Climate Change and the Upper Dolores Watershed:
A Coldwater-fisheries Adaptive Management Framework

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Prepared by the
Dolores River Anglers Chapter of Trout Unlimited
In Association with Mountain Studies Institute

ACKNOWLEDGEMENTS

The Dolores River Anglers chapter of Trout Unlimited is pleased to present the analysis, findings and recommendations resulting from its examination of the potential impacts of climate change on trout habitat and populations in the upper Dolores River watershed of southwestern Colorado.

This report represents a two year intensive effort on the part of a small project team of DRA volunteers, working with two professional environmental consultants (Raymond Rose, PHD environmental engineer and Ann Oliver, MSc Fisheries and Wildlife Biology), and the Mountain Studies Institute of Durango/Silverton (special thanks to Marcie Bidwell, Executive Director; Esme Cadiente, Hydrologist; and Anthony Culpepper, GIS professional). Dolores River Anglers is deeply indebted to these participants but takes full responsibility for all content, including any errors and omissions.

We are also indebted to our funders, the Colorado Water Conservation Board, The Montezuma Land Conservancy, the Southwestern Conservation District, Trout Unlimited (national), Colorado Trout Unlimited, and our local chapter, the Dolores River Anglers.

In association with these generous funders, well over 2,200 hours of “citizen science” volunteer time has been devoted to this project on the part of Dolores River Anglers members, particularly Matt Clark and Duncan Rose (our project co-directors), Raymond Rose (also one of our two consultants) and Dale Smith (secretary of the chapter). Duncan Rose is the author of this document. Our consultants, Raymond Rose and Ann Oliver, provided invaluable counsel and editing assistance.

The primary audience for this document are our DRA chapter members, our dedicated public managers who manage our home waters, our colleagues in other Trout Unlimited chapters and our great Trout Unlimited staff. While carefully based on credible science, it incorporates observations from countless happy hours observing trout and trout habitat in the Study Area by chapter members. It is, then, written for the inquiring angling-related public rather than as a scientific research document for the science community.

A special thanks to the folks facing the tough decisions ahead in managing our invaluable trout fisheries: Jim White, Fish biologist, Colorado Parks and Wildlife; Clay Kampf, Fish Biologist, San Juan National Forest; and Shauna Jensen, Hydrologist, San Juan National Forest.

A special tip of the hat to national Trout Unlimited staff members Garrett Hanks for the very substantive input he provided the project and Matt Mayfield, GIS professional, for his early-on technical suggestions.

This document should be reviewed in close association with its companion document, also prepared by the project team, entitled *Limiting Factors in Mountain Stream Trout Habitat– A State of the Science Review.* Raymond Rose and Ann Oliver (see above) were the principal (consulting) authors of that document with contribution from Duncan Rose.

Trout Unlimited’s stated vision is clear: “By the next generation, Trout Unlimited will ensure that robust populations of native and wild coldwater fish once again thrive within their North American range, so that our children can enjoy healthy fisheries in their home waters.”

It would be difficult to conceive of anything more relevant to that vision for the upper Dolores watershed than this project.

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Climate Change and the Upper Dolores Watershed: *A Coldwater-fisheries Adaptive Management Framework*

SECTION 1: INTRODUCTION AND OVERVIEW

WHY THIS REPORT?

- This report is produced by Dolores River Anglers. Officially certified in 2012, Dolores River Anglers (DRA) is an active chapter of Trout Unlimited (TU), supporting as "home waters" the Upper Dolores River and Mancos River watersheds.
- Found within Southwest Colorado (the "Four Corners" area), these watersheds lie at the transition between high desert and several major mountain ranges. Due to this location, and in the face of the anticipated unrelenting forces of climate change, the Chapter recognizes that fundamental, even radical, ecological changes will likely occur throughout the two watersheds and will continue well into the distant future.
- Projected changes in air temperature and patterns of precipitation will likely have substantial impact on the persistence of trout habitat in our two watersheds, especially in the substantial miles of lower elevation stream reaches. Several of these lower elevation streams are designated by the Colorado Water Conservation Board as "Outstanding Waters", in part for their cutthroat trout habitat—Little Taylor, Upper Stoner, Spring Creek, and Rio Lado.
- The hard reality is that our local fisheries will likely be considerably different from current conditions in as little as 20 years. To most cost effectively sustain our coldwater fisheries for future generations, we feel we need to fully understand what changes to our local waters are most likely to occur. Then, in collaboration with those who manage out local waters, we can assist the linking of those changes to the most appropriate (and most cost effective) long-term, in-stream, and near-stream best management practices ("BMPs").
- To fully understand the impact of the expected changes and to link them to appropriate BMPs, we need to understand how these changes are likely to impact the ecological Limiting Factors that govern the viability of native and wild trout habitat and associated populations in our area.
- To that end, DRA has taken the lead in working with National TU Research staff, local fisheries-related agency staff (Colorado Parks and Wildlife and San Juan National Forest), the Mountain Studies Institute and other conservation oriented organizations in developing and field testing a decision support framework that provides guidance for watershed-wide down to stream-reach BMP investment. This framework is called CAMF—Coldwater-fisheries Adaptive Management Framework.

What Is a Coldwater-fisheries Adaptive Management Framework?

- CAMF is a decision support framework. It is focused at the strategic level of planning and is meant to assist the development of management level trout habitat planning and decision making by providing a multi-scale context (from region to watershed to stream) context. Management planning deals with stream, reach and site-specific management, often in the form of near-stream or in-stream intervention. However, DRA recognizes that geophysical and other ecological factors some distance away from the stream can significantly impact trout habitat persistence and, consequently, management activity may be necessary and effective well away from the stream.

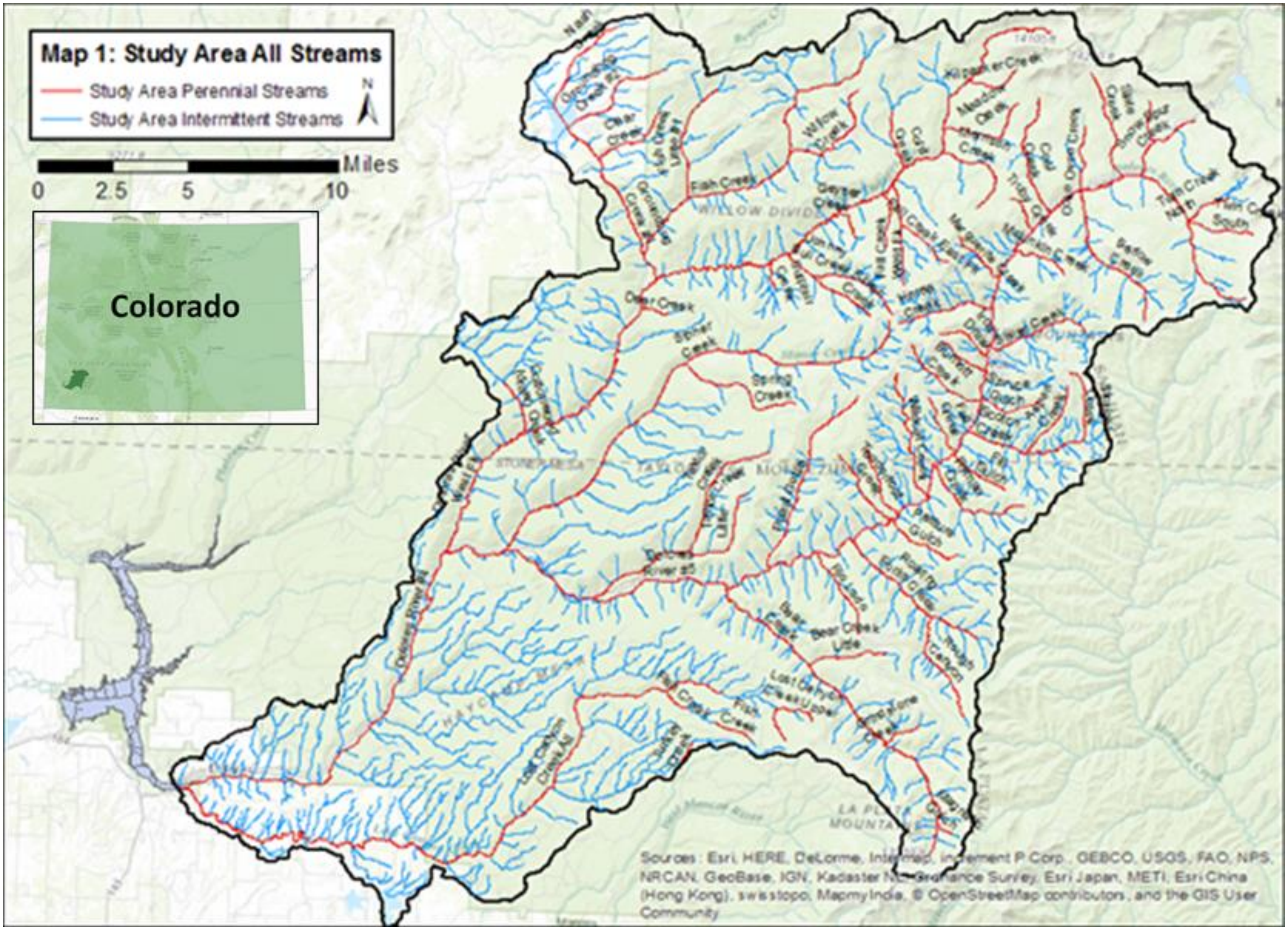
- Effective management planning requires a "big picture" context within which to make the on-the-ground investment decisions. What are the major forces at work at the watershed and even the regional level that are likely to shape trout habitat and affect trout populations in our Study Area over the long run? Understanding these forces makes for more effective mid- and shorter-term management planning.

- CAMF is just such a strategic level context, a strategic framework. It is a carefully structured effort to systematically identify and map long-term native and wild trout **strongholds** within the evolving context of climate change. This effort is specifically focused over the long run (to the year 2100) on the Upper Dolores watershed. The study area (Study Area) encompasses all water draining into the Dolores River from the confluence with Lost Canyon Creek (just above where the Highway 145 bridge crosses the Dolores) up to the headwaters of that drainage area. (Map 1).

- Strongholds are those streams/reaches where habitat conditions are expected to continue to support trout in spite of overall significant changes to fundamental ecological, geophysical and hydrological attributes of mountain streams that may result from climate change throughout the Southwest.

- DRA recognizes that it can play a useful role as a partner to support stream and fish management activities implemented by those agencies charged with managing trout habitat and populations in the Study Area. Identifying strongholds within the context of long-term climate change can provide a useful strategic framework to assist Colorado Parks and Wildlife staff, San Juan National Forest staff and local land owners, in identifying and investing in appropriate BMPs to, in the words of Trout Unlimited's mission statement, "protect, reconnect, restore, and sustain" the diminishing coldwater resources of the Study Area.

- CAMF provides:
    a. A compilation, summarization and systematic analysis of available studies and data on existing trout habitat and population conditions, limiting factors, and climate change predictions relevant to the Study Area;
    b. A listing of streams ranked by long-term climate change vulnerability;
    c. A geographic Information Systems (GIS) based mapping of the data and findings, and
    d. A summarized list of suggested actions to support the TU strategy of protect, reconnect, restore, and sustain.



Map 1: Study Area All Streams
Study Area Perennial Streams
Study Area Intermittent Streams
N
Miles
0 2.5 5 10
Colorado
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

- From this output, the various agencies charged with managing the trout habitat resources within the Study Area and those impacted by such management have available to them an overarching context within which to make both mid-term and short-term, management investment decisions as the long-term nature of climate change evolves.

Our Approach

- Our approach seeks to systematically merge existing trout habitat science, ecological limiting factors, geographic information systems (GIS) analysis, and local stream knowledge to form a strategic framework within which to answer the core question: *"Given increasingly limited private, state and federal resources, and in the face of substantial habitat change, where should our Chapter, working with and through local public and private partners, focus its in-stream and near-stream efforts most cost effectively over the long run?"*
- As noted, the intent of CAMF is to facilitate the systematic identification of trout "stronghold" streams in the face of substantial changes to trout habitat over coming decades due to climate change. These changes are likely to lead to diminished habitat for trout in our area. This knowledge can guide management decisions as to which in-stream and near-stream best management practices are likely to be most cost effective over the long run.
- Our approach embraces three planning/analytic paradigms:
  1. Ecological limiting factors analysis
  2. Adaptive management based planning
  3. Ecological vulnerability analysis

Webster's dictionary defines an **ecological limiting factor** as "an environmental factor that limits the growth or activities of an organism or that restricts the size of a population or its geographical range." Alternatively, "An environmental variable that limits or slows the growth or activities of an organism; also any environmental variable whose presence, absence, or abundance restricts the distribution, numbers or condition of an organism." Our focus is on the identification of limiting factors and associated thresholds for mountain stream trout populations.

Adaptive management planning recognizes that, due to complex forces at work, any of a large number of feasible futures may emerge. Rather than targeting a single future scenario, it seeks to establish a framework of feasible future scenarios, where multiple futures may be equally feasible and yet substantially different. From these multiple feasible scenarios a set of management responses is distilled, each of which should still work should an alternative and substantially different future scenario later emerge that requires a modification of management direction; large-scale solutions that preempt others are to be avoided or minimized. Adaptive management planning is particularly useful in climate change analysis where widely divergent futures are feasible and no single most likely future scenario is identifiable.

Underlying our approach are concepts of **ecological vulnerability**—the degree to which an ecological system can be expected to experience harm from a specified disturbance or set of disturbances. For our purposes, we seek to identify potential major disturbances to trout habitat due to climate change, then identify and rank-order trout-inhabited streams in our Study Area in order of those least likely to be impacted by each major identified disturbance (limiting factor). At the heart of vulnerability is **resistance**—a habitat's capacity to not succumb to threatening disturbances, and **resilience**—its capacity to recover from a disturbance.

- Through employing these three paradigms, the CAMF framework, then, resolves two fundamental questions:
    1. Which streams in the Upper Dolores watershed are likely to provide viable trout populations through the end of the 21^{st} century ("strongholds")?
    2. What management strategies emerge as most relevant?

In resolving these two questions, CAMF, in turn, requires considering two related questions:

3. Which ecological factors, with their associated threshold values, limit the persistence and survivability of trout populations?
4. How are these factors likely to be adversely affected as climate change impacts the Upper Dolores watershed?

HOW THIS REPORT IS ORGANIZED?

The remainder of this report consists of a Summary of Findings and Recommendations followed by nine sections; three appendices supplement the nine sections. The nine sections respond to the four questions identified in the previous paragraph and are themselves oriented around questions in a step-by-step manner that lead to our findings and recommendations.

Section 1: Introduction and Overview

Section 2: Summary of Findings and Recommendations

Section 3: Which habitat-based ecological factors limit the persistence of trout populations?

Section 4: How is climate change likely to affect the Southwest and Southwestern Colorado?

Section 5: What does Rangwala/Mountain Studies Institute's analysis of Climate Change and the San Juan Mountains mean for our Study Area?

Section 6: How is climate change already affecting the Study Area?

Section 7: How are these observed and simulated impacts likely to affect trout habitat in the Upper Dolores watershed?

Section 8: Which streams in the Upper Dolores watershed are likely to sustain viable trout populations through the end of the 21^{st} century ("strongholds")?

Section 9: What strategic management strategies emerge as most relevant?

SECTION 2: SUMMARY OF FINDINGS AND RECOMMENDATIONS

SUMMARY OF FINDINGS:

- With very few exceptions, c*urrent* coldwater-fisheries in the Study Area are healthy; trout populations are viable.
    - There are 46 identified trout streams containing approximately 295 stream miles of self-sustaining trout habitat, with over 1430 square miles of contributing watershed.
    - Four species of trout (cutthroat, cutbow, rainbow and brown), one of char (brook) and one species of salmon (kokanee) inhabit the area.
    - At least one stream has a reach hosting a very pure strain of cutthroat.
    - Virtually every long-term perennial stream has a self-sustaining trout population.
    - If there were no systemic environmental changes on the horizon, there is little reason to suspect that this state would change substantially in the foreseeable future.
- Our careful review of mountain stream ecological systems and trout habitat research has identified the following as Limiting Factors for trout in these habitats:
    - Stream temperature
    - Flow regime (includes volume, rate and periodicity)
    - Stream morphology (includes segment length, connectivity, gradient, barriers and refugia)
    - Pollutants (includes nutrient loadings)
    - Biotic competition and hybridization (wild vs native, cold vs warm water, forage base)
    - Sedimentation (risk of erosion from wildfire)
    - Disease
- After extensive review of the state of the science for each factor, critical threshold values (beyond which trout populations may not persist) were identified and are detailed in a separate companion document (also developed by this study team) entitled *Mountain Stream Trout Habitat Limiting Factors – A State of the Science Review*.
- Highly credible science indicates that substantial systemic ecological changes are already underway, thought to be due largely to the greenhouse effects driving climate change.
- What the exact extent of these changes will be in our area cannot yet be specifically determined. Instead, climate science can give us a characterization of the expected change through the development of several potential scenarios for the Study Area over the timeframe from now to 2100.
- Our review of climate change science specific to the Southwest indicates that changes will increasingly affect our Study Area between now and 2100. The major impacts fall in two dimensions: temperature and precipitation.

- Downscaled research that specifically simulates climate change in the San Juan Mountains identifies three core "clusters" of scenarios found within 72 modeled scenarios that characterize the impact on the Study Area. These clusters are termed: Warm and Wet, Hot and Dry and Feast and Famine.
- Of the three, two (Hot and Dry and Feast and Famine) pose the most serious challenges to trout habitat. Drought is the underlying force for both. In both scenarios, simulations indicate drought will steadily increase in both intensity and duration through the study period.
- While reflecting a less intense impact on our area, Warm and Wet could still pose challenges through increased flow magnitudes, altered flow timing and increased inter- and intra- species competition among fish and among macroinvertebrates.
- Substantial changes are in store for a key driver of climate in our area, namely the Southern Oscillation (El Nino, La Nina and "Normal" weather cycles). These changes, coupled with a warming desert terrain, will directly impact the Study Area.
- Offsetting these drought driving impacts is the effect of our surrounding high mountains, which will continue to add precipitation through orographic effects.
- In all 72 modeled scenarios, temperatures are likely to increase steadily over the analysis period (2016 – 2100). Precipitation may well stay close to current levels (models are inconclusive), but will change "phase proportions" (less snow, more rain) and timing (snow starting later and ending earlier). This transition will change streamflow patterns, likely reducing base flow, thereby resulting in less flow in late summer and early fall.
- Associated evapotranspiration due to rising temperatures will reduce available *effective* precipitation (i.e. precipitation that reaches the stream to benefit trout). This reduction will become increasingly significant as temperatures rise.
- If Hot and Dry or Feast and Famine scenarios prevail, drought will likely increase in both intensity and duration, with potentially severe drought becoming prevalent between 2070 and 2100.
    - Trout habitat will become increasingly challenged, largely through lower flows caused by drought and phase changes in precipitation, increasing stream temperatures, periodic flash flooding, and increased sedimentation due to an increasing wildfire frequency.
    - As air temperatures rise, water temperatures will follow. Elevation, stream shade, stream depth, flow rate, volume, and timing and amount of precipitation will affect how substantially each stream will be affected. Lower, slower, non-shaded streams may be so significantly impacted by 2070 that they no longer support cold-water species.
    - Warm water temperatures cause trout to expend more energy to survive, reducing both growth and fertility. Warm waters also reduce disease resistance.
    - As high headwaters warm, more high-elevation habitat opens up for trout migration where no barriers exist, (while lower habitat degrades for some species); however, that higher habitat is challenged by smaller stream size which is more vulnerable to reductions in flow during drought periods and an increase in flash flooding.

  - Finally, effective streamflow will be increasingly reduced—either permanently or periodically—with smaller and lower tributaries experiencing the greatest impact. Habitat will likely be substantially and increasingly reduced over the analysis period.

- Streams with high headwaters, large watersheds, numerous high-elevation feeder streams, and high levels of northern aspect shading, narrow canyon walls and healthy riparian cover will likely be most resistant and resilient.

- On the positive side, trout populations currently appear very healthy and have appeared so for many decades. Trout populations have survived periods of roughly equivalent extreme stress in prehistoric times and yet thrive today.

- Important data reflecting the state of threshold values for the seven Limiting Factors exist for the Study Area.

  - Two flow gauges exist; only one—just below Rico—has no irrigation diversions above stream and, consequently, reflects entirely natural flow metrics.

  - SNOTEL data from four sites in the Study Area are available, reflecting precipitation (snow-equivalent and rain) and air temperature data.

  - StreamsStats, a hydrologic modeling website from USGS, facilitates modeled streamflow for all streams in the watershed where watersheds are greater than four square kilometers. All precipitation and streamflow values available through StreamStats are derived from regression equations based on data from Study Area SNOTEL sites and other (similar) Colorado watersheds. PRISM, a NOAA supported source of mapped weather data from Oregon State University, is incorporated into the StreamStats modeling.

- Summarizing our findings from downscaled climate change research, the key to trout habitat and population persistence for our Study Area reduces to two critical habitat factors:

  - Hydrological conditions (streamflow at sufficient volume and within tolerable rates of flow for both peak and low-flow levels), and

  - Stream temperatures within acceptable range.

- A listing of streams by vulnerability to streamflow related climate change impacts is presented by quintiles (five separate rank-ordered groups), ranked from least vulnerable to most in Table 8.1. The nine geophysical and hydrological metrics used to rank the streams into quintiles are derived from StreamStats, PRISM, the National Hydrography Dataset and GIS data.

- Stream temperature challenges to trout habitat typically affect reaches of streams rather than entire streams, since lower stretches are much more vulnerable that higher where cooler air temperatures prevail. Reaches projected to exceed trout stream temperature thresholds are presented separately from the geophysical/hydrological quintile analysis.

  - Map 3 is a map of streams reflecting vulnerability to chronic or acute temperature limitations for trout by 2035 due to warming air temperatures.

  - Map 4 overlays temperature vulnerability (2035 time frame) on top of geophysical/hydrological (streamflow) vulnerability and, as such, represents the single best characterization of trout habitat viability/vulnerability (i.e., strongholds) that emerged from this study.

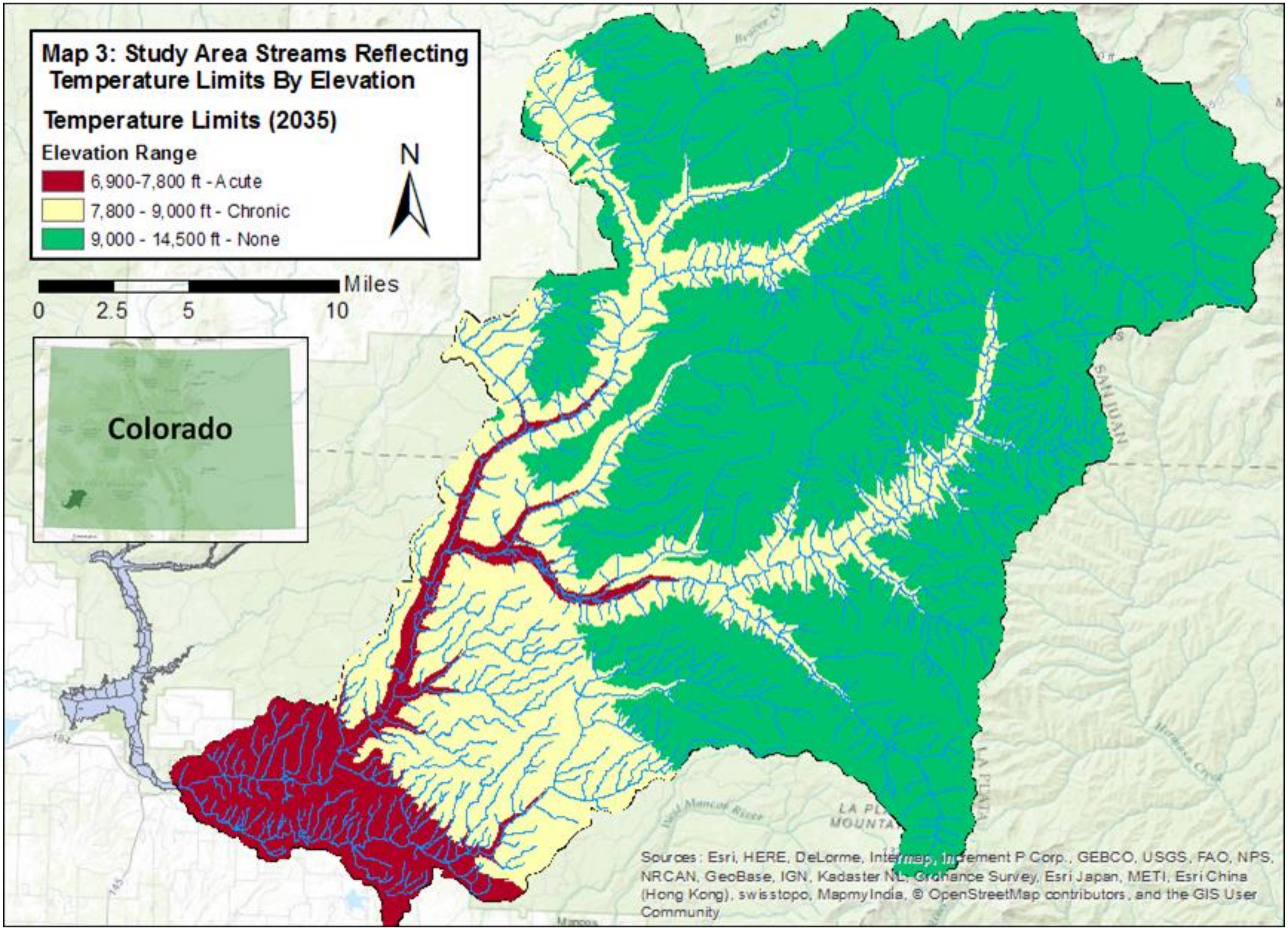
SUMMARY OF RECOMMENDATIONS:

- Consider management responses to the projected changes that are built around strengthening both resistance and resilience of trout habitat. Sustainability of long-term refugia and spawning areas is critical.
- Management focused on resistance and resilience would likely involve an integration of:
    - <u>In-stream construction:</u> Consider carefully selected in-stream and near-stream morphological modifications where cost effective (focusing larger investments on long range strongholds). Protecting, enhancing and creating refuge pools/pockets is essential as is sustaining and providing riparian cover.
    - <u>Increased regulation:</u> As more anglers become concentrated within a steadily reducing habitat range, more regulation such as strictly catch and release, reach closure during high temperatures, reach rotation, barbless (dry?) flies only, and even sign-up periods for specific reaches may have to be introduced. More wildlife officers will likely be required.
    - <u>Integrated management:</u> As the forests become drier and ecosystems and habitats change, coordination across all governmental land management agency teams and across relevant disciplines within those agencies (hydrology, fire management, road and trail maintenance, etc.) becomes vital.
    - <u>Coordination with water users:</u> Coordination with local water districts, irrigation companies, land owners, etc. becomes critical as flows diminish, evapotranspiration rises and irrigation needs increase.
    - <u>Low impact philosophy:</u> Public outreach to promote the importance and value of low impact use of all lands and streams, but especially public lands and streams, becomes increasingly important.
- Climate change is a massive engine. Many streams in our Study Area will face very serious challenges as they approach 2100. Some will respond well to carefully selected mitigation efforts; many, though, may well be outside the range of cost effective management and will either become warmer-water fisheries or will simply dissipate.
- Fortunately, Nature is incredibly resilient. The very good news is that our watershed and its mountain streams have sustained trout through many substantial swings in climate over many millennia. Paleoclimate studies indicate we have experienced several 25+ year droughts in the past 1000 years, yet trout populations still thrive locally.

