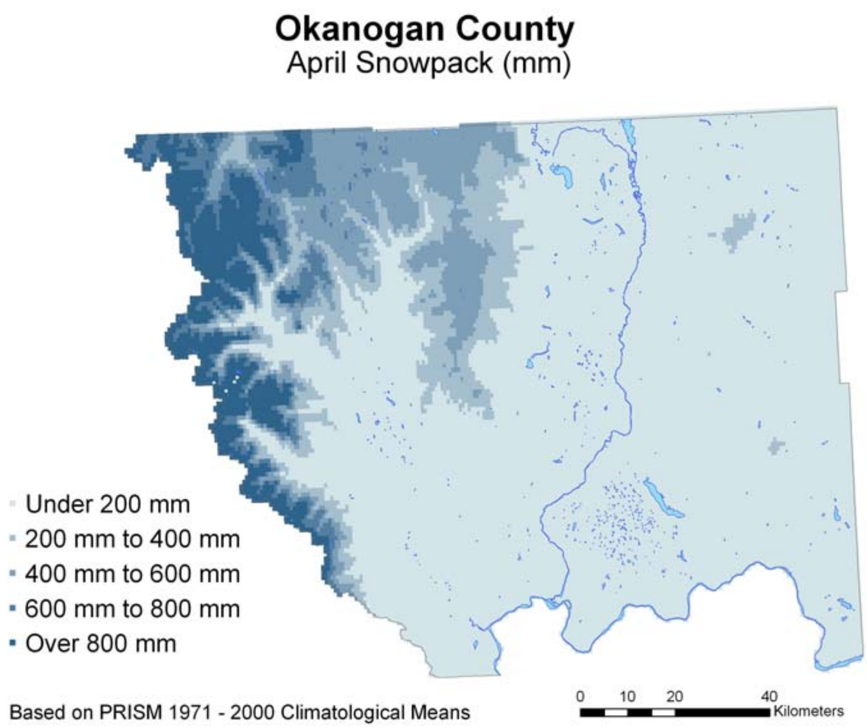
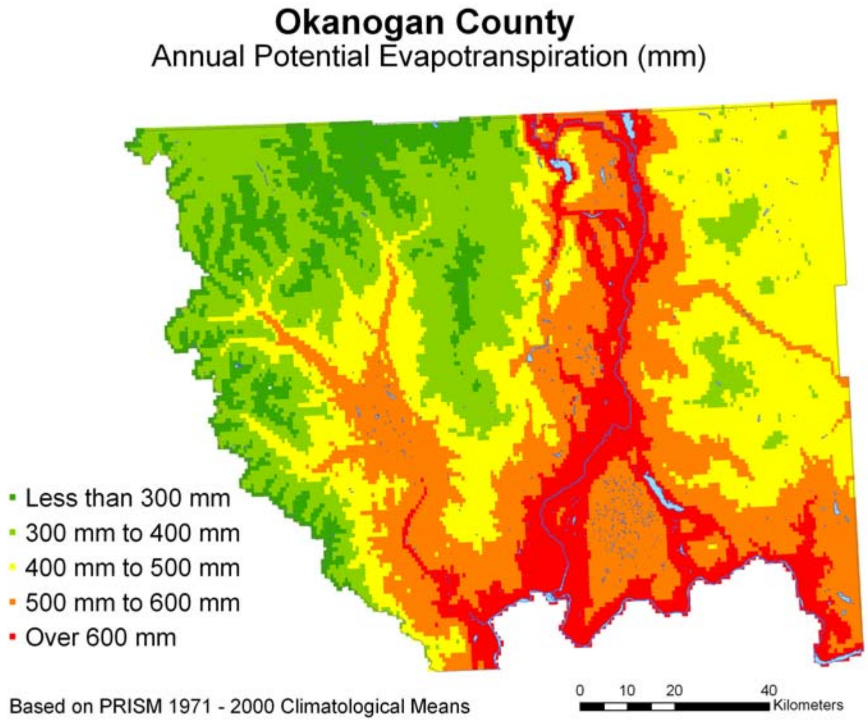


Figure 4. Modelled snowpack for Okanogan County for March (above) and April (below) based on temperature and precipitation from PRISM climatological means (1971 – 2000) and the Thornthwaite-type model approximations for snow accumulation and melt.



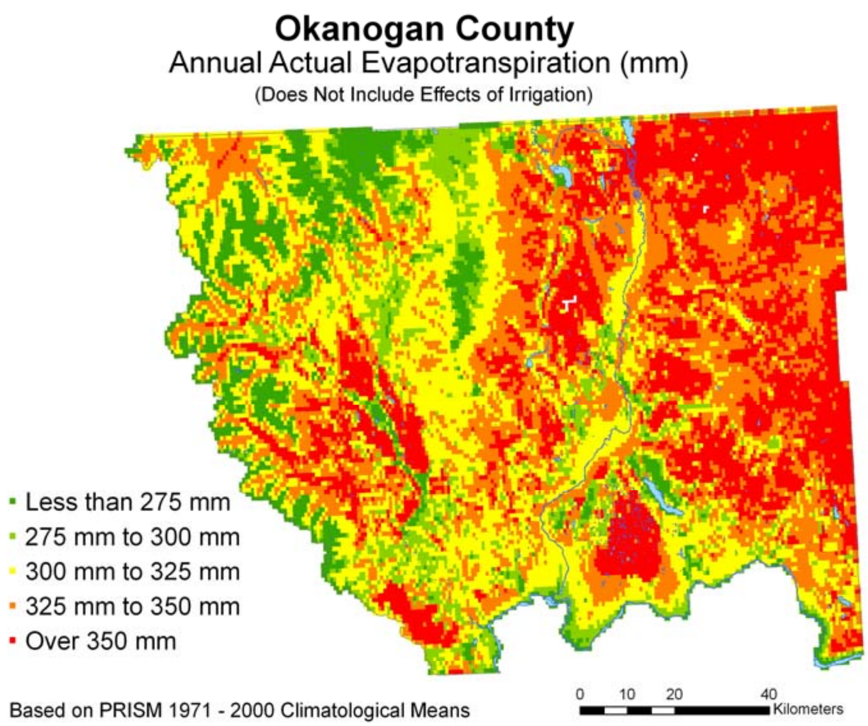
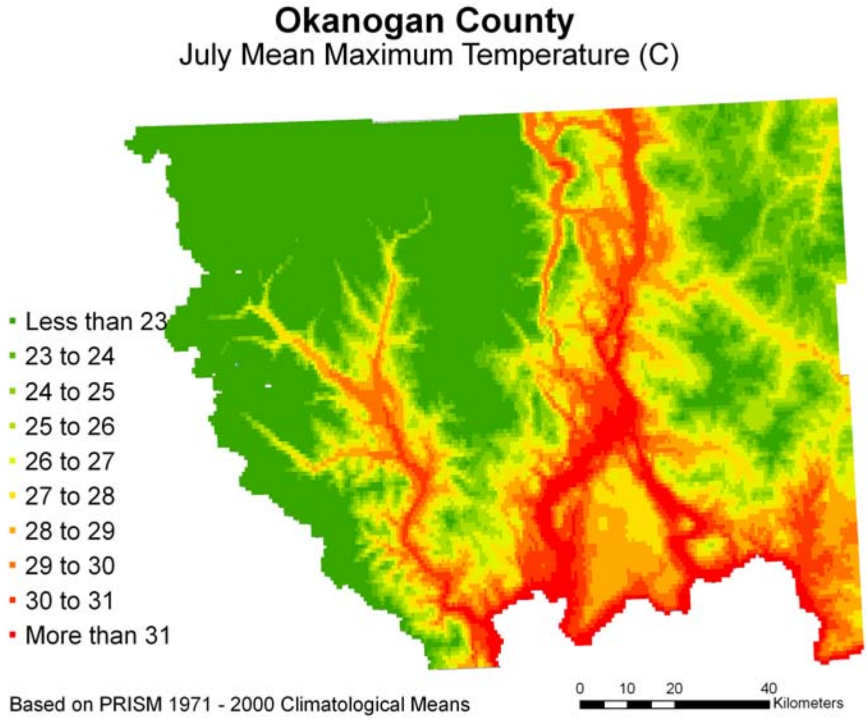


