Technical Memorandum | DRAFT

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From: Ben Harding, AMEC Environment & Infrastructure
Subject: SWSI Climate Impact Support, Development of Projected Depleted Flows
Date: October 8, 2014

This technical memorandum provides estimates of projected depleted flows ("gauged flows") at important stream gauges on major rivers in Colorado and describes the methods used make those estimates. The projections provided here reflect only projected changes in climate assuming current levels of development.

Projected Depleted Flows

Table 1 shows estimates for projected depleted flows for 2050 at eleven stream gauges in Colorado and for seven scenarios of future climate. The scenarios are constructed based on the entire range of available climate model projections in the CMIP3 and CMIP5 archives, using methods described in this memorandum.

Table 1. Projected depleted flows for 2050, acre-feet/year
Values are rounded to the nearest thousand acre-feet or three significant figures.

	Climate Scenarios							
Basin	**Historical**	**100/0**	**90/10**	**75/25**	**Center**	**25/75**	**10/90**	**0/100**
Yampa River near Maybell	1,110,000	941,000	999,000	1,110,000	1,230,000	1,220,000	1,330,000	1,310,000
White River near Meeker	439,000	241,000	272,000	429,000	549,000	518,000	662,000	647,000
Colorado River near State Line	4,560,000	2,390,000	2,920,000	3,980,000	4,470,000	4,820,000	5,640,000	5,930,000
Gunnison River near Grand Junction	1,780,000	926,000	1,130,000	1,620,000	1,740,000	1,850,000	2,170,000	2,180,000
San Juan River near Carracas	446,000	307,000	373,000	455,000	463,000	490,000	540,000	524,000
Los Pinos River at La Boca	150,000	38,000	57,000	131,000	140,000	149,000	178,000	184,000
Dolores River near Bedrock	277,000	128,000	148,000	264,000	277,000	293,000	326,000	337,000
Arkansas at Lamar	136,000	-669,000	-423,000	-286,000	-184,000	-4,000	155,000	316,000
North Platte River near Northgate	313,000	212,000	246,000	257,000	299,000	337,000	380,000	419,000
Rio Grande near Lobatos	409,000	-688,000	-356,000	-160,000	-39,000	215,000	523,000	620,000
South Platte at South Julesburg	395,000	-911,000	-461,000	-294,000	71,000	387,000	729,000	1,070,000

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The significance of the climate scenarios shown in Table 1 is described in the section *Scenarios of projected climate*. In some scenarios, projected depleted flows are less than zero. This means that under that scenario the projection indicates that some established uses will be unable to obtain their historical supply of water.

Overview of Approach

The objective of this work is to develop estimates of future long-term average depleted flows (i.e. "gauged flows") that reflect the hydrologic impact of projected climate on natural streamflow and beneficial consumptive use. Estimates of the impact of climate change on future natural flows are most commonly made using hydrologic models, but this approach cannot be used to estimate the change in depleted flows directly. Instead, a hydrology model must be used to adjust natural flows and beneficial consumptive use separately, and then an estimate of projected depleted flows can be calculated by subtracting projected depletions from projected natural flows. That is the approach used in this work.

The estimates of projected depleted flows are based on climate scenarios defined using an approach developed through work by the CWCB to update the climate change projections developed as part of the Colorado River Water Availability Study, Phase I (CRWAS-I; CWCB, 2012). That work, as part of Phase II of CRWAS (CRWAS-II), will develop revised estimates of projected naturalized flows and beneficial consumptive use for the basins in the domain of the Colorado River Decision Support System, and estimates of projected *change* in naturalized flow and beneficial consumptive use for the entire State of Colorado. CRWAS-II incorporates new climate model projections produced in support of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2012). These new model projections are referred to as the CMIP5 archive and they supplement the CMIP3 archive that supported the IPCC's Fourth Assessment Report (IPCC, 2007) and was used as the basis for CRWAS-I. CRWAS-II also refined the methods used to develop scenarios of future climate on which estimates of future hydrologic change will be based, and those refined methods are the basis for the definition of scenarios described in this memorandum

The historical depleted streamflow and historical consumptive water use data (along with estimates of historical trans-mountain diversions) used in this work were taken from SWSI 2004 (CWCB, 2004) and SWSI 2010 (CWCB, 2011). In some cases, data from CRWAS-I were used to refine data from the SWSI reports.