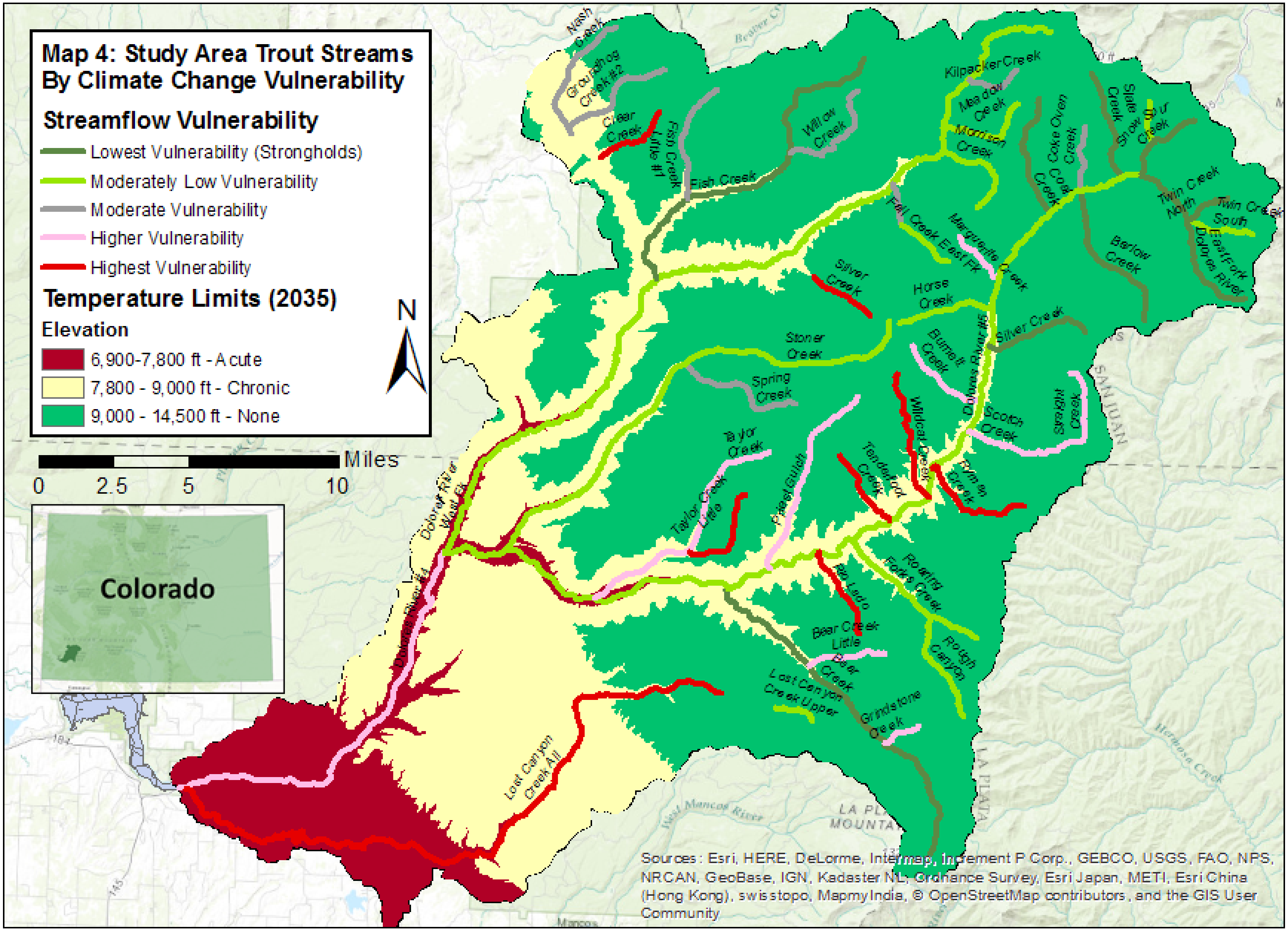
How and why these findings and recommendations emerged is developed in the remaining sections and supplemental appendices of this report.

Table 8.1: Ranking of Existing Trout Streams in Study Area by Long-Term Vulnerability to Climate Change (Low to High)

OBJECT ID	STREAM NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
	Quintile 1: Lowest Vulnerability													
142	East Fork Dolores River	1	11	6.35	1	1	1	1	2	1	1	1	2	
82	Barlow Creek	1	15	5.53	2	1	1	1	3	1	2	2	2	
87	Coal Creek	1	18	4.44	2	2	2	2	2	1	2	2	3	
16	Slate Creek	1	18	3.98	3	2	1	1	4	1	1	2	3	
127	Snow Spur Creek	1	18	3.02	2	2	3	2	2	1	1	4	1	
125	Silver Creek (above Rico pond)	1	19	3.78	2	2	1	1	5	1	2	4	1	
139	Twin Creek North	1	20	1.68	4	5	1	1	4	1	1	1	2	
83	Bear Creek	1	21	13.71	1	1	2	3	4	1	5	3	1	
101	Fish Creek @ SWA	1	21	12.95	1	1	4	3	3	1	4	3	1	55.43
	Quintile 2: Lower Vulnerability													
93	Dolores River West Fk	2	22	34.84	1	1	4	5	3	1	5	1	1	
15	Lizard Head Creek	2	22	1.45	5	5	2	1	2	1	1	3	2	
116	Meadow Creek	2	22	3.45	3	3	3	3	1	1	2	3	3	
130	Stoner Creek	2	22	17.99	1	1	5	5	2	1	5	1	1	
23	Twin Creek South	2	22	2.37	5	5	1	1	3	1	1	1	4	
117	Morrison Creek	2	23	3.56	4	5	2	2	1	1	2	3	3	
121	Roaring Forks Creek	2	23	5.74	1	1	3	4	3	1	4	4	2	
122	Rough Canyon	2	23	3.95	2	2	2	3	3	1	3	3	4	
98	Fall Creek East Fk	2	24	2.06	5	5	1	1	4	1	1	1	5	
108	Horse Creek	2	24	3.40	3	2	1	2	5	1	3	2	5	
113	Lost Canyon (above Dipping Vat Creek)	2	24	1.50	5	5	2	3	1	1	1	3	3	
92	Upper Dolores (#5)	2	24	35.20	1	1	3	4	3	1	5	5	1	115.52
	Quintile 3: Moderate Vulnerability													
88	Coke Oven Creek	3	25	2.39	4	5	3	2	1	1	2	3	4	
96	Fall Creek (Dunton)	3	25	1.47	3	3	1	2	3	1	3	5	4	
102	Fish Creek Little (#1)	3	25	4.18	2	2	3	3	3	1	4	4	3	
111	Kilpacker Creek	3	25	2.00	5	5	1	1	5	1	1	3	3	
1	Nash Creek	3	25	4.72	2	3	4	5	1	1	3	5	1	
128	Spring Creek	3	25	4.58	3	3	4	4	1	1	3	3	3	
107	Upper Groundhog Creek (#2)	3	25	4.27	3	3	4	4	1	1	3	4	2	
141	Willow Creek	3	25	4.31	3	3	4	4	1	1	3	4	2	27.93
	Quintile 4: Higher Vulnerability													
124	Scotch Creek	4	26	4.46	2	2	4	3	4	1	4	1	5	
131	Straight Creek	4	26	2.58	5	5	2	1	5	1	1	1	5	
91	Lower Dolores (#4)	4	27	14.68	1	1	5	5	2	2	5	5	1	
134	Taylor Creek	4	27	8.71	1	2	5	5	2	1	5	4	2	
105	Grindstone Creek	4	28	1.43	5	5	2	2	4	1	2	5	2	
119	Priest Gulch	4	28	6.97	2	2	4	4	4	1	5	2	4	
84	Bear Creek Little	4	29	2.69	4	5	3	3	2	1	3	4	4	
85	Burnett Creek	4	29	3.28	4	5	3	2	5	1	3	1	5	
17	Marguerite Creek	4	29	2.10	5	5	2	2	5	1	2	2	5	46.90
	Quintile 5: Highest Vulnerability													
112	Lost Canyon Creek (All)	5	30	26.15	1	4	5	5	1	5	5	3	1	
18	Silver Creek (Johnny Bull)	5	30	2.41	5	5	3	3	5	1	2	1	5	
140	Wildcat Creek	5	30	4.85	3	3	4	4	5	1	4	1	5	
123	Ryman Creek	5	32	4.30	3	3	5	4	5	1	4	3	4	
86	Clear Creek	5	33	2.87	4	5	5	5	1	1	4	5	3	
135	Taylor Creek Little	5	33	3.46	4	5	5	4	2	1	4	4	4	
120	Rio Lado	5	37	3.29	4	5	5	5	4	1	5	4	4	
136	Tenderfoot Creek	5	37	2.95	4	5	5	5	4	1	4	4	5	50.28
	Total Miles			296.1										296.1



Map 3: Study Area Streams Reflecting Temperature Limits By Elevation
Temperature Limits (2035)
Elevation Range
6,900-7,800 ft - Acute
7,800 - 9,000 ft - Chronic
9,000 - 14,500 ft - None
N
Miles
0
2.5
5
10
Colorado
SAN JUAN
LA PLATA
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community


Map 4: Study Area Trout Streams By Climate Change Vulnerability
Streamflow Vulnerability
Lowest Vulnerability (Strongholds)
Moderately Low Vulnerability
Moderate Vulnerability
Higher Vulnerability
Highest Vulnerability
Temperature Limits (2035)
Elevation
6,900-7,800 ft - Acute
7,800 - 9,000 ft - Chronic
9,000 - 14,500 ft - None
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Colorado
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

SECTION 3: WHICH HABITAT-BASED ECOLOGICAL FACTORS LIMIT THE PERSISTENCE OF TROUT POPULATIONS?

To more effectively identify and map stronghold attributes, CAMF incorporates a “limiting factor” approach. A limiting factor approach identifies those ecological factors and the critical threshold values of those factors, beyond which the trout will no longer occupy that habitat. To the extent it is available, data on Limiting Factors, integrated with climate change science and GIS, have guided the systematic identification of long-term strongholds for trout in the Study Area.

Our careful review of salmonid ecology and habitat research has led to identifying the following trout Limiting Factors for CAMF:

1. Stream temperature
2. Flow regime (includes volume, rate and periodicity)
3. Stream morphology (includes segment length, connectivity, gradient, barriers and refugia)
4. Pollutants (includes nutrient loadings)
5. Biotic competition and hybridization (wild vs native, cold vs warm water, forage base)
6. Sedimentation (risk of erosion from wildfire)
7. Disease

The “state of the science” for each Limiting Factor has been reviewed and documented in depth by the study team, with special focus on identifying associated thresholds where relevant. The review was extensive; it is presented in a separate companion document entitled *Limiting Factors in Mountain Stream Trout Habitat– A State of the Science Review*.

The Limiting Factors analysis has proved invaluable for guiding the project team’s analytic efforts in terms of what to analyze. However, finding direct, on-point data about the state of key factors and associated thresholds in the Study Area has posed some challenges.

DATA ANALYSIS AND CONSTRAINTS

The Limiting Factors serve as a logical framework that focuses and guides the gathering of data relevant to both trout habitat and climate change at the stream level. Key desired variables include such indicators as air and stream temperatures, precipitation, elevation, streamflow volumes and rates, drought history, stream gradients, watershed area and the like.

Field data posed certain challenges. Fortunately, four functioning SNOTEL sites exist in the Study Area, Lizardhead, Scotch Creek, Groundhog, and El Diente Peak. These sites record data for both precipitation (including snow equivalence) and air temperature. Generally speaking, SNOTEL data tend to be reliable data. That said, each site, especially El Diente Peak, has had (usually brief) periods of data gaps since 1980. The SNOTEL site thought to best characterize the Study Area is Scotch Creek, just outside Rico, at 10,000 feet. The Rico area is rather close to the midpoint of the Study Area and is mid-level in elevation at about 8825 feet. Unfortunately for this study, there is there no systematic, long term stream temperature data collection undertaken in the Study Area.

Historically, air temperature was collected in Rico (ended in 2001) and precipitation data was collected at a NOAA site just above Rico (also ended in 2001). We were unable to find any recorded air temperature data for the Rico area other than Snotel data since 2001. It seems federal budget challenges doomed the collection of air temperature data at those sites. The only two NOAA sites in the greater area that do have a continuous history of air temperature data are the Cortez and Telluride airports, neither of which, it is felt, reflect patterns specifically characteristic of the Study Area.

After an extensive effort to identify sources of relevant data for our analysis, we selected the following four major sources:

1. USGS' National Map ESRI GIS shapefiles (especially the National Hydrographic Dataset)
2. Oregon State/USDA's PRISM,
3. USGS' StreamStats, and
4. The U.S. Drought Monitor's Drought Index

The primary targets of our analysis are those trout streams that are likely to be strongholds. The first major analytic effort, then, was to generate a GIS map-base of trout streams in the study area. T**he USGS National Map/National Hydrography Database (NHD)** contains an ESRI GIS dataset of all streams designated by Colorado Parks and Wildlife (then Colorado Department of Wildlife) as perennial streams in the Study Area. Since the Study Area is defined as all water draining to the Dolores River from Lost Canyon Creek (just above where the Highway 145 bridge crosses the Dolores) up to the headwaters of that drainage area, an ESRI "file geodatabase" was created from the NHD from which a base map of streams was developed (see Map 1 in Section 2).

Sixty-eight streams are identified as perennial streams on the NHD (as vetted by Colorado Parks and Wildlife's predecessor, Colorado Department of Wildlife). Not all of those streams, however, continued to flow through the droughts of 2002-2003, and 2012 -2015. Based on anecdotal identification by local agency staff and members of DRA, those streams have been eliminated from the list of stronghold candidates (Little Taylor was retained since it is a designated Outstanding Water by Colorado Water Conservation Board due to its cutthroat "Conservation Population" and excellent water quality).

Other streams have issues that appear to preclude persistent (long-term) trout populations, such as extreme low flow volumes (for example, where water flowed during the 2012/2013 intense drought, but only at a trickle), natural or man-made pollution (natural geologic sources or mine runoff), or geomorphology (such as long reaches of very steep gradient with no refugia) that would likely inhibit persistent use by trout.

The final list of candidate stronghold streams includes 46 out of the original list of 68 streams. The list of streams, by name, in each category (trout and non-trout perennial streams) in the Study Area are shown in Appendices 1 and 2. **Appendix 1 is the list of 46 perennial streams, known or reliably reported to have existing, long-term trout populations, that forms the basis of our analysis.**

The primary impacts of climate change on trout habitat are through changes in temperature and precipitation. Fortunately, three Web sites, **PRISM**, **StreamStats** and the **US Drought Monitor**, provide techniques to generate values that serve as reasonable proxies for undocumented values.

PRISM is a GIS map-based depiction of air temperature and precipitation data. It is developed and managed by Oregon State's PRISM Climate Group (substantially funded by USGS). Point sources of temperature and precipitation data are allocated across a map of the US by imputing values into spatial cells four square kilometers. These cells are assigned temperature and precipitation values based on regression equations using weather modeling algorithms and data from a network of weather stations (e.g., SNOTEL) and satellites. What emerges is a map-based presentation of temperatures and precipitation available for any four-kilometer square cell (and in some cases 800 meter square cells) in the US at a given moment in time. While no regression equation, no matter how sophisticated, can equal the validity of a real data reading at a given site within a cell, PRISM is widely used by hydrologists and climate modelers across the US where actual field data are not available.

PRISM is available at http://www.prism.oregonstate.edu/.

StreamStats is a USGS Web application that integrates GIS and hydrologic analytics to support a variety of water-resources planning, management, engineering and design purposes. StreamStats focuses on natural streamflow characteristics such as mean flow, peak flow, low flow, watershed size and the like. Analysis is available for both gauged and ungauged stream sites. Like PRISM, it uses sophisticated regression equations to quantify characteristics, built from stream data collected at gauged collection sites, to estimate stream hydrologic characteristics for streams that have no data collection sites (ungauged sites).

Actual flow data are available from two gauged sites on the Dolores River, one below Rico and one in the town of Dolores. Only the one below Rico is relevant for our analysis given the substantial change in natural flow reflected at the town site due to irrigation withdrawals above the station (there are no substantial withdrawals above the Rico flow gauge). Actual or imputed hydrologic characteristics are incorporated into a GIS map base so that streamflow data can be visualized using a map interface. The maps draw on the NHD for stream mapping and classification.

Each state is given the opportunity to refine StreamStats based on its own statistical approach, in essence, partnering with USGS in support of the website. Colorado has exercised that option to develop Colorado StreamStats, available on the USGS website. While a powerful tool for analysis, where it imputes data to ungauged streams, it is limited by the applicability of the regression equations incorporated. In Colorado, the equations tend to “blow up” (become increasingly statistically invalid) for predicting low flow where watersheds are less than four square miles in area. Twenty of the 46 streams that have trout populations in our Study Area are near or below that cutoff level. However, that limitation, while important, affects only one of the nine metrics used to rank streams by streamflow vulnerability (see Section 8).

StreamStats is available at http://water.usgs.gov/osw/streamstats/colorado.html.

The U.S. Drought Monitor, as stated on their website (http://droughtmonitor.unl.edu):

> …is a weekly map of drought conditions that is produced jointly by the National Oceanic and Atmospheric Administration, the U.S. Department of Agriculture, and the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln. The U.S. Drought Monitor website is hosted and maintained by the NDMC. The map is based on measurements of climatic, hydrologic and soil conditions as well as reported impacts and observations from more than 350 contributors around the country. Eleven climatologists from the partner organizations take turns serving as the lead author each week. The authors examine all the data and use their best judgment to reconcile any differences in what different sources are saying. As such, it is a blend of quantitative science and expert judgement.
>
> “Drought intensity categories are based on five key indicators, numerous supplementary indicators including drought impacts, and local reports from more than 350 expert

> observers around the country. A drought severity classification table shows the ranges for each indicator for each dryness level. Because the ranges of the various indicators often don't coincide, the final drought category tends to be based on what the majority of the indicators show and on local observations. The analysts producing the map also weigh the indices according to how well they perform in various parts of the country and at different times of the year. Additional indicators are often needed in the West, where winter snowfall in the mountains has a strong bearing on water supplies. It is this combination of the best available data, local observations and experts' best judgment that makes the U.S. Drought Monitor more versatile than other drought indicators.

Drought levels are available as tabular data and as maps down to county level and for selected watersheds.

Data and analytics, largely supported by these four sources and guided by the Limiting Factors analysis, were then integrated with simulated climate change scenarios and focused directly (i.e., "downscaled") on the Study Area. The next section looks at climate change and what it likely means for the Southwest, Colorado, and the Study Area.

SECTION 4: HOW IS CLIMATE CHANGE LIKELY TO AFFECT THE SOUTHWEST AND SOUTHWESTERN COLORADO?

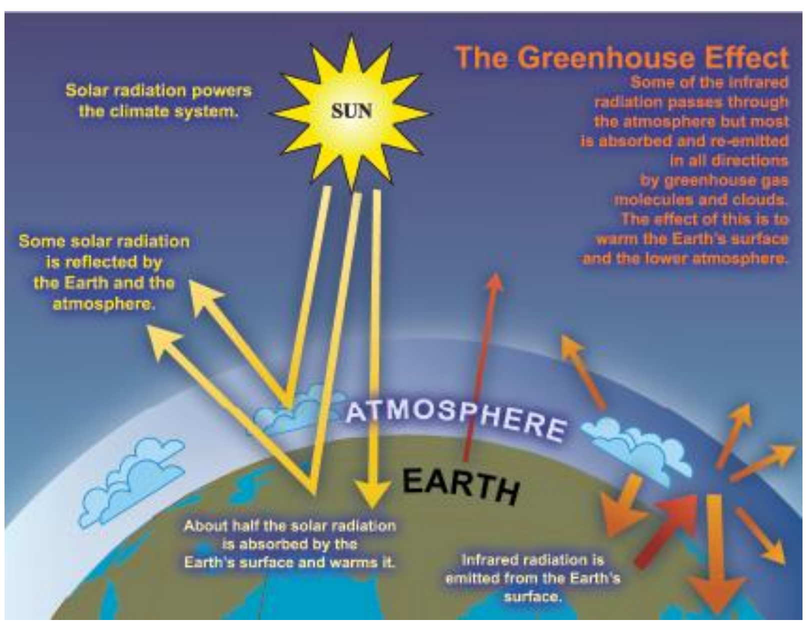
To no one's surprise who fishes the area, coldwater-fisheries in the Study Area are currently quite healthy; populations in all 46 identified trout streams are thriving. A watershed of 1430 square miles, ranging in elevation from just below 7000 to over 14,000 feet, feed 295 miles of trout streams. Four species of trout (cutthroat, cutbow, rainbow and brown), one of char (brook) and one species of salmon (kokanee) inhabit those streams. Virtually every long-term perennial stream supports trout. If there were no systemic changes on the horizon, there is little reason to suspect that this status would change substantially in the foreseeable future.

However, credible science indicates that substantial systemic changes are already underway, thought to be due largely to climate change driven by greenhouse effects. What the exact nature of these changes will be in our area cannot yet be determined. However, climate science can give us a pretty solid characterization of the expected change through the development of several major change scenarios over the timeframe from now to 2100.

WHAT ARE THE BASICS OF CLIMATE CHANGE AND CLIMATE MODELING?

Human activity is increasing the amount of carbon dioxide and related gasses in the atmosphere; this increase is leads to the "greenhouse effect" (Figure 4.1).

> …the Greenhouse Effect, due mostly to greenhouse gases, is largely caused by the fact that the atmosphere emits infrared energy downward, the so-called "back radiation". This single component of the whole Greenhouse Effect process basically then determines all of the other features of the Greenhouse Effect and leads to net Greenhouse Effect warming of the Earth's surface. (http://www.drroyspencer.com/2015/06)



(Figure 1: The Greenhouse Effect. (Source: https://www.ipcc.ch/publications_and_data/ar4/wg1/en/faq-1-3.html)

Increasing greenhouse gasses increase back radiation; increasing back radiation increases earth surface temperatures; increasing surface temperatures have substantial ramifications for the earth's climate. Due to the dramatic implications of a warming earth surface and the rapid rate at which greenhouse gases are increasing, substantial effort around the globe is being invested in understanding—and modeling—those implications on world climate. The effort is organized by the Intergovernmental Panel on Climate Change (IPCC), created by the United Nations Environment Program and the World Meteorological Society. The IPCC is not a research body, but rather reviews and assesses research from around the world. While thousands of researchers and analysts contribute work from its 195 member nations, IPCC is policy-neutral. Policy development and execution is ultimately left to individual nations.

Much of the effort of the IPCC has been to serve as a forum for the coordination and transparent vetting of climate science and, based on that science, climate modeling. Climate modeling is a systematic attempt to portray future scenarios under different assumptions about climate change. Figure 4.2 depicts one perspective of the major integrative components of climate change modeling.