Figure 5. Modelled annual potential evapotranspiration (above) and annual actual evapotranspiration (below) for Okanogan County based on temperature and precipitation from PRISM climatological means (1971 – 2000) and the Thornthwaite-type model for vegetative evapotranspiration. Not differing color scales.



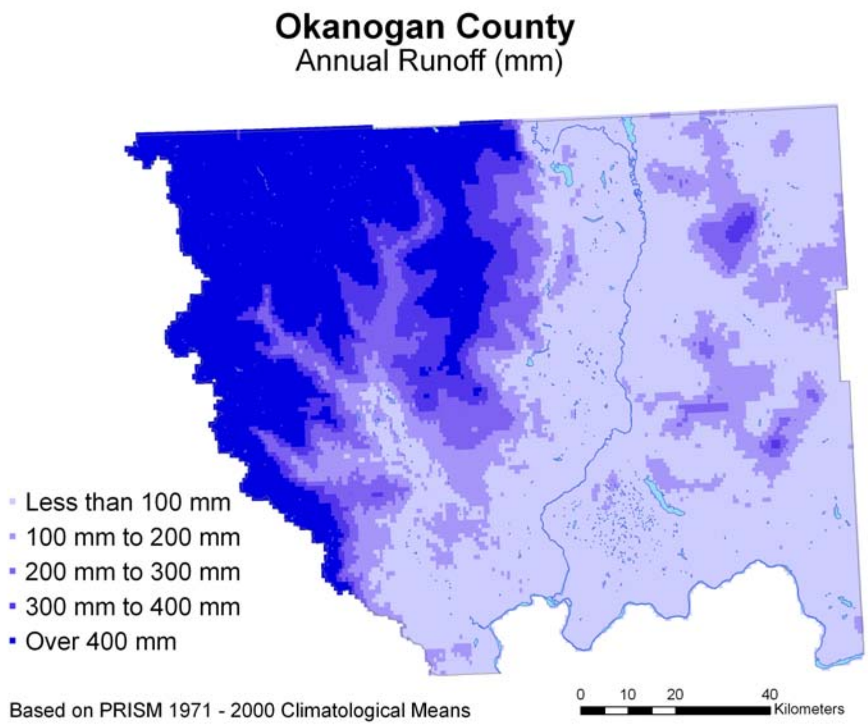


Figure 6. Modelled mean July maximum temperature for Okanogan County (above) based on PRISM climatological means (1971 – 2000), and annual surplus water (below). Water that is surplus to evaporative demand is transported by surface runoff or by sub-surface flow.

Table 1. Annual water balance summary for basins within the Okanogan River watershed (US portion only). Basins are modelled as means of an overlay of 800 m × 800 m (approximately ½ mile × ½ mile) PRISM grid cells. Precipitation, potential evapotranspiration, actual evapotranspiration, climatic water deficit, and surplus (surface and sub-surface runoff) are given in units of inches for each unit area within the basin.