Data were obtained for eleven of the stream gauges included in the SWSI update. For each gauge, the depleted flows were "naturalized" by adding back estimated historical consumptive use (for both agricultural and municipal & industrial uses) and any exports and by subtracting any imports. The resulting naturalized flows and the consumptive uses were separately adjusted using estimates of projected change in natural flow and consumptive irrigation requirement developed using hydrology modeling conducted by the Bureau of Reclamation, and the naturalization process was then reversed to obtain estimates of projected depleted flows. Neither exports nor imports were adjusted in this work.

Estimates of projected depleted flows were made for seven scenarios of future climate that have been developed for CRWAS-II. The estimates represent how the current historical flows might be different if a particular climate scenario came to be. The estimates are based on the current level of development, as represented by historical consumptive use and therefore do not reflect any assumption about future changes in the level of development.

Scenarios of projected climate

An approach developed as part of Phase II of CRWAS was used to define seven future climate scenarios for 2050. Each climate scenario is constructed from a "pool" of ten projections that are selected from the available climate projections in the combined CMIP3 and CMIP5 archives according to an approach described in CRWAS Phase II Climate, Task 1*, Approach for constructing climate scenarios*. Here we provide a brief discussion of the significance of the CRWAS-II climate scenarios.

The seven climate scenarios are listed in Table 2, in ascending order of the degree of stress they will impose on water resources systems. That stress is characterized by a combination of the projected change in average natural flow and the projected change in average consumptive irrigation requirement (CIR), which serves as a proxy for water use. The names of the scenarios are built from the nominal non-exceedance percentiles of projected changes in CIR and runoff that are used to "anchor" a pool of climate projections. In each scenario, the ten climate projections that are "nearest" the nominal point (in terms of the non-exceedance percentile of change in both CIR and runoff) make up the pool of projections that define the scenario.

Comment [FT1]: this doesn't match with below—sure you don't mean descending?

Table 2. CRWAS-II climate scenarios.

Scenario designation	Nominal Water use condition	Nominal Streamflow condition	Overall System Stress
100/0	highest	driest	Highest
90/10	90th percentile	10th percentile	
75/25	75th percentile	25th percentile	
Center	median	median	
25/75	25th percentile	75th percentile	
10/90	10th percentile	90th percentile	
0/100	lowest	wettest	Lowest

In CRWAS-I, projections were initially selected using temperature and precipitation anomalies (projected changes) as a proxy for the natural flow anomaly. For example, it was expected that a projection with a large temperature increase and a large precipitation decrease would have a low natural flow. The complexity and non-linearity of hydrologic processes and effects arising from changes in the seasonality of precipitation confounded that selection method, so a revised approach was adopted whereby projections were selected based on their projected natural flow anomaly. In this Phase II work, consideration of the "water use anomaly" has been added to the selection process. This has been done because the objective for an ensemble of scenarios is to cover the range of impacts to the *water resources system*, and that system is stressed not only by reduced natural flow, but also by increased water use.

The middle five scenarios in Table 2 conform generally to the CRWAS-I selection criteria with respect to natural flow but each is also based on an explicit criterion for the projected change in CIR, which was not a feature of projection selection in CRWAS-I.

100/0. The *100/0* scenario is constructed from the ten projections with the most severe combination of low natural flow and high water use. This is the most stressful scenario, and is almost certainly more stressful than the driest projection used in CRWAS-I.