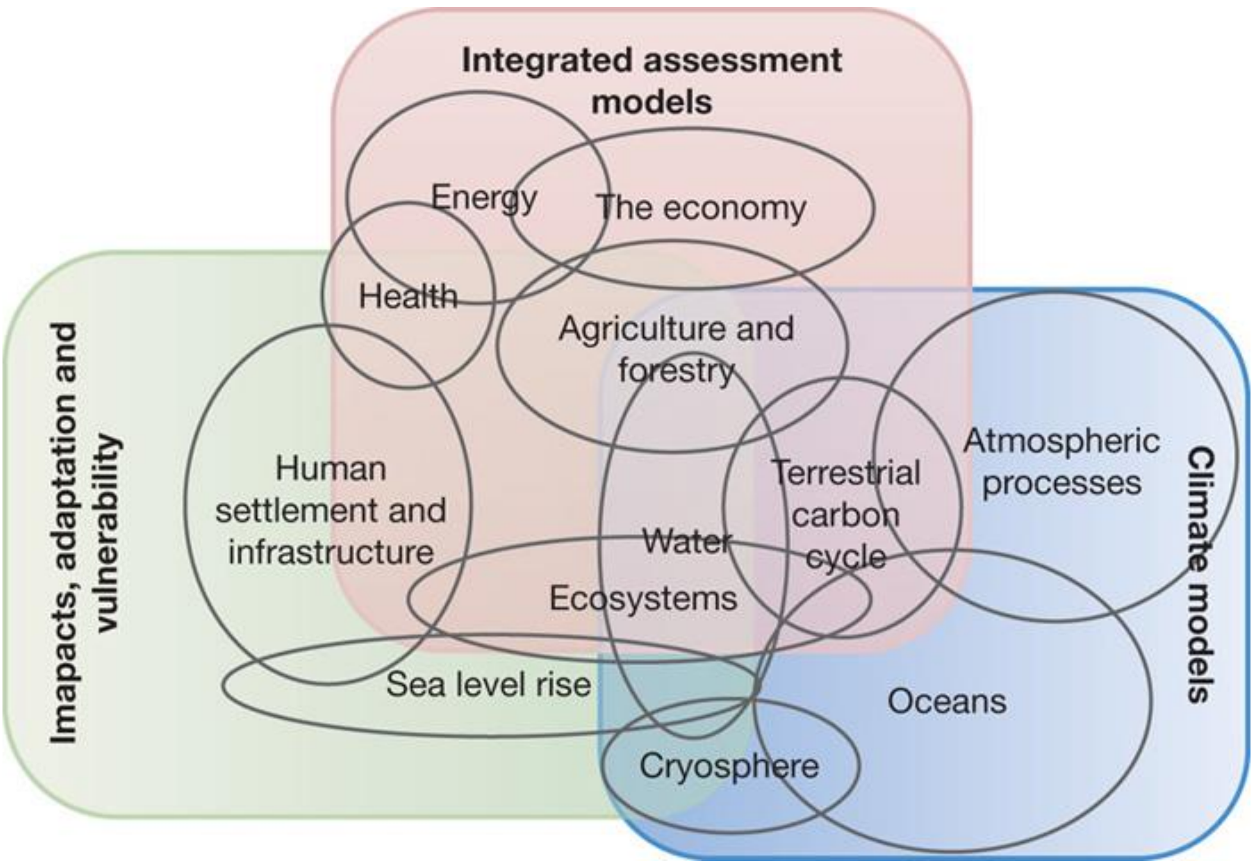


Figure 4.2: Aspects of Integrated Climate Change Modeling (Source: http://www.nature.com/nature/journal/v463/n7282/box/nature08823_BX1.html)

One of the most important climate modeling efforts is the Climate Model Intercomparison Project or CMIP. CMIP is a global framework for an integration of climate circulation simulation models. It posits a framework for assessing extremely complex scenarios through the introduction of Representative Concentration Pathways, known as "RCPs". As described by IPCC:

> The name ‘representative concentration pathways’ was chosen to emphasize the rationale behind their use. RCPs are referred to as pathways in order to emphasize that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. In addition, the term pathway is meant to emphasize that it is not only a specific long-term concentration or radiative forcing outcome, such as a stabilization level that is of interest but also the trajectory that is taken over time to reach that outcome. They are representative in that they are one of several different scenarios that have similar radiative forcing (warming of the earth’s surface) and emissions characteristics. (IPCC Expert Meeting Report, 2007, p. iv)

RCPs are given titles in terms of the expected average watts of energy per square meter that will be added to the surface of the earth by infrared reflection due to greenhouse gasses [for example, RCP2.6 represents a general scenario (“pathway”) where 2.6 watts of energy/square meter are added to the surface over what would have been found had greenhouse gasses not increased]. There are four RCPs; these are succinctly described by Dr. Steve Easterbrook, a climate modeler at the University of Toronto:

- **RCP2.6** represents the lower end of possible mitigation strategies, where emissions peak in the next decade or so, and then decline rapidly. This scenario is only possible if the world has gone carbon-negative by the 2070s, presumably by developing wide-scale carbon-capture and storage (CCS) technologies. This might be possible with an energy mix by 2070 of at least 35% renewables, 45% fossil fuels with full CCS (and 20% without), along with use of biomass, tree planting, and perhaps some other air-capture technologies. *[My (that is, Dr. Easterbrooks’) interpretation: this is the most optimistic scenario, in which we manage to do everything short of geo-engineering, and we get started immediately.]*
- **RCP4.5** represents a less aggressive emissions mitigation policy, where emissions peak before mid-century, and then fall, but not to zero. Under this scenario, concentrations stabilize by the end of the century, but won’t start falling, so the extra radiative forcing at the year 2100 is still more than double what it is today, at 4.5W/m². *[My) interpretation: this is the compromise future in which most countries work hard to reduce emissions, with a fair degree of success, but where CCS turns out not to be viable for massive deployment]*.
- **RCP6** represents the more optimistic of the non-mitigation futures. [My interpretation: this scenario is a world without any coordinated climate policy, but where there is still significant uptake of renewable power, but not enough to offset fossil-fuel driven growth among developing nations].
- **RCP8.5** represents the more pessimistic of the non-mitigation futures. For example, by 2070, we would still be getting about 80% of the world’s energy needs from fossil fuels, without CCS, while the remaining 20% come from renewables and/or nuclear. *[My interpretation: this is the closest to the “drill, baby, drill” scenario beloved of certain right-wing American politicians]*.

(Easterbrook blog, http://www.easterbrook.ca/steve/2011/09/the-cmip5-climate-experiments)

These RCPs will become important in Section 5 where we consider the climate modeling of Dr. Imtiaz Rangwala, downscaled to the San Juan Mountains.

Regional context: What do climate models show for the Southwest and Colorado?

Of dozens of climate change studies reviewed by the project team, five major studies emerged as most representative in their findings and most relevant to our Study Area:

1. *Regional Climate Trends and Scenarios for the U.S. National Climate Assessment; Part 5. Climate of the Southwest* U.S. NOAA Technical Report NESDIS 142-5 (2013).
2. *Assessing the Risk of Persistent Drought Using Climate Model Simulations and Paleoclimate Data; Journal of Climate*, Volume 27, 15 October 2014, pp 75 – 29.
3. *Future dryness in the southwest US and the hydrology of the early 21st century drought;* Daniel R. Cayana, Proceedings of the National Academy of Science USA; www.pnas.org/cgi/doi/10.1073/pnas.0912391107 (2010).
4. *Climate Change in Colorado; A Synthesis to Support Water Resources Management and Adaptation,* Second Edition - August 2014.
5. Dr. Imtiaz Rangwala/Mountain Studies Institute's three "scenario clusters" for the San Juan region *Seeps, Springs and Wetlands: San Juan Basin, Colorado. Social-Ecological Climate Resilience Project (2017*.

In this section, the first four studies will be briefly reviewed to provide a more regional context for the reader; the fifth, Rangwala/Mountain Studies Institute's three "scenario clusters" (which is focused specifically on the San Juan Mountain region), will be considered in some detail in the following Section.

What do regional studies indicate?

Contemporary climate science, and especially climate modelling, is generally considered a "top-down" paradigm. That is, since the late '80s, most international research has focused on piecing together an understanding of climate change from a global systems perspective. This is due, of course, to the intrinsic global nature of the major forces that drive climates around the world (and the rapid increase in computing power to finally aggregate data into a global structure). Changes that occur in one force in one area of the globe often have significant impact on related forces across the globe. After several decades of intensely coordinated research, climate scientists and climate modelers are increasingly confident in their overall understanding of how the bigger forces fit together (although there is still a large amount of work to be done in understanding and quantifying the detail). Many have subsequently started to drill down to lower geographic levels of analysis, called downscaling, to regional and sub regional levels. These lower levels are often extensions of global models pushed to higher levels of local data detail and/or integrated with local weather models.

Fortunately for our study, starting in 2011 The Mountain Studies Institute, located in Durango and Silverton, joined with Dr. Imtiaz Rangwala to downscale global modeling to the San Juan Mountains, where our Study Area is located. Before we examine MSI's findings in some detail, we need to briefly consider selected regional downscaled research to better establish a framework for reviewing MSI's work. To do so, brief summaries of findings or conclusions from each of the first four above-listed reports are presented.

REGIONAL REPORT 1. *REGIONAL CLIMATE TRENDS AND SCENARIOS FOR THE U.S. NATIONAL CLIMATE ASSESSMENT; PART 5. CLIMATE OF THE SOUTHWEST U.S.* NOAA TECHNICAL REPORT NESDIS 142-5 (2013).

In 2013 the National Oceanic and Atmospheric Administration released a series of nine reports, one for each of eight geographic regions of the US and one for the US as a whole. Their reports reviewed the climate history of eight regions and the US, and then posited two future climate pathway scenarios for each. One pathway represented a lower emissions scenario, the other a higher emissions scenario ("emissions" here representing the assumed rate of generation of greenhouse gasses as well as an associated set of assumptions about land use, rate and scale of governance mitigation, and the like). These were meant to set up consistently derived, feasible "bookends" (neither the highest nor lowest possible) around which an understanding of how climate change could very well play out in each region and across the US. They were meant as a starting point for discussion and a structuring for continued research.

The following is the report's summary of findings for the Southwestern region:

Temperature

- CMIP3 models simulate increases in annual mean temperature across the Southwest, with these increases being statistically significant everywhere (for all future time periods and both emissions scenarios). Spatial variations are relatively small, with changes along coastal areas simulated to be smaller than those in inland areas. Warming is simulated to be slightly larger in the northern portion of the region.
- Seasonal temperature changes show greater spatial variability. The greatest warming is seen in summer with a localized maximum in central Utah (see figure).
- There is uncertainty within the range of model-simulated temperature changes, but for each model simulation, the warming is unequivocal and large compared to historical temperature variations.
- Increases in the number of hot days (maximum temperature of more than 95°F) are simulated by the NARCCAP models throughout the region, with the largest increases in southern and eastern areas. Statistically significant decreases in the number of days below freezing are simulated throughout the Southwest.

Precipitation

- The far southern portions of the Southwest U.S. are simulated to experience the largest decreases in annual mean precipitation, while slight increases are indicated for far northern areas (see figure). Statistically significant changes are simulated by most CMIP3 models late in the 21st century and under the high emissions scenario. However, while the models agree on drying in the south, they are in disagreement about the sign of the changes in the northern part of the region.
- The range of model-simulated precipitation changes is considerably larger than the multi-model mean change for both the high and low emissions scenarios, meaning that there is great uncertainty associated with precipitation changes in these scenarios.

- Parts of the Southwest that are already prone to little precipitation are simulated by the NARCCAP models to see an increase in the number of dry days (precipitation of less than 0.1 inches). These decreases are statistically significant over most of the region.

(United States Climate Change Program, p2)

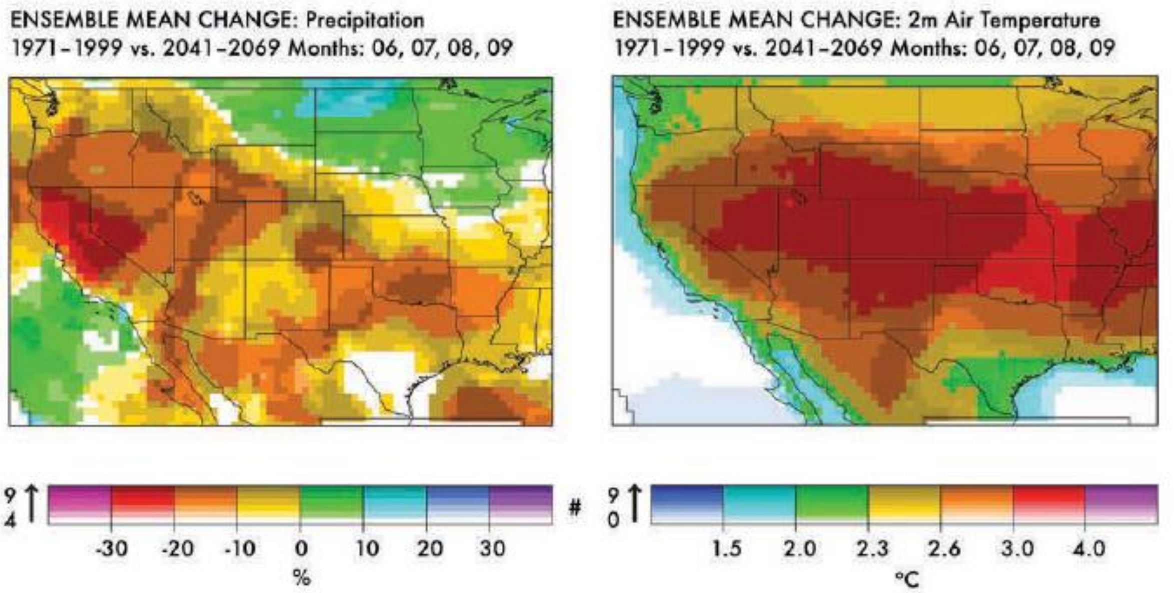


Figure 6.8 NARCCAP precipitation and temperature difference, June–September, 2041–2069 relative to simulated historical means 1971-1999. The degree of change is indicated by the color, whereas the degree of agreement among the nine RCMs is indicated by the intensity of the color. For precipitation (left), the color intensity shows the agreement among the RCMs on the direction of change (i.e., positive or negative percent change in future precipitation); for temperature (right), the color intensity shows agreement among the RCMs on areas where future temperature is projected to be at least 2°C (3.6°F) higher than the 1971-1999 average. Source: Mearns et al. (2009).

Figure 4.3: Illustrative Simulated Changes in Precipitation and Temperature in Southwest US Due to Climate Change. (Source: Garfin et. al., *Assessment of Climate Change,* p. 116)

REGIONAL REPORT 2. Future dryness in the southwest US and the hydrology of the early 21st century drought, Proceedings of the National Academy of Science USA.

This research team integrated hydrologic modeling with the outcomes of 12 global model runs to explore ramifications of climate scenarios on water supplies in the Colorado River Basin.

Their summary:

> Recently the Southwest has experienced a spate of dryness, which presents a challenge to the sustainability of current water use by human and natural systems in the region. In the Colorado River Basin, the early 21st century drought has been the most extreme in over a century of Colorado River flows, and might occur in any given century with probability of

only 60%. However, hydrological model runs from downscaled Intergovernmental Panel on Climate Change Fourth Assessment climate change simulations suggest that the region is likely to become drier and experience more severe droughts than this. In the latter half of the 21st century the models produced considerably greater drought activity, particularly in the Colorado River Basin, as judged from soil moisture anomalies and other hydrological measures. As in the historical record, most of the simulated extreme droughts build up and persist over many years. **Durations of depleted soil moisture over the historical record ranged from 4 to 10 years, but in the 21st century simulations, some of the dry events persisted for 12 years or more (emphasis added).** Summers during the observed early 21st century drought were remarkably warm, a feature also evident in many simulated droughts of the 21st century. These severe future droughts are aggravated by enhanced, globally warmed temperatures that reduce spring snowpack and late spring and summer soil moisture. **As the climate continues to warm and soil moisture deficits accumulate beyond historical levels, the model simulations suggest that sustaining water supplies in parts of the Southwest will be a challenge (emphasis added)**. (Cayana et al., 2010, p. 21271)

REGIONAL REPORT 3. *Assessing the Risk of Persistent Drought Using Climate Model Simulations and Paleoclimate Data*; Journal of Climate

This research team observes that most climate analyses conducted on the Southwest have underweighted the underlying climate mechanics that have triggered extensive and intense drought throughout the Southwest for millennia. This team considers emerging greenhouse effects to be an additional layer on top of the existing paleo-historic climate processes.

Their conclusions:

> "Droughts in the past have had particularly notable human and financial costs. In the United States alone, for instance, the Federal Crop Insurance Corporation spent an average of $1.7 billion annually to compensate losses from 1980 to 2005, and this number has been increasing (Stephenson 2007). In the future, such losses might be curtailed if the full range of natural and forced hydroclimatic variability can be included in megadrought risk mitigation strategies. Here, we have described a method for combining insights from observational data and projections from climate models to estimate the risk of persistent intervals of aridity in the coming century in the U.S. Southwest. In this region where high-quality proxy records of hydroclimate have been used to constrain the underlying features of hydroclimate on decadal and longer time scales, the risk of decadal drought is at least 70% and may be higher than 90%. The risk of a multidecadal megadrought may be as high as 20%–50%, and the likelihood of an unprecedented 50-yr drought is nonnegligible (5%–10%). A number of other regions face similarly high levels of risk including southern Africa, Australia, and the Amazon basin. Moreover, future drought severity will be exacerbated by increases in temperature, implying that our results should be viewed as conservative provided that the models depict accurate forced trends in regional hydroclimate. These findings emphasize the need to develop drought mitigation strategies that can cope with decadal and multidecadal droughts in changing climates with substantial sources of low-frequency variability (emphasis added)." (Ault et al., 2014, pp. 7547 - 7548)

REGIONAL REPORT 4: *Climate Change in Colorado; A Synthesis to Support Water Resources Management and Adaptation, Second Edition* - August 2014.

Moving from the greater Southwest region to the State of Colorado: the Colorado Water Conservation Board updated its seminal Climate Change in Colorado study in 2014. This report is a compelling read for anyone keen to anticipate how climate change is likely to impact the State of Colorado. Projected trends in temperature are well underway and measurable (Figure 4.4).

FIGURE ES-1. Colorado statewide annual temperature, 1900–2012

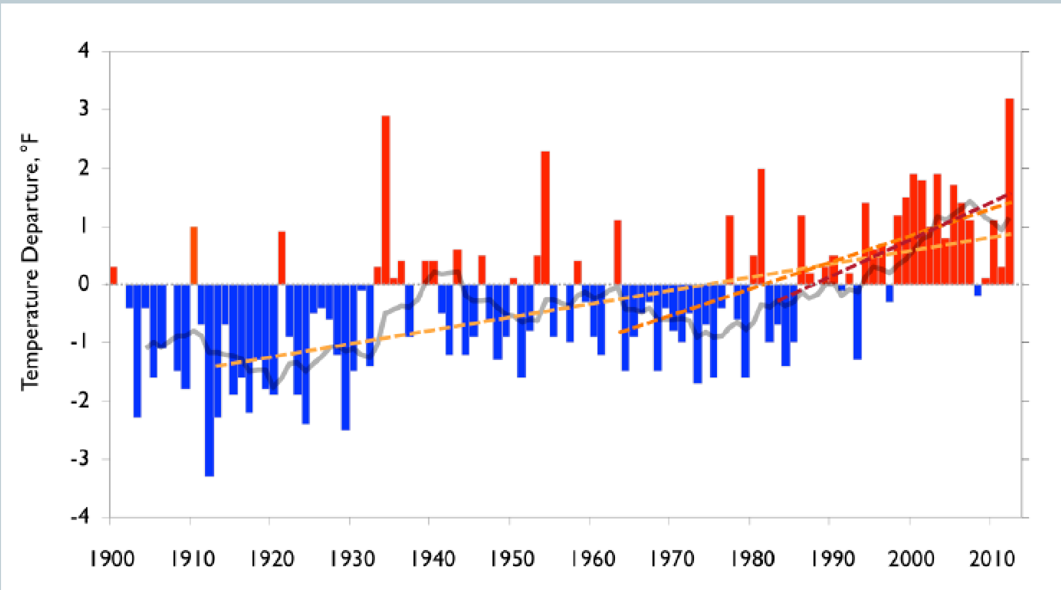


Fig. ES-1. Colorado statewide annually-averaged temperature (°F), 1900–2012. Annual departures are shown relative to a 1971–2000 reference period. The light-orange, orange, and red lines are the 100-year, 50-year, and 30-year trends, respectively. All three warming trends are statistically significant. The gray line shows the 10-year running average. The record shows a cool period from 1900 to 1930, a warm period in the 1930s and again in the 1950s, a cool period in the late 1960s and 1970s, and consistently warm temperatures since the mid-1990s. (Data source: NOAA NCDC; http://www.ncdc.noaa.gov/cag/)

Figure 4.4: Colorado Statewide Annual Temperature, 1900 – 2012 (Source: Lukas, 2014, p. 2)

While the findings are extensive and contain substantial implications for Colorado, a brief characterization of the findings as summarized in the report's Executive Overview follows:

Projections of Colorado's future climate and implications for water resources (Section 5):

- All climate model projections indicate future warming in Colorado. The statewide average annual temperatures are simulated to warm by +2.5°F to +5°F by 2050 relative to a 1971–2000 baseline under a medium-low emissions scenario (RCP 4.5; Figure ES-2). Under a high emissions scenario (RCP 8.5), the simulated warming is larger at mid-century (+3.5°F to +6.5°F), and much larger later in the century as the two scenarios diverge.
- Summer temperatures are simulated to warm slightly more than winter temperatures. Typical summer temperatures by 2050 are simulated under RCP 4.5 to be similar to the hottest summers that have occurred in past 100 years.

- Climate model projections show less agreement regarding future precipitation change for Colorado. The individual model projections of change by 2050 in statewide annual precipitation under RCP 4.5 range from -5% to +6% (Figure ES-2). Projections under RCP 8.5 show a similar range of future change (-3% to +8%).
- Nearly all of the projections indicate increasing winter precipitation by 2050. There is weaker consensus among the projections regarding precipitation in the other seasons.
- In the first projections of future Colorado hydrology based on the latest climate model output, most projections show decreases in annual streamflow by 2050 for the San Juan and Rio Grande basins. The projections are more evenly split between future increases and decreases in streamflow by 2050 for the Colorado Headwaters, Gunnison, Arkansas, and South Platte basins. However, other hydrology projections show drier outcomes for Colorado, and the overall body of published research indicates a tendency towards future decreases in annual streamflow for all of Colorado's river basins.
- The peak of the spring runoff is simulated to shift 1–3 weeks earlier by the mid-21st century due to warming. Late-summer flows are simulated to decrease as the peak shifts earlier. Changes in the timing of runoff are more certain than changes in the amount of runoff.
- Most projections of Colorado's spring snowpack (April 1 SWE) show declines for the mid-21st century due to the simulated warming.
- Most climate projections indicate that heat waves, droughts and wildfires will increase in frequency and severity in Colorado by the mid-21st century due to the simulated warming.

Incorporating climate change information into vulnerability assessment and planning (Section 6)

- Colorado water entities have been at the forefront of incorporating climate change into long-term planning, and their experience can inform future efforts by others.
- Observed records of climate and hydrology are still fundamental to assessing future climate risk, but should be supplemented with information from climate model projections and paleoclimate records.
- Planning approaches that explore multiple futures, rather than assuming a single future trajectory, are more compatible with climate projections and may improve preparedness for a changing climate (emphasis added – this is the basis of adaptive management).
- The uncertainty in projections of precipitation and streamflow for Colorado should not be construed as a "no change" scenario, but instead as a broadening of the range of possible futures, some of which would present serious challenges to the state's water systems.

(Jeff Lukas et al., 2014, pp. 59-60))

Key take-away points of the "regional context" reports

These brief summaries provide only a small glimpse of the extensive analyses that these reports include on climate change and the Southwest. **All of the scenario modeling reports that were reviewed for this study (including the examples above) conclude that the Southwest will likely become increasingly hotter.**

While precipitation scenarios are more ambivalent (some show more, some the same, some much less), all indicate that future precipitation will likely involve less snow pack, with snow showing up later and leaving earlier. Hydrologic studies project an increase in evapotranspiration due to warming whether there is an increase in precipitation or not (Foster, 2016, p. 8). This alone has big ramifications for *effective* precipitation (that is, water available to meet targeted requirements), and impacts human and non-human uses alike.

There is variance among studies as to intensity of the changes, with some studies concluding that our future will be *much* hotter and drier, with even greater challenges for water supplies. One of the most dramatic conclusions by one research team is illustrated in the following quote: "Our results point to a remarkably drier future that falls far outside the contemporary experience of natural and human systems in Western North America, conditions that may present a substantial challenge to adaptation." (Cook et al. 2015, p. 6)

Section 5: What does Rangwala/Mountain Studies Institute’s analysis of Climate Change and the San Juan Mountains mean for our Study Area?

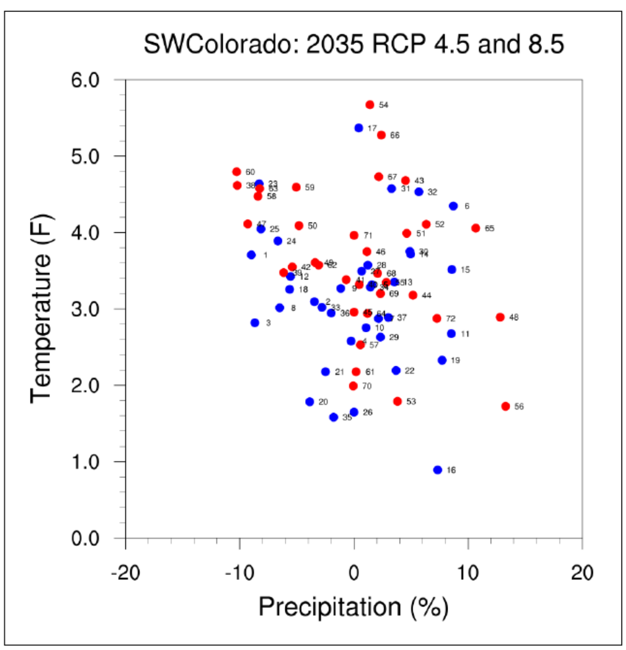
In 2006 the Mountain Studies Institute (MSI) of Durango/Silverton launched the San Juan Climate Initiative, a “scientist-stakeholder partnership for understanding and preparing for climate change in the San Juan Mountains” (www.mountainstudies.org/climate, Nydick et al, 2012). In 2013, MSI partnered with a team of social, climate and ecological scientists to develop a scenario planning project to explore a range of plausible climate futures for southwest Colorado. One of the major thrusts of the initiative was the engagement of Dr. Imtiaz Rangwala, a climate scientist with Western Water Assessment and National Ocean and Atmospheric Administration (NOAA) Physical Sciences Division (whose research is focused on understanding climate change in high mountain areas) to execute climate modeling for the San Juan Mountains.