			Per Unit Area (English Units)				
	Area (ac)	Soil Water Holding Cap (in)	Precip (in)	PET (in)	AET (in)	Deficit (in)	Surp (in)
Aeneas Creek	7749	5.2	15.5	22.2	14.0	8.2	1.5
Aeneas Lake	23564	4.8	14.6	22.9	13.8	9.2	0.8
Antoine Creek	52031	5.2	18.4	18.6	14.1	4.6	4.3
Bonaparte Creek	110545	4.3	17.4	18.3	13.6	4.6	3.8
Brown Lake	3005	3.4	14.0	22.6	12.6	10.0	1.4
Chewiliken Creek	19452	4.4	16.5	19.9	13.8	6.0	2.7
Chiliwist Creek	31313	3.9	16.0	20.9	13.0	7.8	2.9
Columbia River East WRIA	154826	5.1	13.0	23.8	12.6	11.2	0.4
Duley Lake/Joseph Flats	57408	4.6	14.7	22.9	13.3	9.7	1.4
Fish Lake Basin	25462	5.2	17.0	20.1	14.1	6.0	2.9
Johnson Creek	29574	3.8	13.9	23.1	12.9	10.2	1.0
Loup Loup Creek	44914	3.9	17.4	19.4	13.4	6.1	4.0
Mosquito Creek	6958	4.4	16.4	20.8	13.6	7.2	2.7
Nine Mile Creek	12494	5.7	16.7	19.9	14.4	5.5	2.3
North Fork Pine Creek	27043	5.0	15.7	21.8	13.9	7.9	1.8
Salmon Creek							
Conconully Lake	4744	3.2	16.4	19.8	12.9	7.0	3.5
Conconully Resevoir	2847	3.0	16.3	20.0	12.6	7.4	3.7
North Fork Salmon Creek	31313	3.9	24.9	14.7	12.6	2.1	12.2
Salmon Creek	25145	3.5	15.1	21.4	12.9	8.5	2.3
West Fork Salmon Creek	46495	4.0	21.8	16.0	13.1	2.8	8.7
Total Salmon Creek	**110545**	**3.8**	**20.8**	**17.1**	**12.9**	**4.2**	**7.9**
Okanogan River PSIAC							
Okanogan Mainstem and Interfluves							
Lower Okanogan Outlet	42225	4.7	12.8	25.1	12.4	12.6	0.4
Okanogan Interfluve 01	4586	2.6	13.2	25.5	12.2	13.4	1.1
Okanogan Interfluve 02	3479	3.6	14.0	26.2	13.3	12.9	0.7
Okanogan Interfluve 03	7907	3.9	17.1	21.9	14.4	7.6	2.7
Okanogan Interfluve 04	14550	4.6	15.3	22.7	13.7	9.1	1.7
Okanogan Interfluve 05	8540	5.9	13.0	25.3	12.8	12.4	0.2
Okanogan Interfluve 06	2847	4.9	12.8	24.8	12.8	12.0	0.0
Okanogan Interfluve 07	6326	4.7	12.9	24.8	12.7	12.1	0.2
Okanogan Interfluve 08	474	5.8	12.4	25.6	12.4	13.2	0.0
Okanogan Interfluve 09	11861	4.9	13.0	24.6	12.9	11.7	0.1
Okanogan Interfluve 10	5535	3.2	14.1	23.9	12.8	11.1	1.4
Okanogan Interfluve 11	22457	3.9	14.0	23.6	13.0	10.6	1.0
Okanogan Interfluve 12	13601	3.5	14.0	23.8	12.6	11.1	1.3
Okanogan Interfluve 13	22141	3.3	14.4	23.4	12.5	11.0	1.9
Okanogan Interfluve 14	7117	3.6	13.4	24.7	12.4	12.3	1.0
Okanogan Interfluve 15	22615	4.4	13.0	25.0	12.5	12.5	0.5
Okanogan Interfluve 16	24197	4.4	13.9	24.1	12.8	11.3	1.1

Okanogan Interfluve 17	5061	4.1	13.3	25.3	12.6	12.8	0.7
Okanogan Interfluve 18	2847	3.6	13.6	24.9	12.5	12.4	1.2
Total Okanogan Mainstem	**228365**	**4.2**	**13.7**	**24.3**	**12.8**	**11.5**	**0.9**
Total Okanogan PSIAC	**228365**	**4.2**	**13.7**	**24.3**	**12.8**	**11.5**	**0.9**
Omak Creek	100740	4.8	16.7	19.9	13.7	6.2	3.0
Omak Lake	77809	3.2	14.4	22.9	12.2	10.7	2.2
Open Water Columbia	5219	1.7	11.3	27.2	9.4	17.8	1.8
Siwash Creek	35741	4.4	18.0	19.0	13.7	5.4	4.3
Spectacle Lake/Whitestone	31313	4.5	14.5	22.7	13.6	9.1	0.9
Tallant Creek	10912	3.4	14.4	23.0	12.6	10.4	1.8
Tonasket Creek	43332	5.6	18.2	18.4	14.5	3.9	3.7
Tunk Creek	51082	4.9	16.7	19.3	13.9	5.4	2.9
Wanacut Creek	14075	3.8	17.0	20.2	13.3	6.9	3.7
Wanacut Lake	15498	4.4	15.6	21.0	13.9	7.2	1.8
Sinlahekan Creek PSIAC							
Cecile Creek	17396	4.1	22.9	16.1	13.4	2.7	9.6
Chopaka Creek	12336	4.4	19.8	17.6	13.4	4.2	6.4
Palmer Lake	11387	3.4	14.5	22.9	12.4	10.6	2.2
Sarsapkin Creek	9647	4.5	22.9	16.2	13.7	2.5	9.3
Toats Coulee Creek	97577	4.2	26.8	13.8	12.3	1.5	14.5
Sinlahekan Creek							
Blue Lake	7433	3.4	17.8	19.8	13.2	6.7	4.6
Sinlahekan Creek Headwaters	30997	3.9	25.6	14.3	12.5	1.8	13.1
Sinlahekan Interfluve 01	5377	3.8	18.1	19.6	13.5	6.2	4.6
Sinlahekan Interfluve 02	10121	3.1	16.9	20.6	13.1	7.6	3.9
Sinlahekan Interfluve 03	5693	4.5	14.6	23.0	13.3	9.6	1.2
Sinlahekan Interfluve 04	1107	5.8	13.4	24.8	12.8	12.0	0.6
Sinlahekan Interfluve 05	4586	5.5	15.1	21.7	13.2	8.5	1.9
Total Sinlahekan Creek	**65315**	**3.9**	**20.9**	**17.8**	**12.9**	**4.9**	**8.0**
Total Sinlahekan PSIAC	**213657**	**4.1**	**23.4**	**16.0**	**12.7**	**3.3**	**10.7**
Similkameen River PSIAC							
Ashnola River	41593	4.4	37.4	11.1	10.8	0.3	26.6
Pasayten River	155301	4.2	48.7	12.6	12.1	0.5	36.7
Similkameen River	61045	4.4	18.9	20.3	12.8	7.6	6.1
Total Similkameen PSIAC	**257938**	**4.3**	**39.8**	**14.2**	**12.0**	**2.2**	**27.8**
Columbia River West WRIA PSIAC							
Whitestone Creek West WRIA	39537	3.7	15.5	20.8	12.5	8.3	3.0
West WRIA Area							
Indian Dan Canyon	16605	4.0	13.9	23.3	12.3	11.0	1.6
Starzman Lake West WRIA	15657	4.1	13.1	24.4	12.3	12.1	0.7
Total West WRIA Area	32262	4.0	13.5	23.8	12.3	11.6	1.2
Total Columbia River PSIAC	**71799**	**3.9**	**14.6**	**22.1**	**12.4**	**9.7**	**2.2**

Table 2. Annual water balance summary for basins within the Okanogan River watershed (US portion only). Basins are modelled as means of an overlay of 800 m × 800 m m (approximately ½ mile × ½ mile) PRISM grid cells. Precipitation, potential evapotranspiration, actual evapotranspiration, climatic water deficit, and surplus (surface and sub-surface runoff) are given in units of acre-feet totalled for each basin.