90/10**.** The *90/10* scenario is constructed from the ten projections that are nearest to the combination of the 10^{th} percentile of all projected natural flows (i.e. only approximately 10% of the projections have a lower natural flow) and the 90^{th} percentile of all projected values of CIR (i.e. only approximately 10% of the projections have higher CIR.) This is also a severe scenario, but it is not as severe as the 100/0 scenario. It is consistent with the driest projection used in CRWAS-I in that the selection in both cases was based on the 10^{th} percentile of natural flow. However, it is likely that this scenario is more stressful than the driest projection in CRWAS-I because of the use of the 90^{th} percentile of CIR as a selection criterion.

75/25**.** The *75/25* scenario is constructed from the ten projections that are nearest the 25^{th} percentile of all projected natural flows and the 75^{th} percentile of all projected values of CIR. This is scenario is less severe than the 90/10 scenario and is very likely within the upper bound of stress represented by the CRWAS-I projections.

Center**.** The *center* scenario is constructed from the ten projections that are nearest the median (50^{th} percentile) of all projections of natural flow and CIR. This scenario is in the middle of the range of severity.

25/75**.** The *25/75* scenario is constructed from the ten projections that are nearest the 75^{th} percentile of all projected natural flows and the 25^{th} percentile of all projected values of CIR. This is scenario is less severe than the Center scenario, and is very likely within the lower bound of stress represented by the CRWAS-I projections.

10/90. The *10/90 s*cenario is constructed from the ten projections that are nearest to the combination of the 90^{th} percentile of all projected natural flows and the 10^{th} percentile of all projected values of CIR. This scenario shows increases in flow in all basins. It is consistent with the wettest projection used in CRWAS-I in that the selection in both cases was based on the 90^{th} percentile of natural flow. However, it is likely that this scenario is less stressful than the wettest projection in CRWAS-I because of the use of the 10^{th} percentile of CIR as a selection criterion. When characterized over the entire state (as opposed to a particular basin) existing conditions are approximately equidistant from the 25/75 and 10/90 scenarios. Because the projected effects of climate change vary from one basin to another, the point across the range of scenarios in which projected flow is roughly equal to historical flow will also vary and does not always fall between the 25/75 and 10/90 scenarios.

0/100. The *0/100* scenario is constructed from the ten projections with the least stressful combination of high natural flow and low water use. This scenario shows substantial increases in flow in all basins. This is the least stressful scenario, and is very likely less stressful than the wettest projection used in CRWAS-I.

Estimates of projected runoff and CIR were developed from hydrologic modeling done by the Bureau of Reclamation (Brekke et al., 2014). These hydrologic simulations included 112 CMIP3 projections and 97 CMIP5 projections, for a total of 209 projections. Gridded output data from these model runs were obtained from Reclamation. CIR was calculated as the difference between potential evapotranspiration for the vegetation represented in a grid cell (petnatveg) and actual evapotranspiration (et) for that grid cell. Projected runoff was extracted directly from model output data sets. The gridded data were aggregated to the eleven basins listed in Table 1 and change factors for the nominal 2050 time frame were calculated for each variable and each projection by comparing average simulated conditions for the period 1970-1999 to average simulated conditions for the period 2035-2064. Runoff change factors were estimated based on all land area in a basin while changes in CIR were estimated separately for agricultural lands and municipal lands. The change factors for agricultural lands were applied to historical agricultural consumptive use while the change factors for municipal lands were applied to historical municipal consumptive use (which we assume to arise predominantly from irrigation of landscape vegetation.) Municipal consumptive use was assumed to be 40% of municipal diversions.

For each of the scenarios described above, the selected projections making up the pool were combined by averaging their projected change factors for each basin.

Historical Depleted Flows

Historical depleted flows were taken from SWSI 2004 (CWCB, 2004). The depleted flows used in this work are highlighted in Appendix A.