Dr. Rangwala’s work is of particular relevance because most models are only now beginning to incorporate the effects of broad ranges of elevation in their analytic capabilities. Yet it is widely understood that mountain effects have significant implications for climate, and consequently trout habitat, in terms of temperature, precipitation and hydrology. Climate at 5000 feet is substantially different to that at 14,000 feet, even if only a few dozen horizontal miles separate the two locations.

This difference is due, in large part, to the orographic effects of elevation on precipitation: the higher the elevation and the elevation differential, the greater the precipitation. Additionally, elevation is directly tied to air temperature, such that, generally speaking, the higher the elevation, the lower the air temperature. This latter is, of course, very important for trout habitat, especially in an area which otherwise would likely be a high desert environment.

Rangwala et al (2011) established baseline historic trends in the San Juan Mountains area. This was followed by significant effort at “dynamical downscaling” relevant climate models to the San Juans by Dr. Rangwala. From this base Dr. Rangwala used a base of 72 global climate models and two future greenhouse gas emissions scenarios portraying what the San Juan climate might be like in 2035 and

Figure 5.1: Plot of 72 Climate Change Scenarios for San Juan Mountains (cite)



2070 for RCPs 4.5 and 8.5 (a mid-emission pathway and a high-emission pathway from the archives of the Coupled Model Intercomparison Project- Phase 5, Taylor et al. 2012). Measured in terms of change in temperature (y axis) and precipitation (x axis), his graphs provide highly visual depictions of potential futures (Figure 5.1).

Note that "2035" is commonly used to denote near-to-medium term future conditions (the period 2020 to 2050). Note also that the changes are measured against equivalent values for the period 1971 to 2000. Figure 5.1 depicts the various scenario scores that emerged. Note that two RCPs are targeted: RCP 4.5 scenario scores are blue dots—a moderate emission reduction pathway—while RCP 8.5 scenarios are red—a "business as usual" pathway. Each of the scenarios is numbered, representing the specific model run that generated that scenario.

A visual examination indicates that by 2035 southwestern Colorado could see temperatures increase from 1° to almost 6° Fahrenheit and precipitation ranging from a decrease of about 10% to an increase of about 15% (Figure 5.2, left).

Of particular note is the emergence of what Dr. Rangwala identified three clusters (Figure 5.2): (Rondeau et al., 2017). The characteristics of these clusters will be discussed in more detail below.

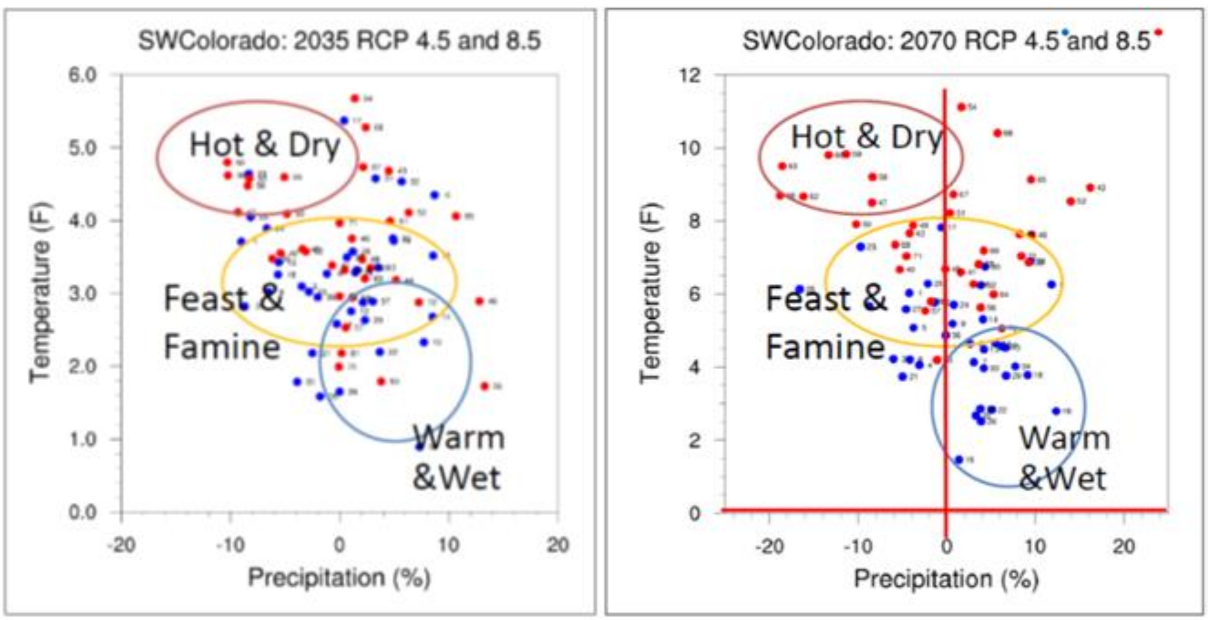


Figure 5.2: Cluster Scenarios by Projection Year (Source: Rondeau et al, 2017)

The scenarios for 2070 (a midpoint period generally representing 2050 to 2100) are more disturbing (Figure 5.2, right). These scenarios indicate that between now and 2070, temperatures may increase between two and eleven degrees Fahrenheit and precipitation changes may range from a decrease of about 16 to 17% to an increase of about the same.

It is important to recognize that, for this modeling effort, each scenario has approximately the same likelihood of occurring.

WHAT IS THE SIGNIFICANCE OF THE CLUSTERS?

While the 72 scenario models are individually instructive in themselves, it is more relevant to understand the core implications of climate change for the Study Area by identifying patterns within the whole set of scenarios. As previously noted, Dr. Rangwala simplifies the set of scenarios into three illustrative clusters. Each cluster underlines a distinct relationship between temperature and precipitation. These clusters are intended as generalizations; even within the clusters details vary across scenarios. Additionally, as is clear from the graphs, not all scenarios fall within the three clusters.

Before examining the implications for climate of each of the three clusters, it is helpful to note that at the heart of the graphic is the 0,0 coordinate; that is, that point where the simulated change in both temperature and precipitation is zero. Moving up the y-axis from the 0,0 coordinate reflects an expected increase in temperature. A move to the right of 0,0 reflects an increase in precipitation, and a move to the left, a decrease in precipitation. **Note that none of the 72 scenarios showed a reduction in temperature.**

A move upward in simulated air temperature is a move toward a hotter climate. The move upward in air temperature means some stream reaches begin to approach the limiting factor of stream temperature, first, chronic (upper limit of healthy), then acute (lethal) temperature thresholds (Figure 5.3, left). A hotter climate also means more evapotranspiration (which implies less soil moisture and more aridity)–a move toward drying streams, should precipitation remain the same.

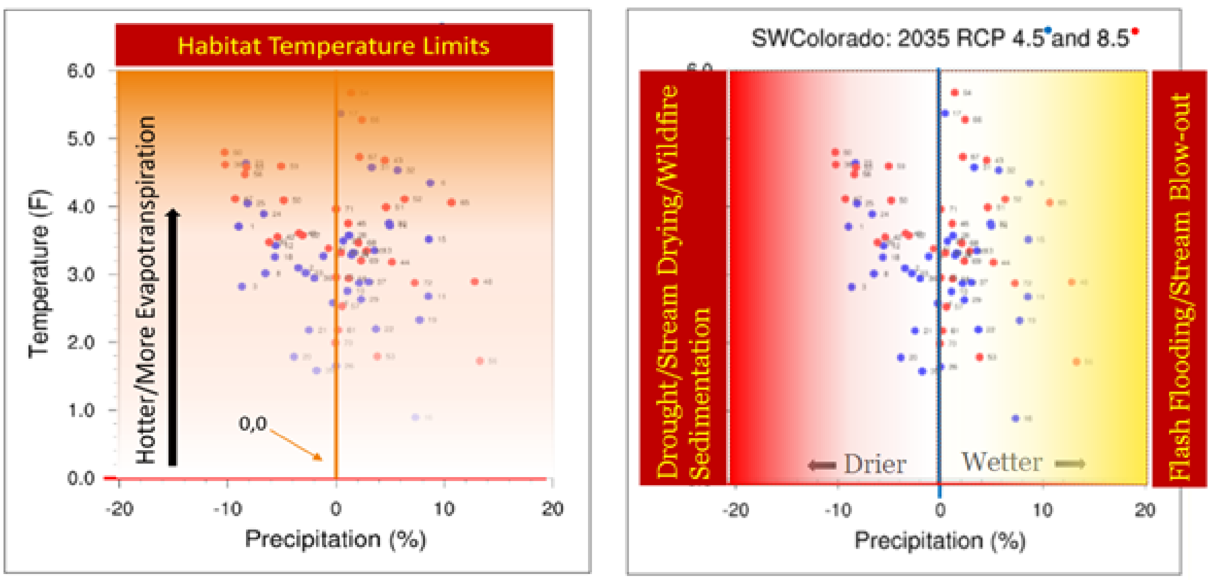
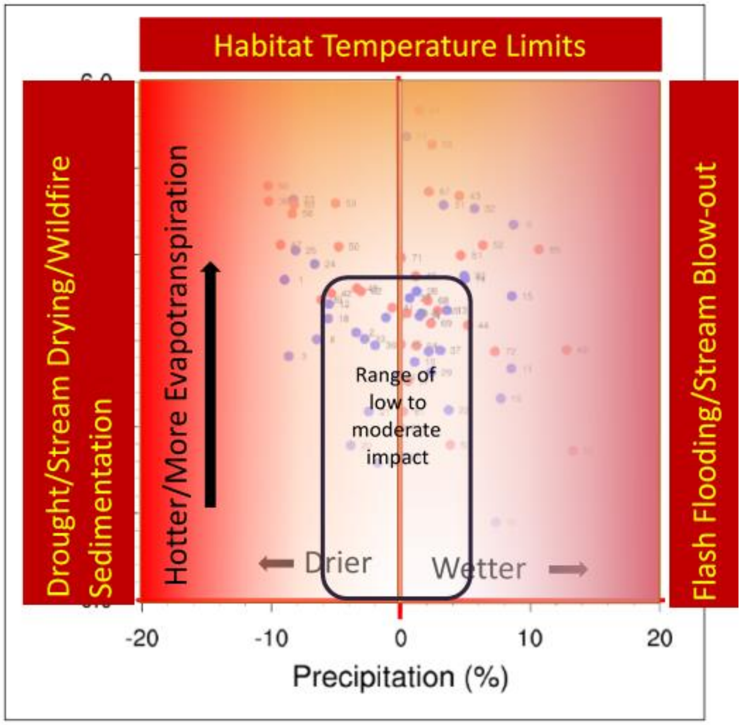


Figure 5.3: Major Boundary Limits Effects on Trout Habitat for Temperature and Precipitation

Likewise, a *decrease* in precipitation approaches the Limiting Factors of 1) flow regime and 2) sedimentation related to an increase in wildfire frequency. An *increase* in precipitation approaches the Limiting Factors of 1) flow regime and 2) sedimentation, with changes in timing, intensity and erosiveness of high flows that can impact trout habitat and reproduction (Figure 5.3, right). Streamflow intensity could reach levels that affect spawning success.

Each of these directional trends (an increase in temperatures or an increase or decrease in precipitation) is constrained—framed by—limiting factor thresholds. This constraining framework is illustrated in Figure 5.4. The box at the lower center of the frame (near and above 0,0) represents the area within which the overall impact on trout habitat in the Study Area is likely to be lower. As one moves outside the box and toward the limits in any direction, the impacts become increasingly more severe.

Figure 5.4: Integrated Major Boundary Limits for Trout Habitat



WHAT DO THE CLUSTERS MEAN IN TERMS OF IMPACT ON THE STUDY AREA?

Building on their scenario development and analysis, MSI and their partners identified likely environmental impacts for a range of climate related attributes for each of the clusters. Their table of attribute impacts (Table 5.1) is highly instructive as to the type and magnitude of climate change impacts we can expect in the Study Area around the year 2035 (recall, 2035 is a midpoint characterization of the period 2020 to 2050) (Rondeau et al., 2017).

Table 5.1: Summary of Climate Change Impacts by Cluster

Three Climate Scenarios for the San Juan Basin Region by 2035

The following summary was compiled from three climate scenarios and a review of literature. The **Hot and Dry** scenario is from hadgem2-es.1.rcp85; **Feast and Famine** is from cesm1-bgc.1.rcp85; and the **Warm and Wet** is from cnrm-cm5.1.rcp45

Scenarios	Hot and Dry	Feast and Famine	Warm and Wet
Temperature	Annual temperature increases by 5F; At lower elevations: summer days with temperature above 77F (25C) increases by 1 month, and nights with temperature above 68F = 10	Annual temperature increases by 3F; At lower elevations: summer days with temperature above 77F (25C) increases by 2 weeks, and nights with temperature above 68F = 20	Annual temperature increases by 2F; At lower elevations: summer days with temperature above 77F (25C) increases by 1 week
Precipitation	Annual precipitation decreases by 10%; less frequent and more intense individual rain events; summer monsoon rains decrease by 20%	Annual precipitation does not change but much greater fluctuations year to year (leading to more frequent feast or famine conditions); El Nino of 1982/83 strength occurs every 7 years	Annual precipitation increases by 10%; more intense individual rain events; summer monsoon rains increase by 10%
Runoff	Runoff decreases by 20% and peak runoff occurs 3 weeks earlier	Runoff decreases by 10% and peak runoff occurs 2 weeks earlier	Runoff volume does not change but peak runoff earlier by 1 week
Heat Wave	Severe and long lasting; every summer is warmer compared to 2002 or 2012 (5F above normal)	Hot summers like 2002 and 2012 occur once every 3 years	Hot summers like 2002 and 2012 occur once every decade
Drought	More frequent drought years like 2002/2012 - every 5 years	Drought years like 2002/2012 occur once every decade	No change in frequency but moderate increases in intensity; fewer cases of multi-year drought
Snowline or Freezing Level	Snowline moves up by 1200ft	Snowline moves up by 900ft	Snowline moves up by 600ft
Wildfire	Fire season widens by 1 month; greater fire frequency (12x) and extent (16x) in high elevation forest	Fire risk during dry years is very high at all elevations b/c of large fuel build up from wet years; on average fire frequency increases 8x, and area burnt increases 11x	Increases in fire frequency (4x) and extent (6x)
Dust Storms	Extreme spring dust events like 2009 every other year; causing snowmelt and peak runoff to be six weeks earlier	Frequency of extreme dust events increases from current but tied to extreme dry years	Same as current
Flood Risk	Flood less frequent but risk increases for big summer rain events	Risk increases substantially during the wet years	Flood frequency increases substantially as well as the overall risk
Growing Season	Increases by 3 weeks	Increases by 2 weeks	Increases by 1 week

Table 5.1 (continued): Summary of Climate Change Impacts by Cluster

Three Climate Scenarios for the San Juan Basin Region by 2035: Descriptive Summary & Hard Numbers

Hot and Dry	❑ Sustained and longer duration drought: 2002-like drought occurs every 5 years ❑ Chronic summer-time dry conditions: Summer monsoons are significantly reduced (-20%) ❑ Chronic summer time heat waves: Every summer warmer compared to 2002 (5ºF above normal)
Feast and	❑ No long-term droughts but more frequent and intermittent severe-drought conditions (2002 drought once every decade) ❑ Large year-to-year fluctuations that go from "hot and dry" to "warm and wet" conditions ❑ Doubling in the frequency of alternating extreme dry and wet conditions relative to present
Warm and	❑ Water availability does not change but climate is warmer ❑ Timing of snowmelt, streamflow, growing season change but more moderate compared to other scenarios ❑ Chronic flood risks because of increases in moisture and more heavy precipitation events

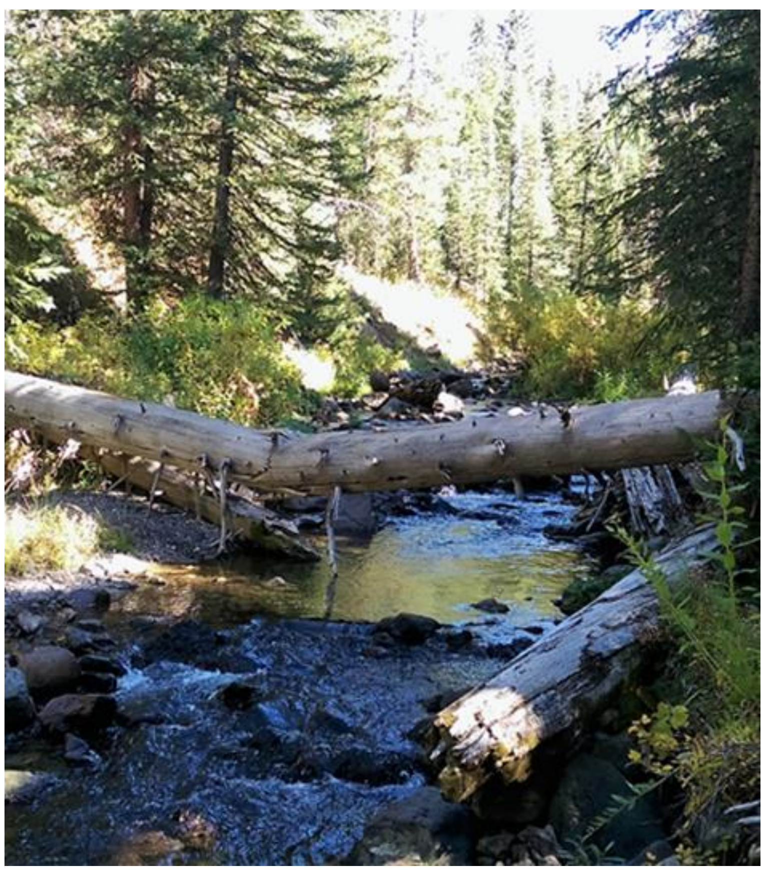
	Hot and Dry	Feast and Famine	Warm and Wet
Annual Temp increase (F)	5	3	2.5
Winter Temp increase (F)	4	3	3
Spring Temp increase (F)	4	2	2
Summer Temp increase (F)	6	4	3
Fall Temp increase (F)	5	3	2
Annual Precipitation (%)	decrease 10%	no change but large year to year variation	increase 10%
Winter precipitation (%)	19	6	13
Spring precipitation (%)	-9	0	6
Summer precipitation (%)	-19	3	8
Fall precipitation (%)	-15	-9	10
Freezing level	shifts up by 1200 ft	shifts up by 900 ft	shifts up by 600 ft
Runoff	> 20% decrease	10% decrease	stays the same as baseline
Timing of peak runoff	3 weeks earlier	2 weeks earlier	1 week earlier
Summer monsoon	decrease by 20%	large year to year fluctuation	increase by 10%
Summer like 2002	every summer	every 3 years	every 10 years
Severe Drought duration	1-5 years	1-2 years	1 year
2002/2012 Drought	every 5 years	every 10 years	every 15 years
Major El Nino event frequency	no change	doubles	no change

(Source: Imtiaz Rangwala, Western Water Assessment & NOAA ESRL, Boulder; Renee Rondeau, Colorado Natural Heritage Program)

MAJOR TAKE-AWAY POINTS FROM THIS SECTION

- Virtually all climate models for Southwest US project substantial changes in store for the Study Area, especially in temperatures. Rangwala/MSI's 72 scenarios, focused specifically on the San Juan Mountains, characterize future climate as one of three major patterns: Hot and Dry, Feast and Famine or Warm and Wet.
- Climate change driven drought appears likely to trigger the most significant potential impact over our analysis period. It is a major driver in two of the three cluster scenarios (Feast and Famine and Hot and Dry).
- In these two groups of scenarios, drought is simulated to become steadily more frequent, more intense and of longer duration.
- The studies indicate drought will increase from periodic drought of 2- to 5-year duration by 2035, through decadal drought by 2070, to perhaps multi-decadal drought by the end of the century.
- Other research teams are more pointed: drought will become intense and long lasting across the southwest, potentially reaching levels by 2100 rarely, if ever, experienced in our Study Area.

How do these projections stand up to actual climate trends in Southwestern Colorado? That question is the focus of the next Section.



SECTION 6: HOW IS CLIMATE CHANGE ALREADY AFFECTING THE STUDY AREA?

The effects of a changing climate are already being felt across the Southwest, the State, and our Study Area. As noted in Section 2 (see especially Illustration 4: *Climate Change in Colorado; A Synthesis to Support Water Resources Management and Adaptation*, Second Edition - August 2014, as updated through 2016 by the Western Water Assessment), average temperatures in Colorado have been climbing for several decades and continued to climb through August 2016, the latest data available. While, as noted in Section 1, certain websites provide interpolated estimates from which a picture of how climate is changing in the Study Area can be developed. Before reviewing that picture, we set the context with a look at the forces that uniquely combine to drive our local climate.

CLIMATE DRIVERS IN THE STUDY AREA

Generally speaking, four major factors combine to shape our local Southwestern Colorado climate:

1. The Pacific Southern Oscillation (El Nino, La Nina, “normal” cycles),
2. Summer monsoon rain,
3. Local geomorphology – particularly the orographic effect of our mountains, and
4. Desert aridity.

Greatly simplified, the additional warming resulting from the greenhouse effect leads to long-term changes in one of the major climate drivers of the Southwest, namely, the Pacific Southern Oscillation. The Pacific Southern Oscillation consists of certain weather patterns that interact with and are driven by major ocean currents flowing in the Pacific Ocean. Changes in the temperature of these ocean currents trigger changes in certain weather patterns. The weather patterns that interact are the increasingly familiar El Nino and La Nina weather cycles, cycles which oscillate around a baseline state called “normal”. In the Southwest, El Nino cycles tend to increase moisture (especially winter moisture), whereas La Nina cycles tend toward drought (Figure 6.1) relative to Normal. Warming temperatures change those cycles. The location, timing, intensity and duration of the Southern Oscillation and its subsequent impact on weather patterns across the West will likely continue to change as long as greenhouse gas production increases.

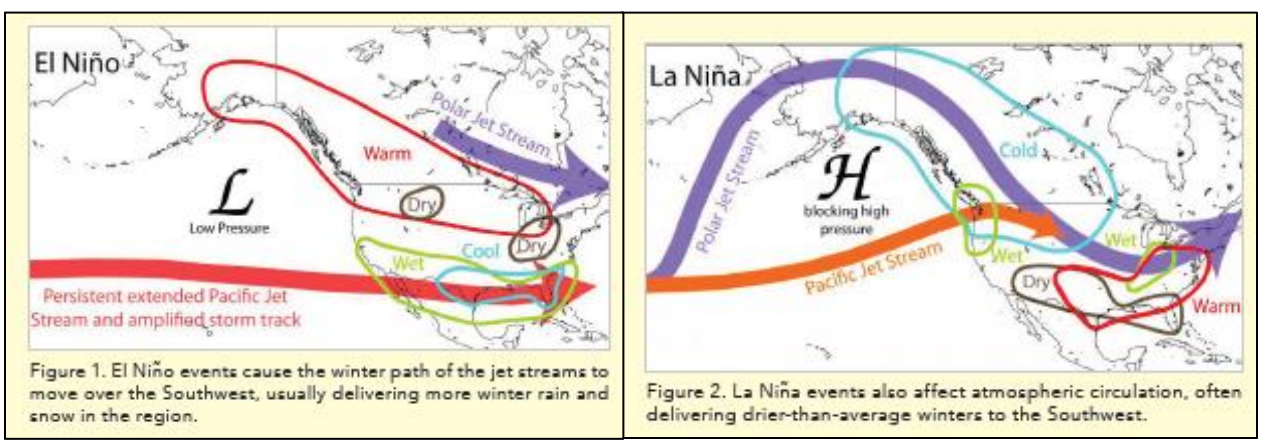


Figure 6.1: Typical El Nino and La Nina Patterns across US

(Source:http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensocycle/enso_cycle.shtml)

The variations of the Southern Oscillation are further affected by our local geography:

- Our study area is at the interface of extensive high desert and substantial mountain ranges. Much of the surface area over which arriving air borne moisture travels (such moisture is predominantly Pacific Ocean moisture flowing from west to east) is arid and will likely become more and more arid in the future. This desert aridity draws moisture from the air as the air passes over.
- As the (now reduced) Pacific moisture hits our mountains, it condenses and falls as precipitation; the higher the elevation, generally the more moisture falls out as precipitation. The lighter air now can flow over the mountain, but with little moisture for the downwind side. This natural phenomenon is called the orographic effect.
- It is because of the orographic effect of the San Juan and La Plata Mountains on Pacific and Gulf moisture flows that we have a trout fishery in the Study Area; otherwise, without the surrounding mountains, our area might well be semi-arid, high desert.
- Increasing surface heat will likely affect orographic patterns in the San Juan and La Platas Mountains. As ground surface temperatures rise, moisture in the air is reduced, causing the elevation at which condensation occurs to also rise. Additionally, the increasing energy radiating from the ground increases evaporation and sublimation in the air column. Both processes can reduce the amount of precipitation falling in our part of the mountains.

To the east, as the Central Plains dry out through increased ground temperatures and the downslope orographic effects of the Rockies, summer monsoonal storms may reduce in number and become more intense.

Virga may well increase in our area. Virga is precipitation which never reaches the ground due to evaporation or sublimation triggered by air and or ground heat-energy. The falling precipitation – rain, ice, snow - is converted back into water vapor before it reaches the ground. As surface temperatures increase over an already hot, arid area, it seems likely that a combination of reduced soil moisture and increased surface heat energy will increase virga, reducing ground-reaching precipitation, and move orographic effects to higher elevation, again reducing surface level precipitation.