			Total Basin (English Units)			
	Area (ac)	**Precip (ac-ft)**	**PET (ac-ft)**	**AET (ac-ft)**	**Deficit (ac-ft)**	**Surp (ac-ft)**
Aeneas Creek	7749	9986	14309	9019	5290	966
Aeneas Lake	23564	28662	45034	27026	18008	1636
Antoine Creek	52031	79752	80850	61023	19827	18728
Bonaparte Creek	110545	160628	168172	125593	42579	35035
Brown Lake	3005	3493	5652	3152	2500	341
Chewiliken Creek	19452	26797	32223	22433	9790	4364
Chiliwist Creek	31313	41665	54466	34034	20432	7631
Columbia River East WRIA	154826	167953	307228	162545	144683	5408
Duley Lake/Joseph Flats	57408	70086	109593	63399	46195	6687
Fish Lake Basin	25462	36156	42739	29986	12753	6170
Johnson Creek	29574	34322	56913	31821	25092	2501
Loup Loup Creek	44914	64968	72707	50014	22693	14954
Mosquito Creek	6958	9494	12085	7910	4175	1583
Nine Mile Creek	12494	17405	20684	14994	5690	2411
North Fork Pine Creek	27043	35311	49153	31238	17916	4073
Salmon Creek						
Conconully Lake	4744	6465	7841	5084	2758	1381
Conconully Resevoir	2847	3864	4741	2994	1747	870
North Fork Salmon Creek	31313	64907	38404	32993	5411	31914
Salmon Creek	25145	31708	44811	26960	17851	4748
West Fork Salmon Creek	46495	84335	61833	50807	11026	33527
Total Salmon Creek	**110545**	**191278**	**157630**	**118838**	**38793**	**72440**
Okanogan River PSIAC						
Okanogan Mainstem and Interfluves						
Lower Okanogan Outlet	42225	45192	88164	43697	44467	1494
Okanogan Interfluve 01	4586	5049	9748	4644	5104	404
Okanogan Interfluve 02	3479	4053	7586	3847	3740	206
Okanogan Interfluve 03	7907	11258	14448	9463	4985	1795
Okanogan Interfluve 04	14550	18579	27566	16568	10998	2011
Okanogan Interfluve 05	8540	9233	17970	9113	8858	121
Okanogan Interfluve 06	2847	3033	5878	3028	2850	5
Okanogan Interfluve 07	6326	6792	13079	6682	6397	110
Okanogan Interfluve 08	474	491	1013	491	522	0
Okanogan Interfluve 09	11861	12833	24333	12721	11612	112
Okanogan Interfluve 10	5535	6526	11021	5891	5130	634
Okanogan Interfluve 11	22457	26133	44115	24267	19849	1867
Okanogan Interfluve 12	13601	15815	26920	14303	12617	1512
Okanogan Interfluve 13	22141	26499	43196	22988	20209	3511
Okanogan Interfluve 14	7117	7946	14649	7382	7268	564
Okanogan Interfluve 15	22615	24523	47182	23608	23574	915
Okanogan Interfluve 16	24197	27994	48602	25784	22818	2210
Okanogan Interfluve 17	5061	5603	10682	5298	5384	305
Okanogan Interfluve 18	2847	3234	5903	2956	2947	278
Total Okanogan Mainstem	**228365**	**260787**	**462058**	**242731**	**219327**	**18056**
Total Okanogan PSIAC	**228365**	**260787**	**462058**	**242731**	**219327**	**18056**
Omak Creek	100740	140280	167000	114739	52260	25540

Omak Lake	77809	93346	148333	78844	69489	14502
Open Water Columbia	5219	4905	11830	4108	7723	798
Siwash Creek	35741	53527	56720	40680	16040	12848
Spectacle Lake/Whitestone	31313	37916	59278	35589	23689	2326
Tallant Creek	10912	13054	20920	11430	9490	1624
Tonasket Creek	43332	65878	66464	52428	14036	13449
Tunk Creek	51082	71220	82083	59012	23072	12208
Wanacut Creek	14075	19947	23725	15609	8117	4338
Wanacut Lake	15498	20193	27124	17889	9235	2303
Sinlahekan Creek PSIAC						
Cecile Creek	17396	33269	23397	19413	3984	13856
Chopaka Creek	12336	20405	18110	13805	4305	6600
Palmer Lake	11387	13775	21762	11733	10029	2041
Sarsapkin Creek	9647	18443	13001	10985	2016	7458
Toats Coulee Creek	97577	217810	111897	99846	12051	117965
Sinlahekan Creek						
Blue Lake	7433	11015	12290	8153	4137	2862
Sinlahekan Creek Headwaters	30997	66214	36987	32365	4622	33849
Sinlahekan Interfluve 01	5377	8092	8799	6041	2758	2051
Sinlahekan Interfluve 02	10121	14278	17381	11011	6370	3267
Sinlahekan Interfluve 03	5693	6924	10898	6332	4566	592
Sinlahekan Interfluve 04	1107	1235	2291	1180	1111	56
Sinlahekan Interfluve 05	4586	5776	8285	5054	3232	722
Total Sinlahekan Creek	**65315**	**113534**	**96931**	**70135**	**26796**	**43399**
Total Sinlahekan PSIAC	**213657**	**417235**	**285097**	**225917**	**59181**	**191319**
Similkameen River PSIAC						
Ashnola River	41593	129601	38448	37526	922	92075
Pasayten River	155301	630819	163123	156205	6918	474614
Similkameen River	61045	96072	103485	64879	38606	31193
Total Similkameen PSIAC	**257938**	**856493**	**305056**	**258610**	**46446**	**597883**
Columbia River West WRIA PSIAC						
Whitestone Creek West WRIA	39537	50961	68435	41180	27255	9781
West WRIA Area						
Indian Dan Canyon	16605	19209	32216	16955	15261	2253
Starzman Lake West WRIA	15657	17034	31854	16061	15792	973
Total West WRIA Area	**32262**	**36243**	**64070**	**33017**	**31053**	**3227**
Total Columbia River PSIAC	**71799**	**87205**	**132505**	**74197**	**58308**	**13008**

Table 3. Annual water balance summary for basins within the Okanogan River watershed (US portion only). Basins are modelled as means of an overlay of 800 m × 800 m PRISM grid cells. Precipitation, potential evapotranspiration, actual evapotranspiration, climatic water deficit, and surplus (surface and sub-surface runoff) are given in units of mm for each unit area within the basin.