Historical Beneficial Consumptive Use and Exports

Estimates of historical beneficial consumptive use were taken from SWSI 2010 (CWCB, 2011). The estimates of agricultural and municipal & industrial water use used in this work are in Appendix B. Exports from and to basins were estimated from Figure 7-32 in SWSI 2004 (CWCB, 2004). The estimated levels of exports and imports are shown in Appendix B. Municipal use in SWSI 2010 was reported in terms of diversions. Municipal consumptive use was assumed to be 40% of diversions.

Historical Natural Flow

Historical natural flow is estimated by adjusting historical depleted flows by the effect of consumptive use, exports and imports. The following equation is used to calculate long-term average natural flows:

$$Q_n = Q_d + CU + E - I$$

Where:

- Q_n :: natural flow,
- Q_d :: depleted flow,
- CU :: consumptive use,
- E :: exports, and
- I :: imports.

When calculating long-term average natural flow, change in storage in reservoirs can be ignored.

Projected Natural Flows

The historical natural flows were adjusted by application of change factors to reflect the impact of projected future climate conditions. The change factors used in this work were developed for each scenario based on the hydrology modeling of the Bureau of Reclamation as described above. Projected average natural flows were estimated for each scenario for each gauge by multiplying the appropriate average annual change factor by the long-term average annual historical natural flow for the gauge.

Projected beneficial consumptive use

Changes in climate will affect the consumptive use of water for agricultural and landscape irrigation and for industrial cooling processes. Agricultural consumptive use and municipal & industrial consumptive use from landscape irrigation were adjusted to reflect the effect of changing climate. No adjustment was made to industrial cooling process use. Municipal & Industrial consumptive use was estimated to be 40% of the diversions in Appendix B.

Comment [FT2]: From what to what?

The consumptive use of water in the basin contributing to a gauge was adjusted by application of change factors to reflect the impact of projected future climate conditions. The change factors used in this work were developed for each scenario based on the hydrology modeling of the Bureau of Reclamation as described above. Projected consumptive use was estimated for each scenario for each gauge by multiplying the appropriate average annual change factor by the long-term average annual historical consumptive use above the gauge. Separate adjustments were made for agricultural and municipal & industrial consumptive use.

Calculation of Projected Depleted Flows

The projected depleted flows are calculated by reversing the naturalization calculation. The following equation is used to calculate depleted flows:

$$Q_{dp} = Q_{np} - CU_p - E + I$$

Where:

- Q_{dp} :: projected depleted flow,
- Q_{np} :: projected natural flow,
- CU_p :: projected consumptive use,
- E :: exports, and
- I :: imports.

References

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Appendix A: SWSI 2004 Flow Data