Recent History of Drought in the Study Area

As noted in Section 3, The U.S. Drought Monitor website is a significant source of drought data. The Drought Monitor site generates soil moisture data for a range of geographically defined areas, such as multi-state regions, states, counties and even drainage basins. Through persistent effort, staff has built records of drought on a county by county basis reaching back to 1949 (published as the "Drought Risk Atlas"). The site team has built an analysis and graphic depiction of drought for selected sites in the state of Colorado using, among other drought indices, the Self-Calibrating Palmer Drought Severity Index (SC-PDSI). The SC-PDSI is a measure of drought severity that is adjusted for differences in regions in baseline soil moisture so that regions can be validly compared.

The graphic below (Figure 6.2) depicts the trend in increasing intensity and duration of drought at the drought monitoring site at Ft Lewis Colorado (the old fort site southwest of Durango near the New Mexico border (the closest site to the Study Area for which such analysis exists) for 63 years, from 1949 to 2012.

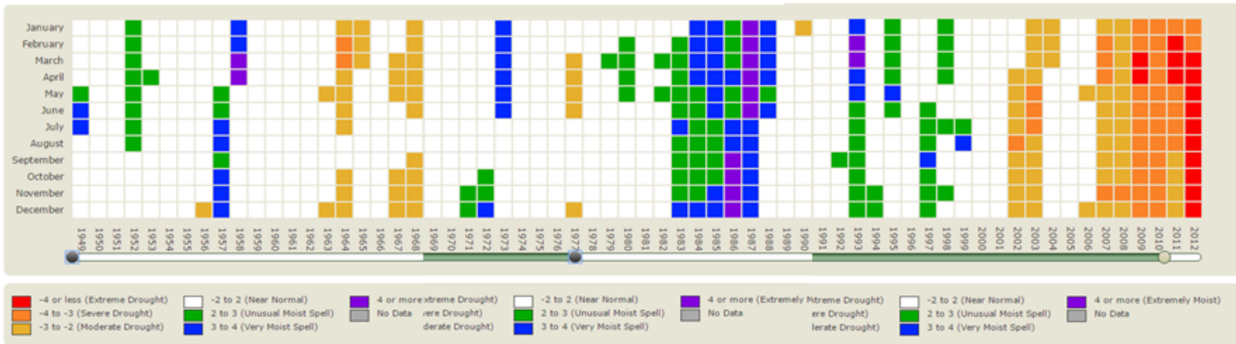


Figure 6.2: Patterns of Drought at Ft Lewis Drought Monitoring Station Recast to 1949 to 2012 (source: http://droughtatlas.unl.edu/Data.aspx)

The transition from blue to green to tan then red reflects a ranging from high soil moisture content (blue) to low (drought). Even without the additional drought years of 2013 through 2016 included, the picture of increasing intensity and duration is clear. According to data downloaded from the U.S. Drought Monitor website, the Upper Dolores watershed has experienced drought greater than 52 consecutive weeks three times since 2000 as illustrated in Table 6.1 below:

Table 6.1: Drought Greater than 52 Consecutive Weeks since 2000 in Montezuma and Dolores County

CO Counties With Drought >52 Consecutive Weeks					
Start Date	End Date	Consecutive Weeks	**Years**	State	County
30-10-01	29-03-05	179	**3.44**	CO	Dolores County
03-01-06	25-09-07	91	**1.75**	CO	Dolores County
24-01-12	09-06-15	177	**3.40**	CO	Dolores County
30-10-01	10-05-05	185	**3.56**	CO	Montezuma County
03-01-06	25-09-07	91	**1.75**	CO	Montezuma County
24-01-12	29-12-15	206	**3.96**	CO	Montezuma County

The Palmer Drought Severity Index (PDSI) classifies soil moisture levels that reach drought levels into one five drought categories as follows:

Table 6.2: Palmer Drought Severity Categories

Category	Description	Possible Impacts
D0	Abnormally dry	Going into drought: short-term dryness slowing planting or growth of crops or pastures. Coming out of drought: some lingering water deficits; pastures or crops not fully recovered.

Category	Description	Possible Impacts
D1	Moderate drought	Some damage to crops or pastures; streams, reservoirs, or wells low; some water shortages developing or imminent; voluntary water use restrictions requested.
D2	Severe drought	Crop or pasture losses likely; water shortages common; water restrictions imposed.
D3	Extreme drought	Major crop/pasture losses; widespread water shortages or restrictions.
D4	Exceptional drought	Exceptional and widespread crop/pasture losses; shortages of water in reservoirs, streams, and wells, creating water emergencies.

When drought in the Upper Dolores is displayed graphically (Figure 6.3), both the intensity (the colors) and the duration (width) become more discernable. The x-axis shows the date range, the y-axis represents the percent of the area in each drought category.

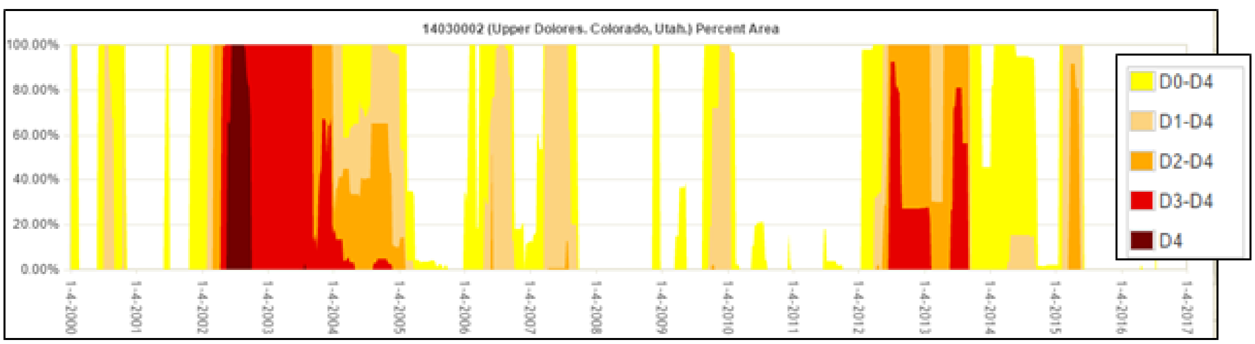


Figure 6.3: Drought intensity (PSDI) range and duration for Dolores County 2000 – 2015 (source: US Drought Monitor)

This graphic indicates that drought in the Study Area tends to be intermittent, with finite beginning and ending points. **This pattern is characteristic of the Feast or Famine cluster pattern.**

IMPACT OF INTENSE DROUGHT ON STREAMFLOW IN THE STUDY AREA

Low flow records for the past 62 years are available for the Rico flow gauge on the Dolores River at about 8500 feet elevation. To get a feel for the intensity of drought in relation to historically typical streamflow in the Study Area, a listing of the year in which the lowest flow through the Rico gauge occurred for each of the 365 days in a year was developed. On that list the year 2002 accounts for 100 of the 365 days, by far the greatest number of record low flows for any given year. The year 2002 then, can be reasonably regarded as representative of intense drought and can provide a reference point for the reduction in flow that can be expected to occur during periods of intense drought.

Given the intensity and duration of the 2002 drought, and given Dr. Rangwala's conclusion that the San Juans will see more and more years like 2002 in the future should scenarios from either the Hot and Dry or Feast and Famine clusters develop, how does the streamflow throughout that year compare to a normal year?

To answer that question, the *mean* daily flow (measured in cubic feet per second over the 62-year period of record) for each day of the year (365 data points) at the Rico gauge station was compared to the *actual* flow for that same day in 2002. A few days (mostly in January) had values above the mean; however, the clear majority of daily flows were substantially below the 62-year mean. All of the daily differences (mean minus actual) were summed and the mean of that sum calculated. The result indicated that the daily flow rate in 2002 was, on average, 44% below the mean daily flow, based on the 62 year period of record.

Simply stated, the typical flow through the Rico gauge for any given day in 2002 was, on average, 44% below that of the long-term average. Clearly, this has dramatic ramifications for trout habitat, to say nothing of future water supply available to the greater community. When the longer-term projections cited in Section 3 of increasingly intense and longer duration droughts (decadal and longer) in the Southwest are considered, then the potential magnitude of the long-term challenges becomes startling.

How rising temperatures can reduce streamflow even with an increase in precipitation

The same heat energy that triggers a change in "phase transition" (warmer temperatures lead to more rain and less snow) also drives higher levels of evapotranspiration. In a 2014 study of the Colorado Rockies, a team of hydrologic researchers modeled the relationship between 1) the energy involved in a phase transition associated with a rise in ambient air temperature of 7.2°F and 2) the amount of increased evapotranspiration that would result from that energy infusion. The resultant model indicated that at that increase of 7.2°F, the loss due to evapotranspiration would result in a reduction in streamflow of ~23% across the Colorado western slope and a reduction of about 19% on the Front Range. As noted in the research, "This reduction in usable water is mostly driven by an increase in summer evapotranspiration due to warming." (Foster et al., 2016, p. 8)

Linking the study referenced above to the Study Area: should any of the Rangwala/MSI scenarios that simulate an increase in precipitation actually develop, such increase would not necessarily directly translate to additional streamflow since the energy inherent in the associated warming could potentially drive levels of evapotranspiration that would more than offset much of the additional precipitation. This effect explains how an area can suffer reduced streamflow in periods of exceptional temperature rise during intense drought even though total precipitation amounts remain the same. Of course, any scenario with more precipitation at a given level of temperature rise is preferred to its counterpart scenario involving less precipitation at that same level of temperature increase.

What about stream temperatures in the Upper Dolores?

Stream temperatures are one of the most critical and potentially most challenged of all of the seven Limiting Factors considered in this study. Unfortunately, there are no stream temperature monitors deployed anywhere in the Study Area. Nor are there any deployed in the Animas River watershed that might serve as proxies (several are being deployed as of this writing because of the Gold King spill).

Of key importance here is maximum stream temperature. The science of stream temperature on trout populations is covered in detail in the companion document, *Limiting Factors in Mountain Stream Trout Habitat–A State of the Science Review*. What is of relevance here is which streams or stream reaches in the Study Area might be subjected to reaching either chronic or acute temperature limits.

As a result of undertaking this study, the importance of stream temperature monitors motivated the DRA chapter to invest in buying eight temperature sensors. Unfortunately, they arrived too late to monitor July temperatures in 2016. Realizing that would be the case, “grab” samples were taken one day each week for four consecutive weeks, with three samples taken each time at the same site. Sites were at 7000, 8000, 9000 and 10000 foot elevations (in all cases, the three readings at each site were within one degree of each other). These weeks in July and August are typically among the hottest of the summer (Table 6.3).

Table 6.3: Stream temperature readings at selected sites on the Dolores River, late July and early August, 2016

Stream Temp: Degrees F at Elevation (feet) Dolores River/Snow Spur					
Date	**7000**	**8000**	**9000**	**10000**	
21-Jul-16	66	61	58	56	Partly cloudy and just after three days monsoon rain
27-Jul-16	76	66	66	65	Sunny and after four days sun
03-Aug	64	60	58	56	Raining @ 9 & 10k and just after 3 days monsoon rain
13-Aug-16	70	63	63	63	Clear afer three days no rain

While four weeks of once-a-week data are certainly far from statistically definitive, it at least provides a reasonable starting point for general interpretation. One data point, the 27 July measure at the 4th Street Bridge in Dolores at 76°F, is already beyond the upper chronic limits and into acute levels. What this small sample might mean for Study Area stream reaches in the future is considered and mapped in Section 7.

MAJOR TAKE-AWAY POINTS IN THIS SECTION

In summary, analysis of regional data shows an increase in the duration and extent of drought since 1949. Data for flows at the Rico station suggest that streamflow was reduced substantially during the most intense drought of that period (2002-2003). This suggests that, while far from conclusive, of the three clusters, Feast and Famine or Hot and Dry appear more representative of what is currently occurring than Warm and Wet.

Section 7: How are these impacts likely to affect trout populations in the Upper Dolores watershed?

In this Section, we continue to drill down to our search for specific stronghold streams and reaches within our Study Area. Here, we look at climate change as it specifically impacts trout habitat in a mountain stream ecological system.

The largest looming threats to our Study Area

While climate change in our study area will likely impact each of the seven of the Limiting Factors of trout habitat identified in our analysis, changes appear to be more likely to affect (in order of consequence)

- Flow regime
- Stream temperature
- Stream morphology
- Fish competition

  Impacted, but to a lesser degree, are

- Sedimentation
- Pollutants
- Disease

How climate change is likely to impact trout habitat in the Study Area

In the Southwest, stream drying due to drought seems to be the single biggest long-term challenge to trout habitat. To review, by mid-century we can expect to see more droughts like 2002 in intensity and lasting in the 4- to 5-year range. By the end of century drought could reflect intensity and duration increasingly greater than 2002, even decadal in length or longer.

Drought would likely impact our fisheries in the following ways:

- Reduction of both snow and rainfall in total for the year and seasonally within the year will lead to a steady and persistent increase in evapotranspiration and a decrease in the number of perennial streams (some perennial streams becoming intermittent or dry) as:
  - Less precipitation flows directly to the stream,
  - Feeder tributaries reduce/dry up, and
  - Slope and depressional wetlands/fens dry out and forest duff moisture is reduced, thereby reducing ground percolation and storage and, subsequently, base flow, especially during seasonally dry periods.
- Total flow would likely reduce in those streams that remain perennial.
- Seasonal flow could change substantially as precipitation transitions from less snow to more rain and reduces in total *effective* (habitat beneficial) amount.

- Snow runoff periods will become shorter and runoff perhaps more intense as spring warms faster (resulting in less percolation, hence, less base flow).
- Monsoon systems could become more intermittent and reduced in scale and duration.
- Consequently, late summer/early fall flows could be substantially reduced, leading to substantial drying.

  In-stream impacts from more frequent, longer or more intense drought could be significant:

  - Refuge pools would reduce in size and number.
  - Riffles would become increasingly shallower, exposing eggs and fry to drying, temperature increases and higher UV.
  - Higher seasonal flows due to snow melt precipitation being replaced with rainfall would likely result in earlier spring runoff, potentially affecting redds and fry and reducing recruitment in cutthroat and rainbow populations.
  - Reduced monsoon activity would likely reduce appropriate redd bedding for fall breeders (brook and brown trout).

Other significant threats include:

- Warming water temperatures reaching threshold limits that
  - Limit recruitment (life-cycle replenishment) in lower elevation streams,
  - Encourage invasion of warmer water species that push out coldwater species in lower elevation streams,
  - Facilitate spread of disease, and
  - Reduce body weight due to increased metabolism to achieve same life history effort within the habitat.
- Higher precipitation and faster snow melt coupled with increasing intensity of storms could lead to significantly more intense flash flooding "blowing out" eggs and fry, and, in worst cases, refugia. Seasonally, intense flash flooding occurring during late summer could affect brown and brook trout spawning; intense spring flash flooding, cutthroat and rainbows.

Increasing stream temperatures could be very problematic:

- As noted in Section 6, stream temperature measurements taken during the typical seasonal late-July peak temperature period in late afternoon at the Fourth Street Bridge in Dolores suggest that the lower reach of the Dolores in the Study Area is already subject to exceeding limiting thresholds for trout habitat as air temperatures warm over the next decades.
- Several of our wider reaches in our largest streams lack riparian cover during the summer/fall low flow period and can be quite shallow, making those reaches particularly susceptible to rapid temperature rise on clear days with high temperatures, especially during periods of sustained high temperatures.
- With increasingly prolonged drought (and associated clear skies), low flows would increase the rate, extent and duration of daily warming.

Likewise, an increase in wildfires could substantially damage trout habitat:

- While wildfire flames themselves are not generally a significant direct threat to trout habitat, sedimentation released through post-fire erosion caused by removal of cover can be a very substantial threat.
- The closer the fire is to a stream reach, the greater the reach covered, the steeper the gradient of the valley walls and the greater the intensity of the fire, the more damage likely would be introduced into the habitat through sedimentation and debris flow.
- Substantial sedimentation directly affects spawning success by clogging the small gravel and sands into which eggs are deposited and incubate.
- Sedimentation and debris flow from wildfires can cover long reaches and linger for years.

What this means for the Study Area

- If drought intensity and duration increases and stream temperatures rise through 2100, many streams with *higher vulnerability* could become supra-annually intermittent (intermittent one or two times a decade—several may reach this state by 2035), then annually intermittent by late mid-century.
- Many streams with *moderate* vulnerability could become supra-annually intermittent by mid-century, then could become annually intermittent by late century depending on the severity of the actual climate change pathway.
- Stronghold streams (those with *lowest vulnerability*) would likely reduce in flow as feeders diminish or dry up, and soil moisture and, consequently, base flow decreases.
- If precipitation increases substantially, stream velocity and volume become substantial challenges to habitat by scouring stream channels and changing or reducing refugia, especially should extreme storm events coincide with key spawning stages (spring and early summer for cutthroat and rainbow and fall for brook and brown).
- Twenty-four of the 46 streams that harbor trout populations are reported by DRA members to have cutthroat populations (see Appendix 2). These streams could see large periodic reductions in recruitment if spring flooding is especially intense.
- Likewise, the numerous streams with substantial brook trout populations would face recruitment issues if high intensity flooding occurred in the fall. Brown and rainbow populations are generally only found in the main stems of the Dolores and West Dolores.
- Stream temperatures in lower, less shaded reaches should be expected to rise to and beyond chronic and acute limits, especially during periods of low flow. The feasible extent of such rise is discussed and mapped in the next section.
- The rate and degree of impact across the watershed will depend largely on the extent to which greenhouse gasses are mitigated by local, state, national and international efforts.

Where are trout populations likely to persevere?

Summarizing our findings from downscaled climate change research, the key to persistent trout habitat and population reduces to two critical habitat factors:

1. Viable streamflow (flow at sufficient volume and within tolerable rates of flow for both peak and low-flow levels) and
2. Viable temperatures – temperatures under the chronic acceptable range.

These two factors largely determine the two primary characteristics of trout strongholds:

1. Refugia
2. Spawning grounds

Stronghold streams are those streams that provide adequate refugia and spawning habitat and remain within appropriate temperature ranges in spite of increasingly substantial disturbances generated by changing climate. It is these streams that can provide the greatest resistance and resilience over the long-term. We conclude, then, that the streams that will be the most likely candidates for sustained habitat and populations to 2100 will have the following characteristics:

- Headwaters that reach to the highest elevations (cooler temperatures);
- The largest watersheds (more water source);
- Watersheds with large areas at high elevations (more and cooler water);
- Moderate gradient (less flash flood velocity and less prone to heating at low flow);
- Many feeder streams and wetlands at higher elevation (more base-flow water source); and
- Shading through riparian cover, north facing aspect and narrower valley “walls” (more shading effect).

Conversely, populations in streams with lower elevation headwaters and feeder streams, smaller and lower elevation watersheds, little riparian cover, high gradient and with wide valley walls and substantial east-west aspect will likely struggle to survive extended drought due to drying and increasing water temps reaching limiting thresholds.

In the next Section, we systematically rank streams according to long-term geophysical/hydrological and temperature characteristics.

Section 8: Which streams in the Upper Dolores watershed are likely to sustain trout populations through the end of the 21st century ("Strongholds")?

How, then, to rank streams by vulnerability to climate change (where are our strongholds)?

As noted in the previous section, certain long-term geophysical/hydrological and stream temperature attributes are key to low vulnerability to climate change. StreamStats provides a source of geophysical data and hydrological analytics, albeit limited by the data issues identified in Section 3. As for temperature, we develop generalized projections of which streams reaches are most subject to critical levels of warming by projecting relationships between air temperature and water temperature and mapping them in GIS.

Both streamflow characteristics and temperature sensitivity are analyzed in this Section where we then identify implications for each of the 46 streams.

Ranking stream vulnerability by StreamStats hydrological attributes

Recall that StreamStats integrates GIS, gauge station data (where available), regression based values for non-gauged streams, and PRISM data where required with on-line, map-based hydrologic analysis. Once a point in a stream is picked on the GIS map via mouse, StreamStats can determine (of relevance to our analysis):

1. The watershed area upstream from the selected point;
2. Various flow rates in cubic feet per second through the selected point, including low flow;
3. Mean annual precipitation (from PRISM);
4. Mean basin elevation;
5. Mean basin wall slope;
6. Percent area above 7500 feet elevation; and
7. Elevation of stream mouth.

Other GIS map sources gathered for the project add

1. Headwater elevation,
2. Average stream gradient,
3. Stream length.

For our purposes, whole streams were analyzed except for the main stem of the Dolores (which was divided into a reach from Lost Canyon Creek to the West Fork, and a second from the West Fork to where it becomes East Fork at Snow Spur Creek). Values for each of the above identified attributes were calculated for all 46 trout streams.

Because of statistical limitations related to the data, a simple ranking by derived value from high to low was generated for each stream for each attribute. Each stream was then assigned a "quintile" value as follows:

1. The ranked list (all 46 streams) was then broken into five generally equal groupings with 9

members each (46 streams divided by 5 groups, one group had 10). This ranking was based on the attribute value for a given attribute for a given stream. For example, Bear Creek had a value of 33.7 square miles for watershed area; it was the eighth largest watershed in the Study Area; it was therefore ranked number eight out of 46 for the watershed size attribute. With nine members per quintile, Bear Creek landed in the first quintile for watershed size.

2. These five groupings, the quintiles, then, represented streams with similar scores for that attribute, with the first quintile (group of 9) listing streams with the top 9 scores, the second quintile listing the nine streams with the second highest scores, and so forth through the five quintile groupings. In summary, a quintile, then, is simply a grouping of elements on a ranked list that represents 20% of the data set.
3. A quintile score was thereby assigned to each stream for each attribute, with a score of 1 awarded to each stream in the first quintile, a 2 to each stream in the second quintile, and so forth through the five quintiles. In each case, a quintile score of 1 represented the nine streams with best scores for a given attribute where best means lowest vulnerability.
4. A **composite score** was then derived for each stream based on the simple, unweighted sum of the quintile scores for each attribute for each stream. **This composite score represents the geophysical/hydrologic (streamflow) vulnerability score for each of the 46 streams.**

To better graphically depict the scoring, a color code has been assigned to each quintile such that the top (least vulnerable streams) quintile is green, the bottom quintile (most vulnerable) is red. Table 8.1 reflects the ranking by composite score for each stream with the individual attribute scores for that stream following, also color coded.

A caution about interpretation: an important aspect of a “low to high” ranking as used here is that the rankings are relative to each other rather than to an absolute benchmark. A ranking of “highest vulnerability” simply means that of the list of 46 streams, that stream is among the highest vulnerability *within that set*. It could be that the lowest quintile would experience only moderate impact in drought, for example. One has to assess the metric values themselves to ascertain just how vulnerable “highest vulnerability” is in terms of habitat impact.

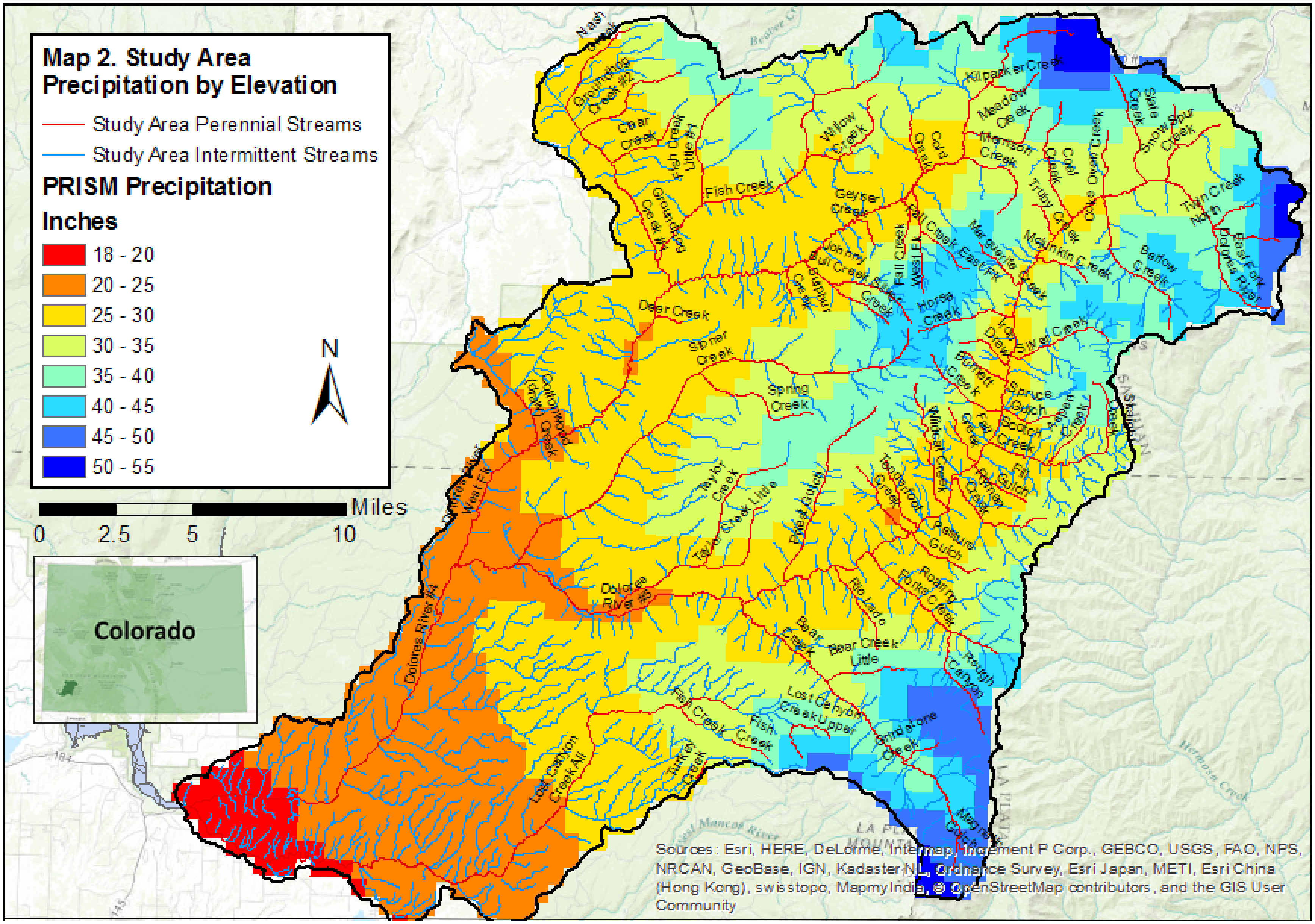
It is also important to note that the ranking has more meaning at the group level than at the individual level. This is due to the generalized way in which the values are determined. (Averages can cover a wide range of values that make up the average*;* mean gradient, for example, can be moderate for a given stream but still contain a substantial stretch of high gradient if it is offset by a long reach of low gradient.) The top quintile members are distinctly different from lowest, but the top quintile is not necessarily dramatically better than the second quintile nor the bottom dramatically more vulnerable than the second lowest.