		Per Unit Area (Metric Units)					
	Area (ha)	**Soil Water Holding Cap (mm)**	**Precip (mm)**	**PET (mm)**	**AET (mm)**	**Deficit (mm)**	**Surp (mm)**
Aeneas Creek	3136	131	393	563	355	208	38
Aeneas Lake	9536	121	371	583	350	233	21
Antoine Creek	21056	131	467	474	357	116	110
Bonaparte Creek	44736	110	443	464	346	117	97
Brown Lake	1216	86	354	573	320	254	35
Chewiliken Creek	7872	112	420	505	352	153	68
Chiliwist Creek	12672	99	406	530	331	199	74
Columbia River East WRIA	62656	129	331	605	320	285	11
Duley Lake/Joseph Flats	23232	118	372	582	337	245	36
Fish Lake Basin	10304	133	433	512	359	153	74
Johnson Creek	11968	97	354	587	328	259	26
Loup Loup Creek	18176	98	441	493	339	154	101
Mosquito Creek	2816	111	416	529	346	183	69
Nine Mile Creek	5056	145	425	505	366	139	59
North Fork Pine Creek	10944	127	398	554	352	202	46
Salmon Creek							
Conconully Lake	1920	81	415	504	327	177	89
Conconully Resevoir	1152	76	414	508	321	187	93
North Fork Salmon Creek	12672	100	632	374	321	53	311
Salmon Creek	10176	89	384	543	327	216	58
West Fork Salmon Creek	18816	101	553	405	333	72	220
Total Salmon Creek	**44736**	**97**	**527**	**435**	**328**	**107**	**200**
Okanogan River PSIAC							
Okanogan Mainstem and Interfluves							
Lower Okanogan Outlet	17088	119	326	636	315	321	11
Okanogan Interfluve 01	1856	67	336	648	309	339	27
Okanogan Interfluve 02	1408	93	355	665	337	328	18
Okanogan Interfluve 03	3200	100	434	557	365	192	69
Okanogan Interfluve 04	5888	117	389	577	347	230	42
Okanogan Interfluve 05	3456	150	330	641	325	316	4
Okanogan Interfluve 06	1152	124	325	629	324	305	1
Okanogan Interfluve 07	2560	120	327	630	322	308	5
Okanogan Interfluve 08	192	147	315	651	315	336	0
Okanogan Interfluve 09	4800	124	330	625	327	298	3
Okanogan Interfluve 10	2240	81	359	607	324	282	35
Okanogan Interfluve 11	9088	100	355	599	329	269	25
Okanogan Interfluve 12	5504	88	354	603	321	283	34
Okanogan Interfluve 13	8960	84	365	595	316	278	48
Okanogan Interfluve 14	2880	92	340	627	316	311	24
Okanogan Interfluve 15	9152	112	331	636	318	318	12
Okanogan Interfluve 16	9792	112	353	612	325	287	28

Okanogan Interfluve 17	2048	103	337	643	319	324	18
Okanogan Interfluve 18	1152	90	346	632	317	316	30
Total Okanogan Mainstem	**92416**	**107**	**348**	**617**	**324**	**293**	**24**
Total Okanogan PSIAC	**92416**	**107**	**348**	**617**	**324**	**293**	**24**
Omak Creek	40768	123	424	505	347	158	77
Omak Lake	31488	81	366	581	309	272	57
Open Water Columbia	2112	43	286	691	240	451	47
Siwash Creek	14464	113	456	484	347	137	110
Spectacle Lake/Whitestone	12672	115	369	577	346	231	23
Tallant Creek	4416	87	365	584	319	265	45
Tonasket Creek	17536	142	463	468	369	99	95
Tunk Creek	20672	123	425	490	352	138	73
Wanacut Creek	5696	95	432	514	338	176	94
Wanacut Lake	6272	113	397	533	352	182	45
Sinlahekan Creek PSIAC							
Cecile Creek	7040	105	583	410	340	70	243
Chopaka Creek	4992	111	504	447	341	106	163
Palmer Lake	4608	86	369	583	314	268	55
Sarsapkin Creek	3904	114	583	411	347	64	236
Toats Coulee Creek	39488	107	680	350	312	38	368
Sinlahekan Creek							
Blue Lake	3008	88	452	504	334	170	117
Sinlahekan Creek Headwaters	12544	99	651	364	318	45	333
Sinlahekan Interfluve 01	2176	96	459	499	342	156	116
Sinlahekan Interfluve 02	4096	80	430	523	332	192	98
Sinlahekan Interfluve 03	2304	115	371	583	339	244	32
Sinlahekan Interfluve 04	448	147	340	631	325	306	15
Sinlahekan Interfluve 05	1856	140	384	551	336	215	48
Total Sinlahekan Creek	**26432**	**100**	**530**	**452**	**327**	**125**	**203**
Total Sinlahekan PSIAC	**86464**	**104**	**595**	**407**	**322**	**84**	**273**
Similkameen River PSIAC							
Ashnola River	16832	111	950	282	275	7	675
Pasayten River	62848	108	1238	320	307	14	931
Similkameen River	24704	112	480	517	324	193	156
Total Similkameen PSIAC	**104384**	**109**	**1012**	**360**	**306**	**55**	**707**
Columbia River West WRIA PSIAC							
Whitestone Creek West WRIA	16000	94	393	528	317	210	75
West WRIA Area							
Indian Dan Canyon	6720	101	353	591	311	280	41
Starzman Lake West WRIA	6336	104	332	620	313	307	19
Total West WRIA Area	**13056**	**102**	**342**	**605**	**312**	**293**	**30**
Total Columbia River PSIAC	**29056**	**98**	**370**	**563**	**315**	**248**	**55**