Site Name	USGS Site Number	Mean Annual Streamflow (AF/year)	Period of Record
Table 3-2 Summary of Selected USGS Stream Gages for the Arkansas River Basin			
Arkansas at Cañon City	7096000	534,289	1890-2002
Fountain Creek at Pueblo	7106500	73,304	1922-2002
Arkansas at Las Animas	7124000	157,836	1939-2002
Purgatoire near Las Animas	7128500	67,633	1922-2002
Arkansas at Lamar	7133000	135,856	1913-2002
Table 3-4 Summary of Selected USGS Stream Gages for the Colorado Basin			
Blue River below Green Mountain Reservoir	9057500	328,785	1942-2002
Eagle River below Gypsum	9070000	412,586	1946-2002
Roaring Fork at Glenwood Springs	9085000	877,836	1906-2002
Plateau Creek near Cameo	9105000	128,999	1936-2002
Colorado River near Kremmling	9058000	733,654	1962-2002
Colorado River near State Line	9163500	4,555,526	1913-2002
Table 3-6 Summary of Selected USGS Stream Gages for the Dolores/San Juan/San Miguel River Basin			
San Juan River near Carracas	9346400	457,983	1961-2002
Los Pinos River at La Boca	9354500	173,947	1951-2002
McElmo Creek near Colorado-Utah State Line	9372000	37,647	1951-2002
Dolores River near Bedrock	9171100	299,576	1971-2002
Table 3-8 Summary of Selected USGS Stream Gages for the Gunnison River Basin			
Taylor River at Almont	9110000	236,409	1910-2002
Gunnison River near Gunnison	9114500	523,465	1910-2002
Tomichi Creek at Gunnison	9119000	124,055	1937-2002
Uncompahgre River at Delta	9149500	218,442	1938-2002
Gunnison River near Grand Junction	9152500	1,783,759	1896-2002
Table 3-10 Summary of Selected USGS Stream Gages for the North Platte River Basin			
Laramie River near Glendevey	6657500	52,312	1904-1982
Sand Creek at Colorado-Wyoming State Line	6659580	7,518	1968-2002
North Platte River near Northgate	6620000	310,389	1915-2002
Table 3-12 Summary of Selected USGS Stream Gages for the Rio Grande			
Saguache Creek near Saguache	8227000	43,934	1923-2002
Rio Grande near Del Norte	8220000	596,901	1890-2002
Alamosa River above Terrace Reservoir	8236000	74,965	1914-2002
Rio Grande near Lobatos	8251500	408,655	1899-2002
Conejos River near Magote	8246500	217,353	1903-2002
Table 3-14 Summary of Selected USGS Stream Gages for the South Platte River Basin			
Poudre	6752000	270,981	1881-2002
South Platte at South Platte	6707500	289,740	1896-2002
South Platte at Kersey	6754000	651,466	1901-2002
South Platte at South Julesburg	6764000	395,314	1902-2002
Table 3-16 Summary of Selected USGS Stream Gages for the Yampa/White/Green River Basin			
Yampa River at Steamboat Springs	9239500	336,638	1910-2002
Yampa River near Maybell	9251000	1,134,945	1916-2002
Little Snake River near Lily	9260000	417,948	1921-2002
North Fork White River at Buford	9303000	229,899	1952-2001
White River near Meeker	9304500	451,554	1909-2002

Appendix B: SWSI 2010 Water Use Data

From Table 4-9 Summary of M&I and SSI demands for each basin and statewide.

Basin	Demand Type	2008 diversion, (AF/year)
Arkansas	M&I	196,000
	SSI	58,400
	Total	254,400
Colorado	M&I	63,000
	SSI	5,480
	Total	68,480
Gunnison	M&I	20,000
	SSI	260
	Total	20,260
Metro	M&I	437,000
	SSI	64,400
	Total	501,400
North Platte	M&I	500
	SSI	—
	Total	500
Rio Grande	M&I	18,000
	SSI	—
	Total	18,000
South Platte	M&I	206,000
	SSI	28,320
	Total	234,320
Southwest	M&I	22,000
	SSI	2,310
	Total	24,310
Yampa/White	M&I	12,000
	SSI	28,590
	Total	40,590
Statewide	M&I	974,500
	SSI	187,760
	Total	1,162,260

From Table 4-12 Estimated current agricultural demand by basin

Basin	Irrigated Acres	Irrigation Water Requirement (AF/year)	Water Supply-Limited Consumptive Use (AF/year)
Arkansas	428,000	995,000	542,000
Colorado	268,000	584,000	485,000
Gunnison	272,000	633,000	505,000
North Platte	117,000	202,000	113,000
Republican	550,000	802,000	602,000
Rio Grande	622,000	1,283,000	855,000
South Platte	831,000	1,496,000	1,117,000
Southwest	259,000	580,000	382,000
Yampa/White	119,000	235,000	81,000
Statewide Total	3,466,000	6,819,000	4,791,000

From Figure 7-32, SWSI 2004, Estimated historical exports/imports

Export Basin	Import Basin	Quantity (AF/Year)
Colorado River	South Platte	400,000
Colorado River	Arkansas	135,000
Colorado River	Rio Grande	10,000
Total		545,000