Many of the attributes are interrelated, such as precipitation and elevation. This is evidenced by comparing a map of elevation with a map of precipitation from PRISM (Map 2). Small watersheds are closely correlated with small streams and small streams to low flow. Small, low flow streams are highly vulnerable to drought. But each of these attributes interact in nature to form the habitat under examination. To that extent, the nine attributes simply reflect different facets of a complex, integrated environment.

Most importantly, the rankings seem to make sense. Streams with small watersheds, low flow and low elevation tend to score poorly. These are the very streams that are most vulnerable to changes in temperature and precipitation. And anecdotal observations during drought periods by DRA members corroborate their relative vulnerability.

Table 8.1: Ranking of Existing Trout Streams in Study Area by Long-Term Vulnerability to Climate Change (Low to High)

OBJECT ID	STREAM NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
	Quintile 1: Lowest Vulnerability													
142	East Fork Dolores River	1	11	6.35	1	1	1	1	2	1	1	1	2	
82	Barlow Creek	1	15	5.53	2	1	1	1	3	1	2	2	2	
87	Coal Creek	1	18	4.44	2	2	2	2	2	1	2	2	3	
16	Slate Creek	1	18	3.98	3	2	1	1	4	1	1	2	3	
127	Snow Spur Creek	1	18	3.02	2	2	3	2	2	1	1	4	1	
125	Silver Creek (above Rico pond)	1	19	3.78	2	2	1	1	5	1	2	4	1	
139	Twin Creek North	1	20	1.68	4	5	1	1	4	1	1	1	2	
83	Bear Creek	1	21	13.71	1	1	2	3	4	1	5	3	1	
101	Fish Creek @ SWA	1	21	12.95	1	1	4	3	3	1	4	3	1	55.43
	Quintile 2: Lower Vulnerability													
93	Dolores River West Fk	2	22	34.84	1	1	4	5	3	1	5	1	1	
15	Lizard Head Creek	2	22	1.45	5	5	2	1	2	1	1	3	2	
116	Meadow Creek	2	22	3.45	3	3	3	3	1	1	2	3	3	
130	Stoner Creek	2	22	17.99	1	1	5	5	2	1	5	1	1	
23	Twin Creek South	2	22	2.37	5	5	1	1	3	1	1	1	4	
117	Morrison Creek	2	23	3.56	4	5	2	2	1	1	2	3	3	
121	Roaring Forks Creek	2	23	5.74	1	1	3	4	3	1	4	4	2	
122	Rough Canyon	2	23	3.95	2	2	2	3	3	1	3	3	4	
98	Fall Creek East Fk	2	24	2.06	5	5	1	1	4	1	1	1	5	
108	Horse Creek	2	24	3.40	3	2	1	2	5	1	3	2	5	
113	Lost Canyon (above Dipping Vat Creek)	2	24	1.50	5	5	2	3	1	1	1	3	3	
92	Upper Dolores (#5)	2	24	35.20	1	1	3	4	3	1	5	5	1	115.52
	Quintile 3: Moderate Vulnerability													
88	Coke Oven Creek	3	25	2.39	4	5	3	2	1	1	2	3	4	
96	Fall Creek (Dunton)	3	25	1.47	3	3	1	2	3	1	3	5	4	
102	Fish Creek Little (#1)	3	25	4.18	2	2	3	3	3	1	4	4	3	
111	Kilpacker Creek	3	25	2.00	5	5	1	1	5	1	1	3	3	
1	Nash Creek	3	25	4.72	2	3	4	5	1	1	3	5	1	
128	Spring Creek	3	25	4.58	3	3	4	4	1	1	3	3	3	
107	Upper Groundhog Creek (#2)	3	25	4.27	3	3	4	4	1	1	3	4	2	
141	Willow Creek	3	25	4.31	3	3	4	4	1	1	3	4	2	27.93
	Quintile 4: Higher Vulnerability													
124	Scotch Creek	4	26	4.46	2	2	4	3	4	1	4	1	5	
131	Straight Creek	4	26	2.58	5	5	2	1	5	1	1	1	5	
91	Lower Dolores (#4)	4	27	14.68	1	1	5	5	2	2	5	5	1	
134	Taylor Creek	4	27	8.71	1	2	5	5	2	1	5	4	2	
105	Grindstone Creek	4	28	1.43	5	5	2	2	4	1	2	5	2	
119	Priest Gulch	4	28	6.97	2	2	4	4	4	1	5	2	4	
84	Bear Creek Little	4	29	2.69	4	5	3	3	2	1	3	4	4	
85	Burnett Creek	4	29	3.28	4	5	3	2	5	1	3	1	5	
17	Marguerite Creek	4	29	2.10	5	5	2	2	5	1	2	2	5	46.90
	Quintile 5: Highest Vulnerability													
112	Lost Canyon Creek (All)	5	30	26.15	1	4	5	5	1	5	5	3	1	
18	Silver Creek (Johnny Bull)	5	30	2.41	5	5	3	3	5	1	2	1	5	
140	Wildcat Creek	5	30	4.85	3	3	4	4	5	1	4	1	5	
123	Ryman Creek	5	32	4.30	3	3	5	4	5	1	4	3	4	
86	Clear Creek	5	33	2.87	4	5	5	5	1	1	4	5	3	
135	Taylor Creek Little	5	33	3.46	4	5	5	4	2	1	4	4	4	
120	Rio Lado	5	37	3.29	4	5	5	5	4	1	5	4	4	
136	Tenderfoot Creek	5	37	2.95	4	5	5	5	4	1	4	4	5	50.28
	Total Miles			296.1										296.1



Map 2. Study Area Precipitation by Elevation
Study Area Perennial Streams
Study Area Intermittent Streams
PRISM Precipitation
Inches
18 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55
N
Miles
0
2.5
5
10
Colorado
Sources: Esri, HERE, DeLorme, Intermap, Increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

DETERMINING STREAM VULNERABILITY TO STREAM TEMPERATURE LIMITS

With very little systematic, historic stream temperature data available in the Study Area, can a reasonable characterization of stream temperature vulnerability to simulated future air temperature increases be developed?

The relationship between air temperature, elevation and water temperature is quite complex. Not only is the sophisticated physics of evaporation, air pressure, and heat exchange involved, but significant issues arise as to the intensity and duration of daily heating, the morphology and hydrology of the stream (flow rate, depth), and the lag time between night time cooling and day time heating. Fortunately, general patterns of relationship have been identified and, given the weak nature of the stream temperature field data in our Study Area, general patterns seem acceptable to sketch a feasible set of projections.

A study published in the *Journal of Environmental Engineering* in 2005 simplified the complex relationship between air temperatures and stream temperatures as follows:

> "The majority of streams in the study showed that water temperature increased approximately 1 to 1.2 degrees Fahrenheit for every 1.8 degrees Fahrenheit increase in air temperature." (Morrill, et al. 2005. P. 2)

This translates to a stream temperature being about 67% of air temperature at any given point in time. While this is a highly generalized statement given the identified complexity, it is a starting point. In Section 6 we noted that actual stream temperature measurements taken during the typical seasonal late-July peak period in late afternoon at the Fourth Street Bridge in Dolores indicated that the lower reach of the Dolores in the Study Area already exceeds chronic limiting thresholds for trout habitat on hot, dry days in late summer. How far upstream in terms of elevation this exceedance runs is unknown, but a reasonable guess is around the 7800 foot elevation level.

What might this mean for future elevation-based temperature limits? Integrating Dr. Rangwala's simulated temperature increases for each cluster for 2035 and 2070 with the temperature samples from late July 2016 as baseline temperature states, and the above referenced conversion factor, Table 8.2 emerges. This table, while simple and loaded with caveats, suggests existing temperature challenges in the lower Dolores main stem will likely worsen by 2035 and could very well reach or exceed chronic limits as high as 9000 feet (just above Rico) well before 2070. This conclusion is supported by SNOTEL data for the Scotch Creek Site near Rico; air temperatures reached levels in the drought years 2002 and 2003 at that site that likely pushed stream temperatures very close to cutthroat chronic levels.

A map of the streams and stream reaches impacted by warming reaching chronic levels around 9000 feet and acute levels around 7800 feet is displayed in Map 3.

Table 8.2 Integrating Simulated Temperature Increase with Elevation and Temperature Limits

Species	Chronic F°	Acute F°
Cutthroat	62.6	71.8
Brook	64.9	71.1
Rainbow	64.8	74.8
Brown	67.3	76.3

	Increase ° F	7000 Ft	8000 Ft	9000 Ft
Baseline Temp °F		76	66	66
Hot and Dry				
2035	5.0	79.1	69.1	69.1
2070	9.0	81.5	71.5	71.5
Feast and Famine				
2035	3.0	77.8	67.8	67.8
2070	5.5	79.4	69.4	69.4
Warmer and Wetter				
2035	2.0	77.2	67.2	67.2
2070	3.5	78.1	68.1	68.1

Elevation is not the only major consideration for stream warming. Much of the lower reach of the main stem of the Dolores (below the confluence with the West Dolores) lacks cover and can be quite shallow during the late summer/fall low flow period. That, combined with lower elevation, renders that reach particularly susceptible to rapid temperature rise on clear, hot days, especially during periods of sustained high temperatures. With increasingly prolonged drought (and associated clear skies), low flows would increase the rate, extent and duration of daily warming.

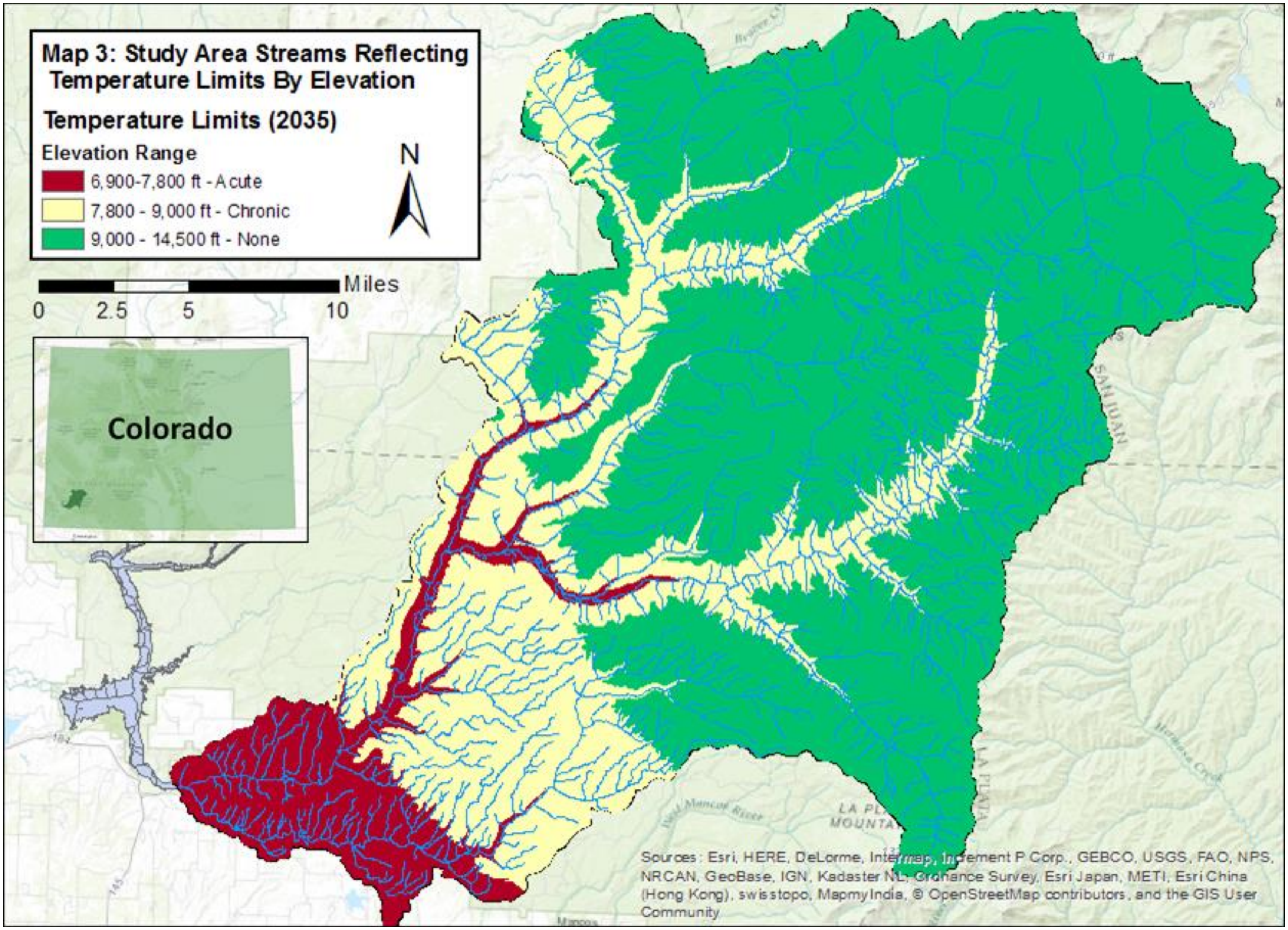
Similarly, there are reaches on the West Dolores at and below Dunton that, while at higher elevation, that experience sluggish flow, have shallow depth and are highly exposed to direct sunlight in the low flow period. No temperature data exist for these reaches. These reaches will likely have issues, too.

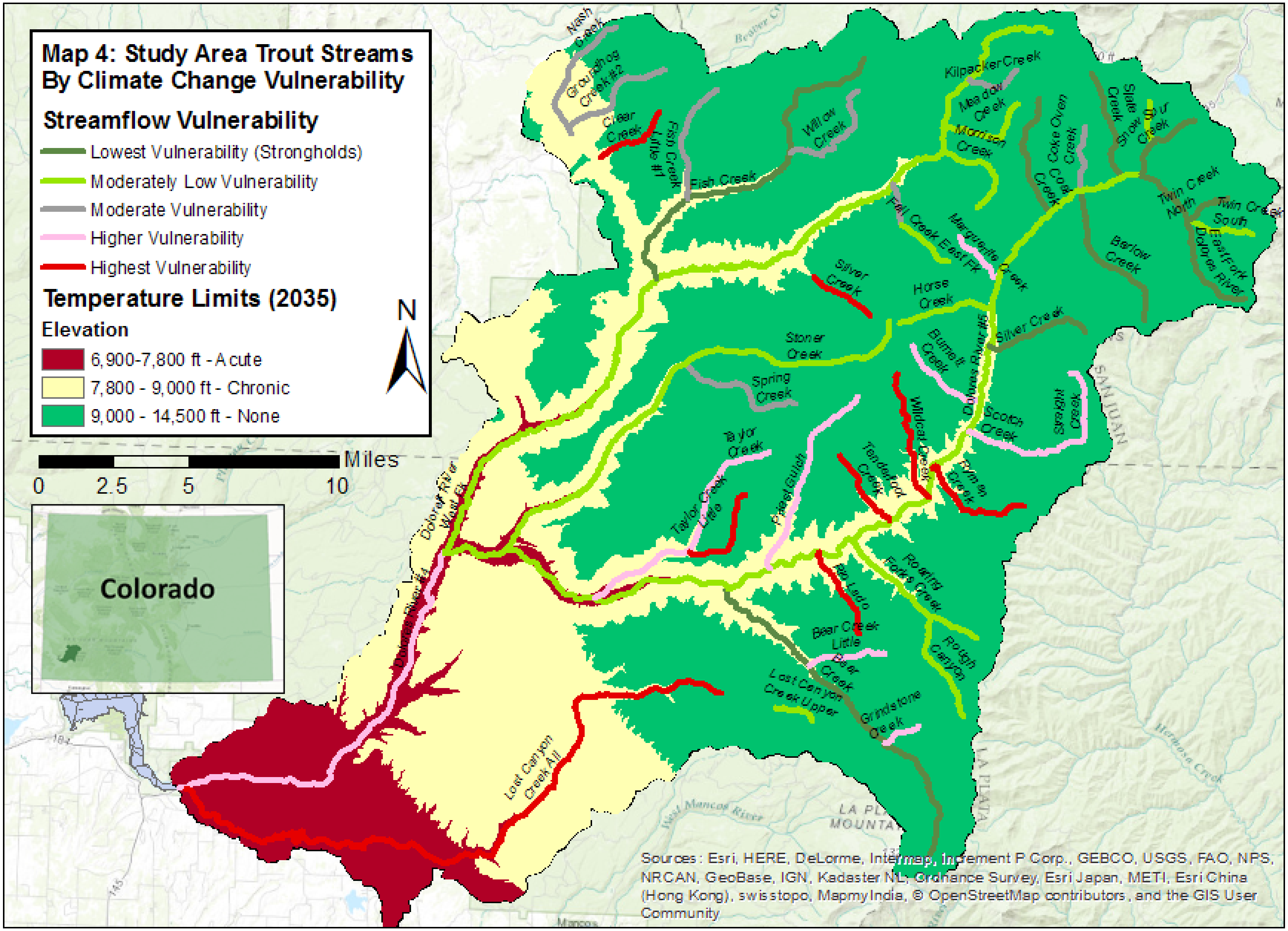
INTEGRATING THE GEOPHYSICAL (STREAMFLOW) ANALYSIS WITH THE TEMPERATURE ANALYSIS—IDENTIFYING STRONGHOLD REACHES

Overlaying the map of temperature challenges by elevation with the map of streams ranked by geophysical/hydrological (streamflow) attributes graphically portrays a feasible, generalized state of trout habitat by stream in the Study Area through 2035 (Map 4). This depiction would likely substantially worsen as the end of the century approaches with chronic and acute stream temperature limits reaching into higher elevations and mid and lower quintile streams becoming increasingly challenged unless substantial and persistent steps are taken to deduce greenhouse effects.

Clearly, climate change could play out in many ways. **The depicted state is by no means presented as the actual end state, but rather a characterization of what is quite feasible.** From this, an "order of magnitude" framework is established for the Study Area that hopefully assists in the difficult strategic and tactical management decisions that lie ahead.

Looking at the ranking table and the integrated vulnerability map, it is clear that substantial changes may well be in store for the Study Area. That said, persistent climate change mitigation (that is, a significant and timely reduction of greenhouse gasses) should lead to habitat conditions that are only moderately more challenging than what has been experienced since the turn of this century. However, worst case scenarios, those where virtually no effective action is taken (leading to 25-year super-droughts with 8° to 10° F air temperature increases), could see an extensive elimination of all but the most resistant/resilient fisheries by 2100 (reducing the Study Area from ~295 miles of currently viable fisheries to perhaps as little as 50 to 65 miles).


Map 3: Study Area Streams Reflecting Temperature Limits By Elevation
Temperature Limits (2035)
Elevation Range
6,900-7,800 ft - Acute
7,800 - 9,000 ft - Chronic
9,000 - 14,500 ft - None
N
Miles
0
2.5
5
10
Colorado
SAN JUAN
LA PLATA
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community



Map 4: Study Area Trout Streams By Climate Change Vulnerability
Streamflow Vulnerability
Lowest Vulnerability (Strongholds)
Moderately Low Vulnerability
Moderate Vulnerability
Higher Vulnerability
Highest Vulnerability
Temperature Limits (2035)
Elevation
6,900-7,800 ft - Acute
7,800 - 9,000 ft - Chronic
9,000 - 14,500 ft - None
N
Miles
0
2.5
5
10
Colorado
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

SECTION 9: WHAT STRATEGIC ADAPTIVE-MANAGEMENT STRATEGIES EMERGE AS MOST RELEVANT?

Climate change is a massive engine. Countering its impact (to the extent it can even be achieved) will be both challenging and expensive. Strategies coalesce around two concepts: adaptation and mitigation. Adaptation involves understanding, then accepting, what is likely to be. Mitigation looks at countering an emerging reality to achieve and sustain an end state through the judicious application of limited resources. The challenge of the fisheries management team, simply stated, is to find and effectively execute the best blend of the two.

Such a blending would likely involve an integration of

1. Selected in-stream and near-stream modifications,
2. Increased stream angling regulation,
3. Integrated management across managing parties and affected support organizations,
4. Close coordination across water districts and major water users, and
5. Low-impact-use communication/education programs for the using public.

1. SELECTED IN-STREAM AND NEAR-STREAM MODIFICATIONS

The five most significant geophysical threats to the Study Area's mountain stream trout habitat from climate change are stream drying, stream temperature warming, extreme flash flooding, warmer-water fish competition and sedimentation due to wildfire. For the first three threats, the proximity of refugia in times of stress is critical. Likewise, trout habitat requires adequate spawning grounds. Sustaining existing refugia and spawning grounds and providing additional of each strengthens both the resistance and resilience of existing trout habitat. Both are related to effectively managing a changing geomorphology and hydrology.

Refugia pools and pockets

Functional refugia require:

- A sustained appropriate temperature range for the entire food chain;
- Protective cover from predators, UV;
- Continuous sufficient depth (minimum of ~ 15"); and
- Resistance to periods of intense high flow.

If and as flow diminishes (Hot and Dry or Feast and Famine), the introduction of pool-creation based best management practices (BMPs) becomes increasingly relevant. Given the back-country nature of most of the Study Area tributaries, it is unlikely that much heavy equipment work would be cost effective, if even doable. However, much of the main stem of the Dolores below Snow Spur Creek and the West Dolores below Dunton is rather accessible with such equipment. For the much larger amount of remote streams and reaches, there is a well-known set of pool/pocket-based, in-stream BMPs that are directly relevant to creating and sustaining pools and pockets that are trail crew oriented and use natural, site-available materials.

Assuring effective stream and reach connectivity

Barriers on streams to upward migration are a two-edged sword. On the one hand, they can protect critical cutthroat habitat from aggressive encroachment from non-cutthroat species or protect cold-water species from warmer-water species. On the other hand, they cut off return migration should the drying of smaller reaches require vacation of that habitat by going over the barrier until adequate streamflow returns or high flow carries the protected trout over the barrier.

Of the 21 culverts that exist over trout inhabited reaches in the Study Area, four act as barriers to migration between the tributary and the Dolores main stem (with drops between the end of the culvert and lower pool greater than four feet). These four are:

1. Taylor Creek at US145,
2. Horse Creek at US145,
3. Coke Oven Creek at FS535, and
4. Meadow Creek on FS535 below Navajo Lake Trailhead lane.

(Fish Creek at FS611 has a three-foot drop which is just below the limiting height of about 44".)

Fish in these tributaries have no option to migrate back into their respective tributary should drying or blow-out force them over the barrier on a temporary basis.

Wildfire risk-mitigation zones

Wildfire can wreak havoc on streams due to erosion-driven sedimentation and debris flows. Preempting major wildfire through risk mitigation is an emerging best practice in wild lands management. Serious consideration should be given to designating at least the stronghold streams as high value habitat so that investment in pre-emptory mitigation practices that reduce the intensity and duration of wildfire can take place. Prompt post fire riparian restoration should also have a high priority.

Cost effective decision making

Like all near-stream and in-stream investment, the key here is cost effectiveness. We suggest that the map of Streams by Vulnerability (Map 4, previous section) provides insight into cost effective decision making. Long-term investment should be targeted on less vulnerable streams, accepting that higher vulnerability streams will likely have a shorter remaining functional life should Hot and Dry or Feast and Famine continue to emerge.

2. Increased Stream Angling Regulation

Unless a Warm and Wet scenario emerges, the longer-term future will see more anglers (as angler population increases) chasing fewer fish on fewer and fewer miles of stream. This increasing intensity of fishing, of course, puts greater and greater stress on existing trout populations, especially on populations in the many small tributaries. Unfortunately, these small tributaries are the primary streams harboring cutthroat populations. Managing this stress may require the staged application of increasingly restrictive stream regulations. These might include:

- Strict catch and release,
- Barbless flies only,
- Dry flies only,

- Periodic closure of streams (Montana closes on a daily basis when temperatures reach a certain level),
- Rotation of closed streams for recovery time, and even
- Sign up periods for specific reaches may have to be introduced.

More wildlife officers to enforce the expanded regulations will likely be required.

3. Integrated management across managing parties and affected support organizations

As the forests become drier and ecosystems and habitats change, cross-discipline coordination (hydrology, fire management, road and trail maintenance, etc.) and sharing of expertise among Colorado Parks and Wildlife, the National Forest Service and Mesa Verde National Park management teams becomes vital.

4. Closer coordination across water districts and water users (especially irrigators)

Coordination with local water districts, irrigators and water users becomes critical as natural flow diminishes and irrigation increases. The competition for in-streamflow will become increasingly contentious. Administrative calls and court challenges concerning streamflow rights will likely increase.

5. Low-impact-use communication/education programs for the using public

Community outreach to inculcate a public valuing of the low-impact-use of all lands and streams, but especially public lands and streams, becomes important. This effort should go hand in hand with increasing restrictions placed on stream access and use. Additionally, the development of a cadre of volunteers to supplement professional staff and crews may well become even more important as budgets continue to be challenged and drought, blow-out and wildfires increase the demand for labor hours.