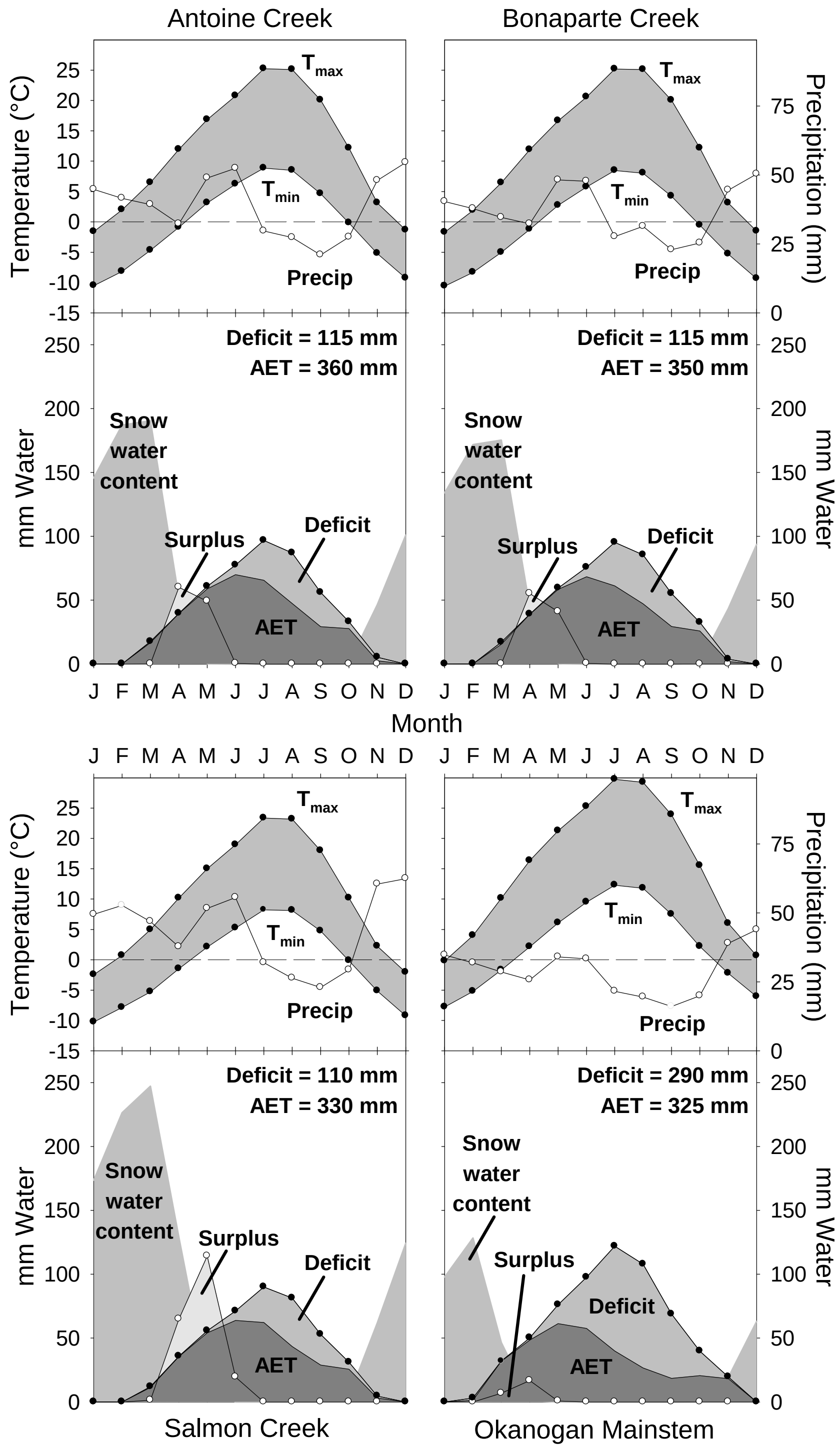


Figure 7. Water balance derived from PRISM climatological means (1971 – 2000) over the course of a year for Antoine Creek, Bonaparte Creek, Salmon Creek, and the Okanogan Mainstem basins (US portions only). Each panel shows temperature and precipitation above and the resulting water balance below. All four basins are shown with the same scale for temperature, precipitation, and water balance. Values reflect averages of all 800 m × 800 m PRISM grid cells in the basin.

DISCUSSION

These calculations are based on the simplest, complete water balance model. This water balance model has been used in all parts of the United States (and elsewhere) for over 50 years to examine watershed hydrological cycles. The method is simple because it is parameterized on temperature and precipitation only, assuming average values for other parameters. Other methods include explicit consideration of incoming and outgoing radiation, cloudiness, wind speed and direction, the daily profile of temperature, and the depth profile of soil water-holding capacity. These other methods require accurate input data that are rarely available over large landscapes. While these other models offer the potential for more accurate calculation, they are more likely to suffer from false precision. These results are therefore best used in a relative sense. Total basin water parameters are unlikely to be absolutely accurate (calibration of this model to specific conditions in the Okanogan would require considerable field research time). But relative values are likely to be very accurate. Soil and atmospheric conditions are similar over the OCD, and therefore, a difference in 10% between watersheds is likely to be a very accurate assessment of relative conditions. This model could be improved with field calibration of results and analysis of irrigation diversions. This model is most sensitive to changes in summer temperature. However, PRISM projects temperature well.

Landscape-scale water balance calculations are best used as relative indicators. Caveats to this analysis follow:

- This model does not consider evaporation from standing bodies of water such as lakes, reservoirs, streams and rivers.

- This model does not consider the effects of irrigation – neither the diversion of water to storage nor the evapotranspiration of irrigation water from crops.

- This model does not account for increased evaporation due to high wind. Accordingly, the model will understate evaporation in areas that are continually windy (i.e., near the Columbia River) compared to areas with similar temperature, precipitation, and soil water-holding capacity that are less windy. Consideration of wind requires more information than is available for such a large study area.

- The model does not consider the effects of differing levels of vegetation. The model assumes continuous coverage by some sort of vegetation. Areas that are too dry to support continuous vegetation will have lower evapotranspiration than the model predicts.

- The grid cell size is 800 m. There is considerable heterogeneity within each grid cell. In areas where grid cells are covered by a considerable portion of water (such as those grid cells adjacent to the Columbia and Okanogan Rivers and lakes, modelled evapotranspiration will be underestimated.

- Aspect and slope considered as flat. South and southwest exposures have higher evaporative demand than north and northeast exposures.

- Water that is surplus is considered to leave the system. The model does not account for re-absorption further downstream. Water percolation below 150 cm is also not considered.

- The model is based on climatological averages between 1970 and 2000. Extreme events in any one month tend to affect the averages. PRISM calculates spatial variation in temperature and precipitation using all the high quality meteorological stations in the US (Figure 8). PRISM grid cell values for areas containing meteorological stations may vary somewhat from the meteorological station values because meteorological values are regressed to elevation. I checked the precipitation values for Omak 2 NW, Moses Mountain Snowtel, Salmon Meadow Snowtel, and Conconully, and the PRISM grid cell values are close to (but not exactly) the station values.