[For a much broader ranging discussion about emerging issues for managing climate change impacts that is focused specifically on trout habitat by some of the big names in trout science, see the final chapter (What Can We Do About It?) of the excellent *Climate Change, Aquatic Ecosystems, and Fishes in the Rocky Mountain West: Implications and Alternatives for Management.* Bruce E. Rieman and Daniel J. Isaak.]

Conclusion

There is nothing particularly mysterious about climate change. It has been a basic force on earth since the emergence of our world “from the void”, both driving and subsequently responding to the effects it creates. Science has a rather clear grasp, even if yet somewhat incomplete, of the nature of and relationships among the major forces of that change. What is new—and extremely challenging—is the rate at which the change is occurring.

The very good news: our watershed and its associated trout habitat has survived many substantial swings in climate over many millennia. Paleoclimate studies indicate we have experienced several 25 plus year droughts in the past 1000 years, yet trout populations still thrive locally. More recently, our area survived three substantial droughts, each greater than two years of continuous duration, in just the past 15 years. While some streams did become seasonally intermittent (and some completely dry) and all reduced substantially in size and flow, all seem to have recovered, with help from our fisheries managers, to current levels of trout populations.

The lesson? Nature is incredibly resilient. Research indicates that trout can show substantial DNA adaptation in as little as 10 - 20 generations – about 40 - 80 years (. What is unknown is over how many drought cycles and of what intensity and duration, trout habitat and populations can recover from over the long run. But if history is a guide, some will indeed adapt.

The engines driving climate change are massive. Many streams in our Study Area will face very serious challenges as they approach 2100. Some will respond well to carefully selected mitigation efforts; many, though, may well be outside the range of cost effective management and will either become warmer-water fisheries or will simply dissipate. To slightly adapt the conclusion of Reinholt Neibuhr's famous Serenity Prayer, "May we have the wisdom to know the difference."

APPENDIX 1: LIST OF PERENNIAL STREAMS IN THE DOLORES WATERSHED CONFIRMED OR RELIABLY REPORTED TO HAVE TROUT

1. Barlow Creek
2. Bear Creek
3. Bear Creek Little
4. Burnett Creek
5. Clear Creek
6. Coal Creek
7. Coke Oven Creek
8. Dolores River West Fork
9. East Fork Dolores River
10. Fall Creek (at Dunton)
11. Fall Creek East Fork
12. Fish Creek
13. Fish Creek Little
14. Grindstone Creek
15. Horse Creek
16. Kilpacker Creek
17. Lizard Head Creek
18. Lost Canyon (above Dipping Vat Creek)
19. Lost Canyon Creek (All)
20. Lower Dolores (from Cross canyon Creek to West Fork)
21. Marguerite Creek
22. Meadow Creek
23. Morrison Creek
24. Nash Creek
25. Priest Gulch
26. Rio Lado
27. Roaring Forks Creek
28. Rough Canyon
29. Ryman Creek
30. Scotch Creek
31. Silver Creek (above Rico pond)
32. Silver Creek (into Johnny Bull)*
33. Slate Creek
34. Snow Spur Creek
35. Spring Creek
36. Stoner Creek
37. Straight Creek*
38. Taylor Creek
39. Taylor Creek, Little
40. Tenderfoot Creek
41. Twin Creek North*
42. Twin Creek South
43. Upper Dolores (From West Fork to Snow Spur)
44. Upper Groundhog Creek (#2, above Groundhog Lake)
45. Wildcat Creek
46. Willow Creek

* Not confirmed by DRA members fishing the creek since 2010

APPENDIX 2: LIST OF STREAMS IN THE DOLORES WATERSHED WITH CONFIRMED CUTTHROAT POPULATIONS*

1. Barlow Creek
2. Bear Creek
3. Coal Creek
4. Coke Oven Creek
5. Dolores River West Fork
6. East Fork Dolores River
7. Fall Creek East Fork (Dunton)
8. Grindstone Creek
9. Kilpacker Creek
10. Little Taylor Creek
11. Lizard Head Creek
12. Morrison Creek
13. Nash Creek
14. Priest Gulch Creek
15. Rio Lado Creek
16. Roaring Forks Creek
17. Rough Canyon Creek
18. Slate Creek
19. Snow Spur Creek
20. Stoner Creek
21. Taylor Creek
22. Tenderfoot Creek
23. Twin Creek North
24. Wildcat Creek

*Confirmed by actual catches by DRA members

APPENDIX 3: MAXIMUM AIR TEMPERATURES AND ESTIMATED STREAM TEMPERATURES FOR JUNE, JULY AND AUGUST AT SNOTEL SITE SCOTCH CREEK (#465), 1986 TO 2016

Note that stream temperatures approach cutthroat chronic limits of 62.6°F in the drought of 2002 and 2003 (yellow highlight).

Scotch Creek Site (ID 465)	June		July		August	
	Air Temerature Maximum (degF)	Equivalent Stream Temperture (degF)	Air Temerature Maximum (degF)	Equivalent Stream Temperture (degF)	Air Temerature Maximum (degF)	Equivalent Stream Temperture (degF)
1986					81	
1987	76	50.92	80	53.6	77	51.59
1988		0		0		0
1989	66	44.22	71	47.57	73	48.91
1990	65	43.55	67	44.89	67	44.89
1991	60	40.2	60	40.2	63	42.21
1992	60	40.2	60	40.2	60	40.2
1993	59	39.53	60	40.2	80	53.6
1994	83	55.61	83	55.61	83	55.61
1995	77	51.59	86	57.62	83	55.61
1996	80	53.6	84	56.28	85	56.95
1997	78	52.26	86	57.62	78	52.26
1998	86	57.62	86	57.62	81	54.27
1999	79	52.93	85	56.95	76	50.92
2000	80	53.6	83	55.61	83	55.61
2001	82	54.94	85	56.95	82	54.94
2002	87	58.29	91	60.97	87	58.29
2003	82	54.94	90	60.3	81	54.27
2004	80	53.6	79	52.93	78	52.26
2005	79	52.93	85	56.95	76	50.92
2006	79	52.93	82	54.94	74	49.58
2007	80	53.6	85	56.95	78	52.26
2008	78	52.26	79	52.93	79	52.93
2009	76	50.92	80	53.6	80	53.6
2010	80	53.6	85	56.95	76	50.92
2011	77	51.59	80	53.6	80	53.6
2012	81	54.27	82	54.94	77	51.59
2013	81	54.27	82	54.94	76	50.92
2014	79	52.93	83	55.61	77	51.59
2015	83	55.61	78	52.26	78	52.26
2016	84	56.28		0		0

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Limiting Factors in Mountain Stream Trout Habitat—Review of the Science

Prepared in Collaboration with Trout Unlimited,
Colorado Parks and Wildlife, San Juan National Forest,
and Dolores River Anglers Chapter of Trout Unlimited (DRA)

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Introduction

1. The Challenge

Throughout this country, native and wild trout populations face increasingly serious challenges to survival well into the long-term future. Fundamental, even radical, changes to the ecological systems that sustain trout will likely be occurring throughout our watersheds for at least the next 75 years. These changes are driven largely by accelerating climate change, and are in the context of historical 10- to 25-year drought cycles. In order to most cost effectively protect, reconnect, restore, and sustain our coldwater fisheries into future generations, we need to fully understand what changes to our local waters are most likely to occur over the next decades and link those changes to the most appropriate in-stream and near-stream, long-term strategies and best management practices (BMPs). These long-term strategies and BMPs must be well grounded in science and "facts on the ground," as well as readily adaptable as conditions continue to evolve.

This set of long-term strategies and best management practices is called a Coldwater-Fisheries Adaptive Management Plan (Plan or CAMP). Developing such a Plan is the subject of this document, and is sketched in the "How to Use" section in this document.

The heart of this effort is captured by the term *strongholds*—that is, stream reaches, identified through a limiting factors analysis, where, with the application of appropriate long-term strategies and best management practices, native and wild trout populations are likely to survive for the enjoyment of future generations.

2. An Overview

A key to understanding ecological systems, and likely changes to those systems, is the core ecological concept of "limiting factors." Limiting factors are those that limit the growth, abundance, or distribution of a population of organisms within an ecosystem. They limit the growth, abundance, or distribution of a population of organisms in an ecosystem. An example for trout would be water temperatures that rise to the point that trout no longer can survive. That is, to the trout population, water temperature is a limiting factor.

To better understand and prepare for the effects of predicted changes, and to link those changes to appropriate strategies and BMPs, we need to understand how they are likely to affect the ecological limiting factors that govern the viability and health of native and wild trout populations in within a geographic area. To that end, this document offers a decision-support framework that provides step-by-step guidance for systematically identifying and mapping watershed-wide, stream-reach, and site-specific strategies and BMPs.

The decision support framework provides planning guidance at scales from watershed-wide to reach or site including:

- Identification and quantification of relevant limiting factors for native and wild trout populations.
- Finding and using data on relevant geomorphic, hydrologic, and biologic components for local fish populations and habitat.
- Recommendation of actions that respond to limiting factor conditions with application of long term strategies and best management practices.

The Plan provides context, at a watershed, stream, or reach level, within which to prioritize Trout Unlimited's (TU's) Protect, Reconnect, Restore, and Sustain efforts within a long-term framework, one that is intended to make use of information that is emerging from improving local climate change predictions. In short, the Plan is a dynamic structure, process, and document.

3. Ecological Context and Limiting Factors

Trout have evolved over some 40 million years to become what many consider to be the centerpiece of the coldwater stream ecological systems that anglers find so appealing. The trout populations that thrive in these ecosystems require adequate food, holding habitat, clean and cold water, sufficient oxygen, and spawning habitat, as described in TU's *My Healthy Stream* [1]. The reader is referred to this document and to TU's *Conservation Success Index, User Guide* [2] for more information, and both should be used along with this document in developing a CAMP. Affecting the viability of both holding habitat and spawning habitat are such critical factors as sufficient stream segment length, adequate water flow and depth (flow regime), and freedom from detrimental interspecies competition.

All of these key ecosystem characteristics are closely interrelated, due in part to co-evolution. For example, without clean, cold, and oxygenated water, virtually all of the invertebrates and terrestrials that are the bulk of the food supply for trout would not exist. Likewise, effective holding habitat for trout includes the organic debris that forms the base of the trout food chain.

After extensive literature review, and for purposes of this planning process, the ecosystem characteristics are reduced to the following seven core, limiting factors for trout populations:

1. Water temperature
2. Flow regime
3. Stream morphology
4. Pollutants and nutrients
5. Biotic interactions

6. Sedimentation
7. Disease

These core factors define the primary boundaries of the niche occupied by trout in an ecological system. They can be described by threshold values that, if exceeded, may cause some or all affected trout populations to collapse.

Ecosystems are subject to changes in nature, and have been since earliest life on earth. Generally, changes have occurred relatively slowly and the adaptive capabilities of the involved species have enabled accommodation. Indeed, the current cutthroat species native to the Western Rockies, which have evolved over millennia, include sub-species particularly adapted to specific, widely varying regional conditions, varying from Arizona high desert to high altitude lakes and streams in the Rockies.

The concern is that climate patterns now may be changing so rapidly that native species will struggle to adjust to survive, much less thrive. Those streams and reaches of streams that have habitat characteristics that are currently, or will be in the future, near the threshold levels of the limiting factors will be the most likely to become impaired for trout in the face of rapid change.

This document is designed to assist the user in identifying within a specific area (watershed, stream, stream reach) conditions that are most likely to approach or exceed the limiting threshold values for one or more factors within a period of time. The remaining reaches, therefore, are likely candidates for the sought-after strongholds—those streams or reaches of streams within which trout are may at least survive—even, ideally, thrive—in the face of climate change. It is in these geographic areas that coldwater fisheries management efforts—long term strategies and near-stream and in-stream BMPs—likely should be staged and concentrated.

How to Use

1. Purpose and Fundamental Questions

As noted in the Introduction, this document describes a structured process for developing a spatially explicit Coldwater-Fisheries Adaptive Management Plan (Plan or CAMP) for a watershed or set of streams. The Plan includes:

- A collection of maps and data documenting existing conditions, climate change predictions, and streams and reaches identified through limiting factors analysis.
- A prioritized list of in-stream and near-stream actions following the Trout Unlimited (TU) strategy of Protect, Reconnect, Restore, and Sustain (PRRS).

The Plan is intended to help local TU Chapters, Councils, or National Staff, working with Land and Wildlife Managers, consider the following types of questions:

- Which streams and stream reaches in the target area are most resilient to forces that are subjecting the ecosystem under study to change? Why? Of these, which streams and reaches, then, are solid candidates to be regarded as long-term, trout habitat strongholds? (A strong argument likely can be made that these strongholds are the prime candidates for the bulk of the long term, substantial project investment.)
- Conversely, which streams and stream reaches are most vulnerable to change? What ecosystem conditions are most subject to change? What is the expected rate of change? (Vulnerability, organized by limiting factors, should be a consideration in both the magnitude and timing of proposed near-stream and in-stream projects.)
- Given the conditions that are being affected, what are the most cost-effective, mid-range and long-term strategies and Best Management Practices (BMPs) that should be implemented. (This possibly could include the abandonment of the stream or reach to warm water fishery status.)

Streams and reaches that are projected to be near or to exceed threshold levels for one or more factors (the “vulnerable” streams and reaches) might still merit investment, but the magnitude and timing of the investment would be guided by the expected period of time over which the investment would be useful. For example, if temperature is expected to compromise the viability of a stream or reach in, say, 30 years, then the magnitude of investment effort to keep the stream viable within that timeframe should be considered in context with the projection.

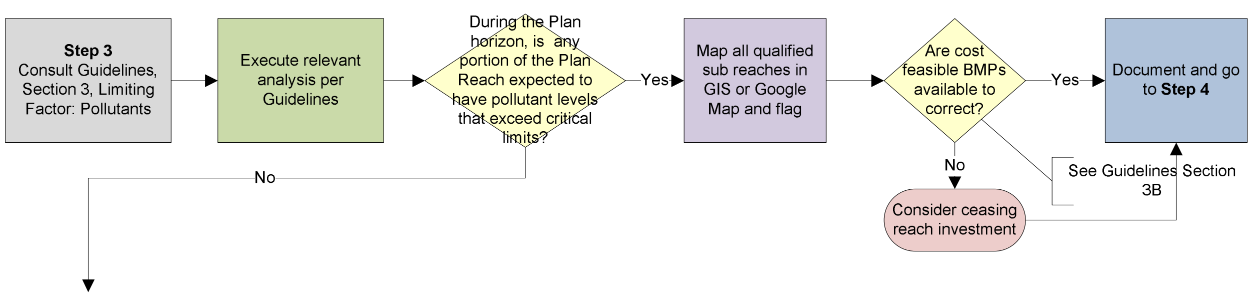
2. Approach and Decision Support

Development of a Plan follows from decision support that is part of this document, and is:

- Based on the best available coldwater-fisheries science using, as noted in the Introduction, a limiting factors analysis approach.
- Developed from operational guidelines so that a non-technical user ("lay person") can be led through a structured decision process.
- Enabling transparency in action planning and providing stream reach- and site-specific insight into river and watershed management issues and potential solutions.
- Using available GIS data and local, best-judgment agency and angler information to supplement data gaps.
- Recognizing TU's Protect, Reconnect, Restore, and Sustain (PRRS) strategy and the aim of TU's *Conservation Success Index* (CSI), cited in the Introduction.

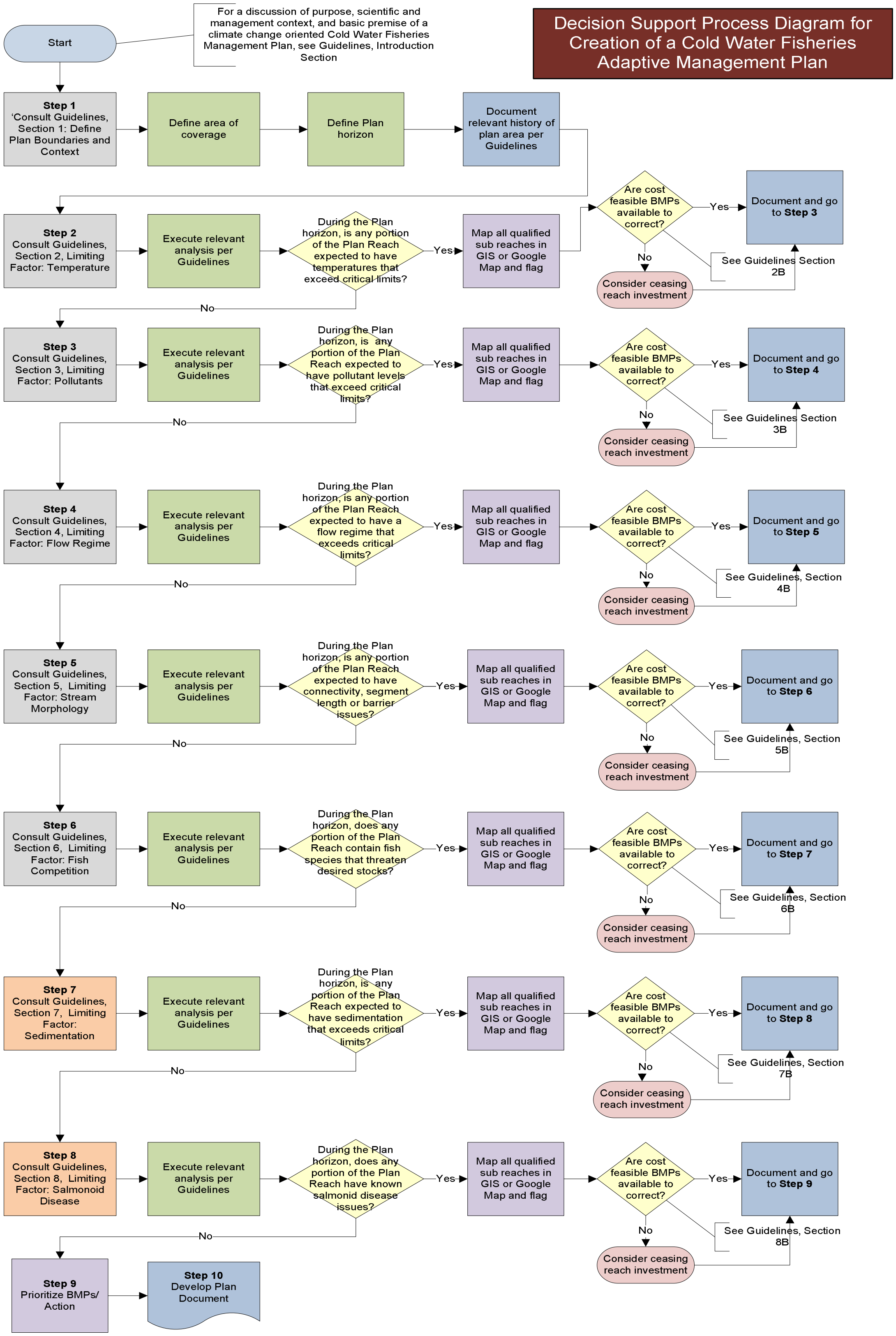
Figure 1 shows both the decision components and the linkages among the components for a systematic analysis of a limiting factor.

Figure 1. Example of Decision Components for a Limiting Factor Analysis



Moving through the components from left to right in the figure above takes the analyst from reviewing guidelines for that factor (in this case, Flow Regime), through posing the question: "During the Plan Horizon, is this factor an issue in this stream or reach?" If it is, then the locations of areas of concern are mapped (streams or stream reaches where the threshold of the factor is exceeded for the period of time under consideration) and applicable strategies and BMPs are considered, followed by an assessment of cost feasibility. If not, the analyst proceeds to the next factor, "not relevant" being noted. The final step is documentation of the decision and the appropriate actions before proceeding to the next factor. Figure 2 shows the full decision support process for the seven limiting factors.

Figure 2. Full Decision Support Process Diagram



Once all the factors are analyzed, the strategies and BMPs that emerge are prioritized. The findings and prioritized recommended actions are presented then in the Plan.

3. Role and Application of Information

The information upon which the analysis depends can derive from either GIS-based or "boots-on-the-ground" approaches. In boots-on-the-ground, data follow from a systematic, empirical assessment, using recognized field procedures, or from the best judgments of anglers and managers familiar with the stream or reach; or, most likely, a combination of the two.

4. Similarities and Differences with Trout Unlimited's Conservation Success Index (CSI)

Since 1959, TU has been responding to the fundamental question, "How do we best conserve trout and salmon?" Over the decades TU has pioneered state-of-the-practice science about trout and trout ecology and from it are an evolving set of trout-oriented, best management practices.

One of the most definitive analytical steps was taken by TU with the development of the Conservation Success Index (CSI). It was designed as a "landscape-level planning tool" to "help strategically conserve and restore trout and salmon through characterization of the range-wide status for native salmonids and the status of wild trout populations at the sub-watershed scale (typically, 10,000 to 3,000 acres)." The CSI is based on "rule sets" upon which scores ranging from 1 to 5 are assigned to attributes of a sub-watershed, which are organized into four groups:

1. Range-wide condition
2. Population integrity
3. Habitat integrity
4. Future security

A composite score is determined for each of the four groups so that the relative health of the study area can be characterized by CSI ranking and, consequently, compared with other study areas.

Developing the CSI for a study area has two parts: a top-down consideration applied by TU scientists and specialists using a GIS approach for selected geographic areas, and a bottom-up approach using data gathered or validated by local chapters. The analysis results yield not only a profile score for each of the four CSI groups, but also maps for each of those scores for the study area. The combination of scores and maps provides a powerful picture for developing strategies to manage the conditions indicated.

While the analysis is intended to provide insights from the watershed down to the stream, stream reach, or site level, most of the applications of the CSI Index process to study areas so far are very generalized. This seems to be due primarily to lack of data for the top-down execution of the analysis. It limits the CSI's applicability for targeting and prioritizing projects at the stream, stream reach, and site level.

The limiting factors approach described in this document is based on actual threshold metrics, rather than a scaling from 1 to 5. While the binary assessment (in which conditions either meet or exceed threshold criteria) does not provide a way to scale the measured conditions (for example, good, fair, poor), it has the significant advantage of depicting whether a stream or reach is at its ecological limits. This enables an understanding and basis for decision making about appropriate actions as the effects of climate change are projected into the future on, say, a decade-by-decade basis.

5. Documenting the Study Area Boundary, Context, and the Plan Horizon

Like any planning process, initial steps should include defining carefully the geographic area to be studied (for CAMP purposes this will almost always be a watershed, catchment, stream or stream reach), and the timeframe over which it is to be studied.

Every study area comes with a context that should be documented. This context will include at a minimum:

1. Geomorphological framework (total miles of perennial streams, high mountains, high desert, rolling hills, low elevation, high latitude, etc.)
2. Habitat structure and nature
3. Intervention history

Habitat nature reflects such characteristics as native and wild species presence, major food sources (type and timing), patterns of season and climate, and typical flow regime characteristics. Intervention history includes determining if the area was stocked, and, if so, with what, when, by whom, and where. It also includes documenting modifications made to stream morphology such as diversions, channelization, and the like, and why.

Climate change is likely to become an increasingly major aspect of any coldwater-fishery management plan in the US. The Plan horizon should reach sufficiently into the future such that in-stream and near-stream mitigation investment decisions can incorporate anticipated climate change impacts into the decision process. Many climate change analyses look out to the year 2100 with major intermediate steps anticipated in 2035, 2050, and 2075.

6. Limiting Factors and Climate Change

Global climate patterns are changing and have been doing so measurably since at least the mid-1950s. Every part of the US, indeed the globe, is affected. Nowhere do anticipated changes have greater adverse implications for the US than in the Southwest. The nature and degree of change is expected to be highly dependent on location. How climate change affects trout populations may vary substantially, depending especially, for example, on habitat elevations and latitudes. Trout in lower-elevation streams in central Wisconsin or those in small headwaters in the southern Appalachian Mountains of Western North Carolina undoubtedly will face different adaptive challenges than those in coastal Oregon or the Aldo Leopold Wilderness of Arizona.

A major advantage of the limiting factors approach described in this document is the opportunity for considering the *current* conditions of a stream or reach using the limiting factors thresholds and comparing them with projections of what they might *become* based on climate change modelling. Of the potential climate change effects, which are likely to push the habitat conditions over a limiting factor threshold (dooming the habitat) and when might that be likely to occur? Are the forces manageable, at least in the short run, and, if so, over what period of time are management responses relevant?

Climate science has matured substantially over the past 30 years. Global climate modelling currently may be as sophisticated as any modeling effort in science. The fundamental processes are increasingly well understood and the scenarios derived from the modeling are increasingly detailed. The challenge now is to link what the models are telling us to where the in-stream management work should be done; that is, to downscale the global models to apply to where habitat management decisions are made, where "boots hit the water"—specifically, at the watershed, catchment, stream, and reach levels.

That said, while climate science has become far more robust, it cannot tell us the future. This is because many of the drivers of climate change ("forcing assumptions") will be affected, even substantially modified, through concerted efforts by societies around the globe to avoid at least the more adverse impacts. When and how much effort will be expended is unknown. Much of climate science output has been structured to generate a range of *scenarios* that facilitate "what if" analysis based on input assumptions. These scenarios can, and do, vary widely depending on best judgments made by the modelers about what these societies will adopt as mitigating strategies and how fast those choices are implemented. More extreme scenarios serve as "bookends" that frame a range of feasible outcomes. For this reason, best-practice planning efforts that deal with climate change incorporate the term "adaptive." Adaptive plans are those that recognize that the context within which solutions are to be developed likely will change and that actions based on an analysis of that context should be designed to be flexible to accommodate redirection as the future actually emerges.

Chapter 1
Water Temperature as a Limiting Factor

Trout health and survival are strongly affected by water temperatures, which may increase from climate change. Determining water temperature needs for trout and assessing habitat conditions is an important part of the effort to maintain healthy trout populations.