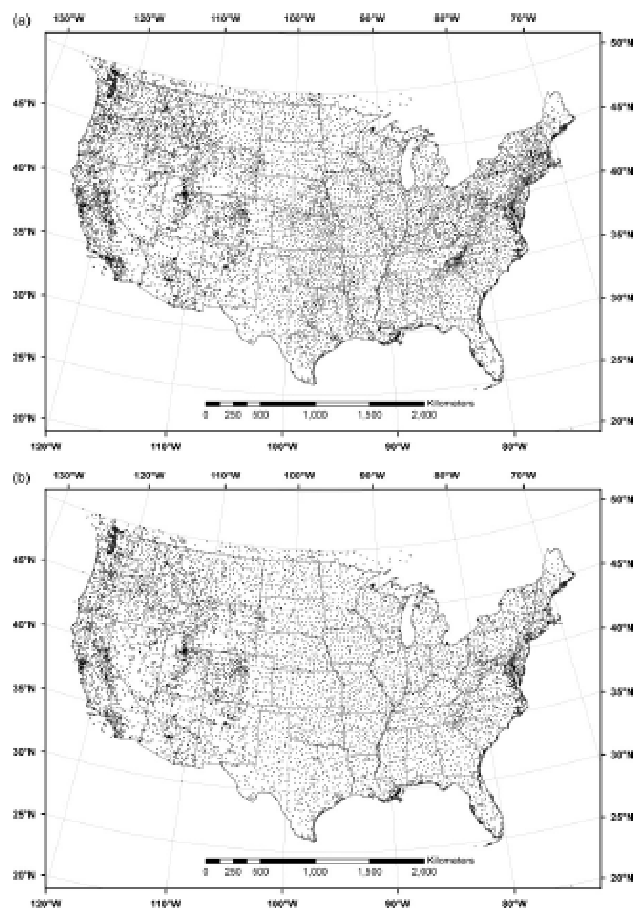


Figure 1. Locations of (a) surface precipitation stations and (b) surface temperature stations used in the interpolation.

Figure 8. Meteorological stations used by PRISM. PRISM uses essentially all meteorological station data and snow course information in the United State to generate interpolation equations. The PRISM interpolations account for orographic factors better than other models and so are probably the best approximations available for areas with varied topography. The PRISM model handles local rain shadows, cool air drainage, and local effects of bodies of water. However, any model represents and approximation of climate, and areas with a low density of meterological stations to guide the equations may be modelled poorly (Figure from Daly *et al.* 2008).

Climate sensitivity of the Okanogan River watershed

The University of Washington Climate Impacts Group modelled how global climate change would be reflected in the Pacific Northwest. Twenty global circulation models of future climate were downscaled for the Pacific Northwest (see details on-line at http://cses.washington.edu/cig/res/ia/waccia.shtml). Because PNW climate projections are for warming and moderately increased annual precipitation, the effect on vegetation and water supply is not immediately apparent. Using the climate projections for the Pacific Northwest, I calculated Deficit for forested plots in Eastern Washington. Under the modelled climate scenarios, Deficit is projected to increase throughout Eastern Washington, but within Washington State, the impacts in the Okanogan River watershed could be among the highest (Figure 10).

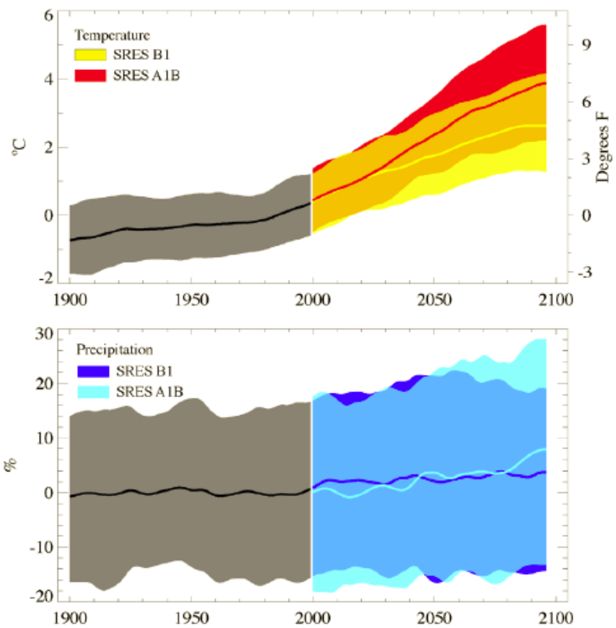


Figure 3. Simulated temperature change (top panel) and percent precipitation change (bottom panel) for the 20th and 21st century global climate model simulations. The black curve for each panel is the weighted average[9] of all models during the 20th century. The colored curves are the weighted average of all models in that emissions scenario ("low" or B1, and "medium" or A1B) for the 21st century. The colored areas indicate the range (5th to 95th percentile) for each year in the 21st century. All changes are relative to 1970-1999 averages.

Figure 9. Modelled climate change for the Pacific Northwest in the 21st century. Graphs represent the ensemble of the 20 IPCC global circulation models downscaled to finer resolution by the University of Washington Climate Impacts Group. The A1B emissions scenario represents a "medium" emission scenario reflecting business as usual with a balanced mixture of energy sources. The B1 emissions scenario represents a rapid conversion to a service-oriented economy with extensive use of non-fossil fuel energy sources (Figure from Littell *et al.* 2009).

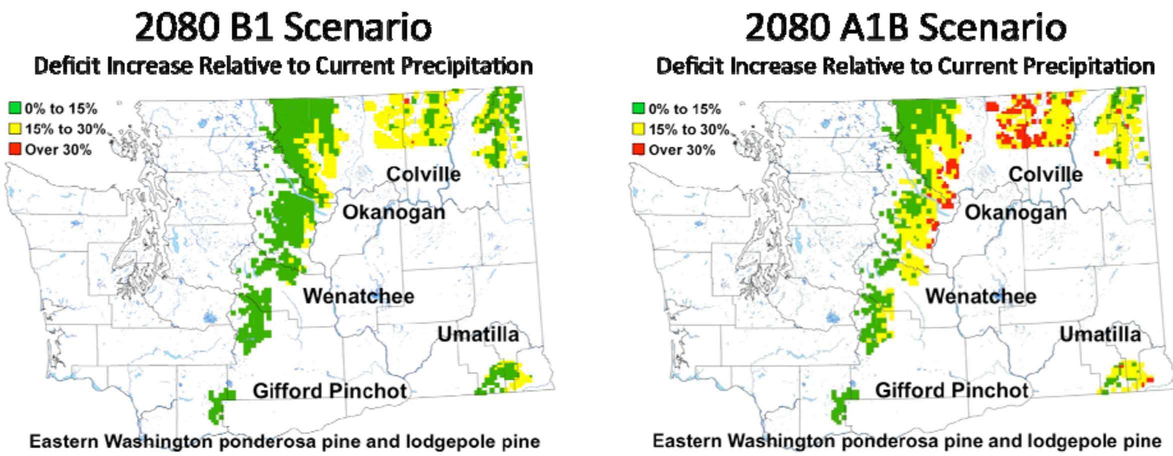


Figure 10. The modelled temperature and precipitation for the B1 (low-emission) and A1B (medium-emission) scenarios were examined for USDA Forest Service monitoring plots containing ponderosa pine and lodgepole pine. Model results for all plots containing ponderosa pine and lodgepole pine indicated higher climatic water deficit in 2020, 2040, and 2080. Climatic water deficit for plots in the Okanogan National Forest and the Colville National Forest rose the greatest percentage. By 2080, assuming the B1 emission scenario, many forest plots are projected to have an increase in Deficit greater than 15% of the current annual precipitation (left). By 2080, assuming the A1B emission scenario, more than half of the forest plots are projected to have an increase in Deficit greater than 15% of current annual precipitation (right). Models project that Deficit will increase for all plots, and AET will decrease for almost all forest plots now containing ponderosa pine or lodgepole pine. It is unlikely that forest structure and composition of these plots will remain unchanged.

In light of these projections for increased climatic water deficit in and near the Okanogan River watershed, decisions based on water availability in the recent past (1971 – 2000) may become increasingly inaccurate. The calculations in this report were based on climatological averages from 1971 – 2000, and those values may not provide an accurate projection of future conditions.

Appendix: Equations for calculation of annual actual evapotranspiration (AET) and annual climatic water deficit (Deficit). Annual values in this report refer to the sum of the monthly values calculated from Eq. 1 – 13. See Figure 1 for a depiction of terms.

Monthly precipitation, P_m, is divided into a monthly rain fraction ($RAIN_m$) and a monthly snow fraction ($SNOW_m$) for each month by the monthly melt factor F_m:

$$T_a \leq 0°C: F_m = 0 \quad [1]$$

$$0°C < T_a < 6°C: F_m = 0.167 \times T_a \quad [2]$$

$$T_a \geq 6°C: F_m = 1 \quad [3]$$

where T_a is the mean monthly temperature. Thus,

$$RAIN_m = F_m \times P_m \quad [4]$$

$$SNOW_m = (1 - F_m) \times P_m \quad [5]$$

The melt factor F_m is also used to determine the monthly snowmelt, $MELT_m$:

$$MELT_m = F_m \times (SNOW_m + PACK_{m-1}) \quad [6]$$

where snow pack for a given month, $PACK_m$, is given by:

$$PACK_m = (1 - F_m)^2 \times P_m + (1 - F_m) \times PACK_{m-1} \quad [7]$$

The monthly water input (or supply) to the system is then:

$$W_m = RAIN_m + MELT_m \quad [8]$$

When water input exceeds potential evapotranspiration ($W_m - PET_m \geq 0$), evapotranspiration proceeds at the potential rate and excess recharges the soil water. If the soil is already at its water-holding capacity, soil moisture remains constant and the excess water is runoff. PET is given by:

$$PET_m = 29.8 \times Days \times DL \times \frac{e_a(T_a)}{T_a + 273.2} \quad [9]$$

where $Days$ is the number of days in the month, DL is the average day length for the month, and $e_a(T_a)$ is the saturation vapour pressure at the mean temperature T_a. The value of $e_a(T_a)$ is given by:

$$e_a = 0.611 \times \exp\left(\frac{17.3 \times T_a}{T_a + 237.3}\right) \quad [10]$$

PET is modelled as an exponentially increasing function of temperature. An increase from 20°C to 22°C increases PET much more than an increase from 10°C to 12°C. At 48.32° latitude in July, the sensitivity to temperature is shown in Figure 11. Temperature sensitivity depends on day length, which in turn depends on time of year and latitude.

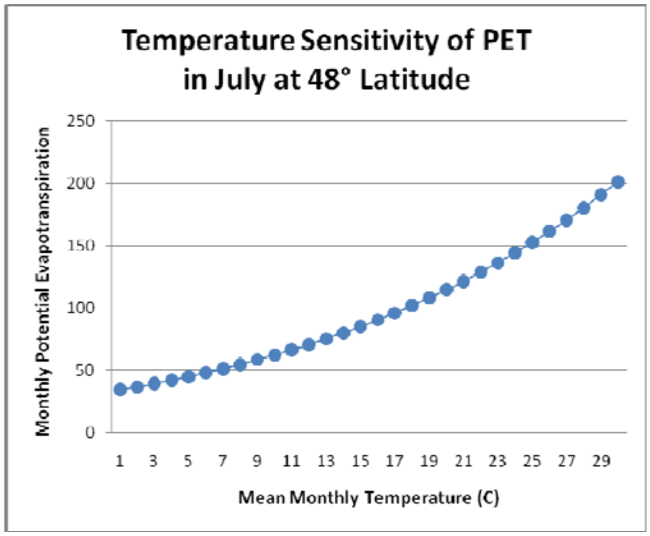


Figure 11. Temperature sensitivity of potential evapotranspiration in Thornthwaite-type models.

The length of the day, *DL*, in hours, is taken from Dingman (2002) and is given by:

$$DL_m = \frac{2 \times \cos^{-1}\left[-\tan(\delta_m) \times \tan(\Lambda)\right]}{\omega} \qquad [11]$$

where δ_m is the solar declination angle at noon on the 15th day of the month, Λ is latitude, and ω is the angular velocity of the earth's rotation (0.2618 radian hr^{-1}).

Soil water balance is given by:

$$SOIL_m = \text{minimum}\{SOIL_{max}, [(W_m - PET_m) + SOIL_{m-1}]\} \qquad [12]$$

where $SOIL_{max}$ is the soil water-holding capacity in the top 200 cm of the soil profile.

When PET is greater than water input ($W_m < PET_m$), evapotranspiration equals the water input plus a fraction removed from soil water storage. Soil water extraction becomes more difficult as the soil becomes drier. The fraction removed from soil water storage is given by:

$$\Delta_{SOIL} = SOIL_{m-1} - SOIL_m = SOIL_{m-1} \times \left[1 - \exp\left(-\frac{(PET_m - W_m)}{SOIL_{\max}}\right)\right] \qquad [13]$$

Actual evapotranspiration (AET_m) then equals the smaller of PET_m or ($\Delta_{SOIL} + W_m$). Deficit is the difference between PET_m and AET_m.

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