1.1 How is water temperature a limiting factor?

Water temperature affects the growth, reproduction, and survival of trout. Even small increases in temperature can change the distribution and abundance of trout species. In addition, trout can be more vulnerable to increasing temperatures if they also are suffering from adverse flow conditions (for example, drying) or diminished food supplies, which are also potential consequences of climate change. Survival at low temperatures can be a problem, as well, for example, where low water conditions result in winter freezing throughout the water column.

What are useful water temperature thresholds?

Temperatures expressed in Fahrenheit, or °F, are common and normal for trout fishermen and women, whereas scientists routinely present temperature information in degrees Celsius, or °C. In this chapter, water temperatures are shown in separate columns in both °F and °C in Tables 1 – 3. Elsewhere in the text, values expressed in Fahrenheit have their equivalent in Celsius provided in parentheses.

Most of the temperature values in Tables 1 – 3 are shown in *three* significant figures, where sources have provided, for example, 17.0 or 22.1°C, because scientific studies routinely enable that degree of accuracy. Elsewhere in the text, however, only *two* significant figures are used, for example, 50 or 70°F. This is to avoid overwhelming readers with too many digits to deal with, in text already blooming with numbers, including from temperature scale conversions. After all, most readers only rarely contemplate temperatures in tenths of degrees, body temperature being an example of an exception that uses three significant figures, including tenths of a degree.

Readers are invited to consider actions that might cause water temperatures to change by, say, single or double digits of whole degrees, that is, with no numbers after a decimal point. For example, solar shading with vegetation might be considered as part of an effort to reduce by 5 or 10°F the temperature in a section of stream that has a measured average of 68°F. This would be as compared with intending to reduce it by 5.4°F to bring it exactly under a 62.6°F threshold, a level of detail that runs a risk of causing dismay. It would be in addition to the exasperation that already may result from attempts to compare field measurement data, having its variabilities, with a three-significant-figure threshold value, such as the 62.6°F Colorado acute water quality criterion. In this document, we want to show relevant, precise scientific information but also to otherwise use numbers in a manner that invites their familiarity and usefulness in the real-life context of trout fishermen and women, to assist in their feeling equipped to contemplate effective responses for trout population protection.

Water temperatures at which trout species prosper, as well as those at which they die, have been determined through laboratory and field studies. Table 1 shows ranges of temperatures that have been identified, by species, as optimum for growth (OGT) [3-5]. Also shown are those too high for most individuals to survive, the upper incipient lethal temperature (UILT). These threshold values potentially are useful in assessing trout habitat conditions [3]. More water temperature results, including temperature effects on reproduction, egg incubation, and juvenile survival, for example, are provided briefly in Section 1.2 of this chapter.

Table 1. Ranges of Optimum Growth and Lethal Water Temperatures Reported for Trout

Trout Species	OGT, °F	UILT, °F	OGT, °C	UILT, °C
Cutthroat	49 – 64.4	75.6 – 82	9.5 – 18.0	24.2 – 28
Brook	50.0 – 66.2	74.3 – 77.9	10.0 – 19.0	23.5 – 25.5
Rainbow	50.0 – 66.2	75.2 – 80.1	10.0 – 19.0	24.0 – 26.7
Brown	45 – 66.2	70.7 – 80.1	7.0 – 19.0	21.5 – 26.7

The optimum growth temperature (OGT) is that at which growth rates are maximal, as determined under experimental conditions. It means growth rates decrease at temperatures above and below that value. The upper incipient lethal temperatures (UILT) are those at which there is 50 percent mortality in a population over a specified interval of time, typically one to seven days.

Chronic and acute temperature thresholds have been determined for Colorado coldwater fishes, including cutthroat, brook, rainbow, and brown trout, and are shown in Table 2 [6]. They are based on original study results and not reviews or compilations from other work. The *chronic* criteria are intended to protect fish from *sub-lethal* warm temperatures that can adversely affect long-term growth, reproduction, and survival. They are expressed as the maximum weekly average temperature (MWAT), which is the seven-day mean of consecutive daily mean temperatures.

The *acute* criteria are intended to protect fish from *lethal* exposures to very warm temperatures. They are expressed as daily maximum (DM) temperature, which is the highest two-hour average water temperature measured over a 24-hour period. The acute criteria are based on UUILT values, which are ultimate upper incipient lethal temperatures. It is the value at which the uppermost UILT (upper incipient lethal limits, with examples shown in Table 1) no longer increases with increasing acclimation temperature. It is considered a “final maximum temperature threshold” [6].

Table 2. Chronic and Acute Water Temperature Criteria for Colorado Coldwater Stream Species

Trout Species	Chronic, ˚F	Acute, ˚F	Chronic, ˚C	Acute, ˚C
Cutthroat	62.6	71.8	17.0	22.1
Brook	64.9	71.1	18.3	21.7
Rainbow	64.8	74.8	18.2	23.8
Brown	67.3	76.3	19.6	24.6

The U.S. Environmental Protection Agency (EPA) contends that aquatic ecosystems can withstand some stress and occasional adverse effects, so protection all the time and everywhere is not necessary. If 95% of animals and plants are protected from chronic or lethal effects, that has been considered adequate for exposure to toxics, for example [7].

In applying this approach to aquatic ecosystem management, Colorado ranked chronic and acute temperature criteria for individual coldwater species from most to least sensitive, and determined the 5th percentile value from its data. It concluded, however, that it did not obtain adequate protection for its most sensitive species, cutthroat trout, in the unmodified EPA approach. Colorado's response was to adjust to ensure cutthroat trout protection, promulgating thermal limits more directly based on that temperature-sensitive species, which also affords protection for the others. Its resulting criteria for coldwater streams are shown in Table 3, including lower thresholds for the reproductive season, October – May [6]. Colorado expects these criteria not to be exceeded more than once over three years.

Table 3. Chronic and Acute Water Temperature Criteria for Colorado Coldwater Streams

Interval of Time	Chronic, ˚F	Acute, ˚F	Chronic, ˚C	Acute, ˚C
June – September	62.6	70.2	17.0	21.2
October – May (Reproductive Season)	48	55.4	9.0	13.0

From a comprehensive assessment, Colorado determined that these sensitive-species-based temperature criteria (protecting cutthroat trout, in particular) were attainable for a large majority of its coldwater streams. Approximately 85% of its coldwater stream miles are headwaters, typical cutthroat habitat, and also potential, if not known, residence for brook, rainbow, and brown trout populations [6].

How does water temperature affect trout?

Water temperature is a critical factor for trout because it determines the suitability of a habitat for a species through its role in physiological processes that affect growth, behavior, reproduction, and survival throughout all life stages [3, 8]. Water temperature is a sensitive indicator of habitat suitability because small changes in temperature can affect species distribution and abundance. Modeling of how trout distribution may change in response to climate change in the western United States has shown that stream temperature, together with flow regime, and biotic interactions, likely will drive shifts in fish species distribution [9]. Therefore, water temperature is important to monitor, especially given a changing climate [8, 10, 11].

Water temperature affects physiological processes in fish that determine growth, food consumption, metabolism, reproduction, and survival [3, 12, 13], and which also influence behavior and habitat selection [3, 8, 14]. Some physiological or biochemical processes, including growth, food consumption, and activity have an optimum temperature. For example, the rate of growth may increase with increasing water temperature to a point and then decline [3]. In fact, studies have shown that growth rate is the most sensitive physiological process to water temperature [3, 15].

Water temperatures that are too high (or too low) can lead to death, either immediate or delayed [3, 16]. The temperature extremes that result in death are influenced by the developmental stage of the fish and the temperature range to which it is accustomed [3]. Fish tend to select an environment near their optimal growth temperature, and generally have an optimal range of temperatures [3] or “zone of efficient operation” [17].

Through its effect on growth, temperature plays a key role in determining the age when fish become sexually mature. Variation in the fecundity (number of eggs) of female salmonids is strongly related to their body length, which is an indication of maturity [18, 19]. Water temperature also has a strong effect on recruitment of individuals from one-year class to the next in high-elevation populations [8, 20-22].

Water temperature’s effects on growth, reproduction, and survival lead to effects on fish behavior, in general, and to differences in habitat selection among salmonid species and subspecies [16]. Temperature can drive daily movements, seasonal movements, and competitive interactions [8, 16]. Therefore, water temperature is useful as an indicator of habitat suitability. Mean summer water temperature, together with available stream length, can be used to identify potentially suitable habitat for cutthroat trout, for example [8, 19, 20].

Researchers studying cutthroat, brook, rainbow, and brown trout found that stream temperature, flood seasonality, and the presence of other species strongly affected habitat occupancy. The coldest streams were occupied by cutthroat and brook trout; rainbow trout occurred in warmer streams; and brown trout in the warmest streams [9].

The influence that water temperature has on local and basin-scale habitat selection, species distribution, health, and movements make it a useful parameter for assessing and monitoring trout habitat and populations. Identifying thermal criteria for species is critical to the ability to maintain or restore both native and sport trout fisheries [16]. Not only is water temperature a key driver of the distribution, abundance, and health of a population, but it is also a sensitive indicator, because even small changes can have substantial effects [10, 11, 16].

The upper temperature tolerance limit generally corresponds to the maximum water temperatures at the lower end of the distribution of the species within a drainage [16, 23]. The optimum growth temperature generally corresponds to the upper end of thermally suitable habitat [16, 23-25].

1.2 What are relevant water temperature thresholds?

Suitable water temperature conditions for most trout species occur from about 50 to 70°F (10 to 21°C). A narrower range, roughly 55 to 65°F (13 to 18°C), seems to support ideal growth rates. Between about 72 and 77°F (22 and 25°C), survival becomes compromised, species dependently. Trout in earlier life stages are more vulnerable to higher (and lower) temperatures than adults. Reproductive functions need lower temperatures, around 45 to 55°F (7 to 13°C).

The water temperature threshold values summarized in Table 1 indicate the optimum growth temperature (OGT) and upper incipient lethal temperature (UILT) for cutthroat, brook, rainbow, and brown trout. Table 2 shows chronic and acute water temperature criteria by trout species, as established by Colorado. In Table 3 are the chronic and acute temperature thresholds that Colorado applies to its coldwater streams. The following paragraphs provide additional temperature metrics and threshold values for different life stages of trout, as reported in studies. There are not necessarily the same metrics available for all four species, the cutthroat, brook, rainbow, and brown trout.

Cutthroat trout

Optimum growth temperatures. A laboratory study determined the optimal growth temperature (OGT) for Colorado River cutthroat trout (CRCT) to be 60 and 62°F (16 and 17°C), the small difference being the result of a difference in feed [26].

Upper lethal temperatures. A study of Rio Grande cutthroat trout found an ultimate upper incipient lethal temperature (UUILT) of 73°F (23°C) for fry and 71°F (22°C) for juveniles [27].

Reasoning that the Bonneville cutthroat trout is an evolutionarily similar subspecies to CRCT [5, 28, 29], researchers studying CRCT concluded from a Bonneville cutthroat study that an average daily maximum temperature for the warmest 7-day period, i.e., the maximum weekly maximum temperature (MWMT) for CRCT was in the range of 76 – 85°F (24 – 29°C) [5]. The critical thermal maximum temperature (CTM) for CRCT, initially acclimated at 68°F (20°C), was determined to be 85°F (29°C) [5, 26].

Recruitment and reproduction temperatures. Field and laboratory studies found a minimum temperature to support minimal CRCT recruitment was 46°F (7.8°C) as the warmest 30-day mean of the average daily stream temperature (M30AT), while 48°F (8.9°C) M30AT was necessary for high recruitment [5, 8, 20-22].

CRCT generally spawn during or following peak flows from snowmelt [8]. Studies found that CRCT spawning begins when either maximum daily temperatures reach or mean daily temperatures exceed 45 – 50°F (7.2 – 10°C) [6, 30-32]. CRCT eggs hatched after 30 days at 50°F (10°C), with each 1.1°F (0.6°C) decline corresponding to a two-day delay in hatching [6, 33]. CRCT fry emerge 570 – 600 degree-days after spawning [21]. In high elevation streams, CRCT may complete spawning as late as early July, with emergence in late August through early October [6, 19, 21].

Brook trout

Optimum growth temperatures. An OGT of 57°F (14°) has been determined for brook trout [16]. An OGT range of 50 – 66°F (10 – 19°C) has been cited for adults and 54 – 59°F (12 – 15°C) for juveniles [3]. An optimum range of 45 – 69°F (7 – 20°C) has been indicated where life stage is unspecified [3].

Upper lethal temperatures. A UILT of 75 – 78°F (24 – 26°C) has been described for brook trout where life stage is unspecified and 74 – 78°F (23 – 26°C) for juveniles [3].

Rainbow trout

Optimum growth temperatures. Over the temperature range of 46 – 68°F (7.8 – 20°C), the OGT for rainbow trout was determined to be 56°F (13°C) [16]. Another study found the OGT for adults to be 50 – 57°F (10 – 14°C) and for juveniles to be 50 – 60°F (10 – 19°C) [3]. An optimum range of 50 – 72°F (10 – 22°C) has been cited where life stage is unspecified [3].

Upper lethal temperatures. The UUILT was determined to be 76°F (24°C), with a 95% confidence interval of 75 – 76°F (23 – 24°C) [16]. Other research cited the UILT as 80°F (27°C) where life stage is unspecified and 75 – 80°F (24 – 27°C) for juveniles [3].

Brown trout

Optimum growth temperatures. The OGT for brown trout where life stage is unspecified is 50 – 60°F (10 – 16°C) and 45 – 66°F (7 – 19°C) for juveniles [3]. An optimum range of 39 – 75°F (4 – 24°C) has been given where life stage is unspecified [3].

Upper lethal temperatures. The UUILT for brown trout has been cited as 72 – 77°F (22 – 25°C) for adults and 77 – 86°F (25 – 30°C) where life stage is unspecified [3].

Recruitment and reproduction temperatures. Brown trout are thought to have poor recruitment at low water temperatures [14, 34-36].

1.3 What influences and interacts with this limiting factor?

Studies have indicated that key factors influencing or predicting stream temperature fall into three categories: air temperature, geomorphology, and landscape position [5, 37-39]. In modeling to predict the persistence of CRCT in the Upper Colorado River Basin, researchers found that air temperature, latitude, cumulative upstream drainage area, slope, aspect, average elevation for an entire stream reach, and either average summer (June – September) stream discharge or summer (June – September) discharge as a percentage of annual average discharge were the best predictors of stream temperature metrics [5].

What are air temperature effects?

Solar radiation, including both short- and long-wave radiation, has a dominant effect on stream temperature [40, 41]. The type of substrate also influences stream temperatures. Aspect, shading, and vegetation affect the amount of solar radiation received by the water. They, in turn, are influenced by fire and vegetation management [41]. Warming from radiation may be offset by increased evaporation from reduced relative humidity [40].

From a study of Idaho mountain streams, researchers concluded that increased solar radiation following wildfires accounted for 9% of the increase in stream temperatures, despite burning having affected 14% of the basin. Within the burn area, however, stream temperatures were 2 – 3 times higher than basin averages, and radiation gains were attributed to 50% of the warming [42].

Using modeling to evaluate the effects of three major variables—air temperature, solar radiation, and stream flow—on stream temperatures, researchers rather startlingly concluded, however, that air temperatures increases, potentially from future climates, "could account for a much larger proportion of stream temperature increases (as much as 90% at a basin scale) than wildfire" [43]. They noted this highlights the potential limitations of fire management activities as part of efforts to manage climate change effects on stream temperatures. They suggested that wildfire suppression and fuel management might have most appropriate application in protecting small but prized fish populations [43].

Stream temperature can be highly correlated with air temperature, because both are driven by solar radiation [5, 39, 41]. Therefore, air temperature can be a useful indicator of water temperature in some stream segments [5]. However, this linear relationship between stream and air temperatures exists only at air temperatures above 32°F (0°C) and below about 68°F (20°C). At warmer or colder air temperatures, a strong correlation does not exist [44].

Air temperature generally decreases with elevation, a relationship known as the environmental lapse rate. Average rates across various environments range from 1.8 to 3.6˚F (approximately 1 to 2°C) per 1,000 ft (305 m) [45, 46]. This range, however, is a generalization; there is no constant relationship between elevation and air temperature [46].

In addition to elevation, researchers considered watershed size, slope, and orientation, and land-surface attributes, including riparian vegetation, grasses, and grazing, in an effort to predict maximum summer water temperatures in mountain streams. They concluded that elevation had the largest effect, and contended that was not surprising since small streams had limited thermal capacities. That is, having relatively small volumes, they would be expected to respond rather readily to air temperatures, which would be cooler as elevations increased [47].

Interestingly and importantly, they found that mean basin elevation correlated much better than point elevation with stream temperature. They speculated that it better characterized the spatially distributed effect of air on stream temperature. They recommended that basin elevation be the surrogate, not point elevation, when stream temperature data were not available. For example, using mean basin elevations, thermal regimes among streams could be ranked, they noted [47]. That is considerably short of saying stream temperatures could be predicted from basin elevations and air temperatures.

They mentioned there could be localized effects on stream temperature, such as, turbulent-flow characteristics, dam-building by beavers, and springs and seeps contributing coldwater inflows that were not incorporated in their modeling. But it was riparian tree abundance and cattle density, which were considered, that had the next greatest effect on stream temperature, after elevation. They concluded, given that geomorphic characteristics cannot readily be changed, that attention be given to human disturbances, for example, cattle distributions, timber harvests, and road crossings, where management of thermal regimes in mountains streams was intended [47].

Stream temperatures are sensitive to streamflow [42, 48]. If water supply to streams diminishes due to a changing climate and results in lower flow volumes and rates, stream temperatures may become more vulnerable to heating. However, this vulnerability might be offset by cooling from increased snowmelt entering streams [45, 49] or from groundwater flow contributing a higher proportion of total stream flow [40, 48].

Time of exposure [16, 50-53], flow regime [5, 9], species or subspecies [16] interspecific interactions [5, 7, 54, 55] barriers and stream length [5, 8, 56, 57], population size and genetic integrity [5, 23, 58-60], random catastrophic events [5, 8, 23, 57, 61-66], pollutants [67] and disease [3, 68] are factors that can interact with temperature to influence the presence and health of populations of native and non-native trout.

What about other influences?

It is important to consider not just stream temperature but multiple interacting factors for specific locations to conserve native trout into a future affected by climate change [5]. To predict the probability of cutthroat trout persistence in sub-basins of the Upper Colorado River Basin through 2040 and 2080, modelers integrated not only water temperature metrics, but also stream fragment length, time horizon, effective population size, capacity to buffer stochastic environmental events (for example, fire, debris flow, freezing, and drying), and habitat capacity. They found that cutthroat trout population persistence was most sensitive to stream temperature and to stream segment length. Those populations occupying shorter segments, 0.6 mi (4 km) or less, and lower elevations were most likely to disappear by 2080 [5].

In other studies, the distributions of cutthroat, brook, rainbow, and brown trout in Western streams were modeled based on predicted changes in temperature, flow conditions, biotic interactions, topographic variables, and land use characteristics. The researchers predicted that cutthroat trout will lose 58% of its habitat from temperature increases beyond the physiological optima and negative biotic interactions. Cutthroat trout already have been excluded from much of their native habitat due to competition from non-native species. Based on the modeling, nonnative brook trout and brown trout will lose 77% and 48%, respectively, of their habitats, attributed to temperature increases and winter flood frequency resulting from warmer, rainier winters. Rainbow trout habitat is projected to decrease by 35%, less than the other species because changes in flow conditions that benefit the species somewhat offset adverse temperature effects. The findings show that while water temperature is a significant habitat variable, other factors may interact with temperature to affect further the response of trout species to climate change [69].

Chapter 2
Flow Regime as a Limiting Factor

The timing, duration, magnitude, and frequency of flows in a stream, commonly referred to as the flow regime, play a significant role in the habitat condition and life history of trout. As a major driver of habitat and condition, as well as trout reproduction and survival, flow regime can both support and limit the presence of native and wild trout.

2.1 How is flow regime a limiting factor?

The life histories of individual trout species and subspecies are closely adapted to the flow regime prevalent in the regions where they evolved [8]. Due to evolutionary differences, flow regime plays a significant role in governing the successful establishment of non-native wild trout populations in a stream, and therefore the degree of biotic interaction, for example, predation, competition, and hybridization, among trout species and subspecies in that stream [70-73].

Higher stream flows transport and deposit gravels that provide substrate where eggs can be laid, hatch, alevins can mature, and fry emerge. Important is the timing when these gravel beds will be deposited, and when and whether they will be silted in or scoured out. In concert with temperature, flow regime can influence when trout spawn and migrate [8, 74].

Flow regime also is key in trout growth and survival through its influence on habitat. At higher flows, a larger volume of habitat is available than at lower flows [75, 78]. The magnitude and duration of higher flows determines the formation and maintenance of important in-stream habitat conditions, such as, riffles, runs, pools, bars, and overhanging banks and woody cover, through the movement of bed-load sediment and the delivery of large woody debris. These affect the presence (or absence) and distribution of cover and refuge from predators and from high flows, substrate for macroinvertebrates, stream productivity, and habitat complexity [77-80].

2.2 What are relevant flow regime thresholds?

While there are no flow regime limits, no thresholds, to cite, there is context to consider. In particular, high flows can scour eggs or alevins from redds and carry away just-emerged fry. Trout that spawn in the fall are vulnerable to winter floods and those that spawn in the spring, to summer floods [70, 81, 82]. This sensitivity to flow regime can limit the trout species and subspecies occupying a particular stream [74].

Colorado River cutthroat trout (CCRT) spawn in the spring, during or after peaks of snowmelt-driven flows [8, 83-88]. Depending on elevation, flow, and temperature, CRCT may spawn as early as April and as late as early July, with fry emerging from the end of August through the beginning of October [8, 75, 83, 89-92]. Some populations of Colorado River cutthroat trout have been extirpated during persistent drought [8, 93].

The historic range of rainbow trout extends from Alaska to Mexico and includes British Columbia, Washington, Oregon, California, Idaho, and Nevada. They spawn in early spring, following the early spring runoff in their native range [88, 94]. Snowmelt and rain-on-snow-driven peaks in late spring can wash away redds and emerging fry [82].

Brook trout are native to eastern Canada from Newfoundland to western Hudson Bay, south to Minnesota, and to northern Georgia in the Appalachian Mountains. Brook trout spawn in the fall. Their embryos incubate through the winter and fry emerge in late spring to early summer [95]. Therefore, high spring flows can limit brook trout recruitment [8].

Brown trout are native to Europe, North Africa, and Western Asia. They spawn in the fall. As with brook trout, high spring flows can limit brown trout recruitment [8].

2.3 What influences and interacts with this limiting factor?

What are key effects on stream flow?

The timing, duration, magnitude, and frequency of flows in streams are determined primarily by climate, including patterns of precipitation and temperature, and the stream's drainage area. Within Colorado's upper Dolores River watershed, snowpack and snowmelt affect flow regime, as well as late summer and early fall monsoon rains. Many higher elevation tributaries of the Dolores main stem have perennial (year-round) flow, while some lower tributaries have intermittent flow.

Groundwater conditions also affect stream flow. Where the groundwater table is higher than the stream bottom, groundwater will enter the stream, it being a gaining reach. Where the groundwater table is lower, groundwater will receive flow from the stream, this being a losing reach.

Removal of water by diversions, pumps, or infiltration galleries reduces downstream flows. Dams can delay downstream flows. These tools that control or remove water can affect flow regime periodically or year-round.

Potential climate change effects on flow regime have been described [96-99]. Consequences on precipitation, crop irrigation requirement, hydrology, streamflow, and water availability were determined in Phase I of the Colorado Water Availability Study (CRWAS) [100], based on consideration of five climate change scenarios, were cited in the Colorado Drought Mitigation and Response Plan, Annex C. Climate Change Implications, and are summarized below [101, 102]:

Precipitation:

- Generally, increases in the winter months and decreases in the summer months, although average winter increases are smaller in the southwestern portion of the Study Area.

- Increase in temperatures causes a shift from snow to rain in the early and late winter months.

Crop irrigation requirement:

- Increases for all climate projections (average annual increase by 1.9 to 7.4 inches depending on projection).
- Increases are primarily due to higher temperature and lower irrigation-season precipitation, which increase the number of growing season days for perennial crops, and crop demand for irrigation water.
- Peak crop irrigation requirement continues to occur in the same month as it has historically.
- Average annual growing season increases by 8 to 32 days.

Hydrology:

- At over 80% of the sites, the majority of climate cases suggest a decrease in annual flow, with annual flow more likely to decrease in southwestern watersheds and at lower elevations.
- At 75% of sites, all climate cases showed a shift toward earlier runoff, and at all locations, some climate cases showed a shift toward earlier runoff. Runoff shifts earlier by an average of 8 days.

Streamflow:

- Flows are generally higher than historical in May and June and lower in July through March.
- The historical annual low-flow values generally fall within the range of projected low-flow values.

Water availability:

- Upstream locations on main rivers and smaller tributaries generally have less flow available to meet future demands as a percent of modeled streamflow than gages farther downstream that include more tributary inflow.
- Most locations show less water availability for three of the five climate projections, although one projection shows more water available at the locations selected to display CRWAS results.
- Generally, more water availability in April and May, corresponding to the shift in natural flow hydrographs.
- The historical annual minimum water availability values generally fall within the range of projected minimum water availability values for 2040.

These projected changes, exacerbated by the potential need to divert stream flow for crop irrigation requirements, could result in lower stream water volumes for trout, and increased risk of egg, alevin, or fry scour in early spring and early winter [8, 76].

Researchers studying the effects only of precipitation and temperature on streamflow determined that temperature effects have been minimal over the 20th century. That is, precipitation overwhelmingly has been accountable for variability in streamflow, not temperature. They built on the findings of others who had studied a 50-year period of information from 82 river basins that had negligible human disturbance, expanding in the new work to the conterminous U.S. (all lower-48 states) with data from 1900 – 2008. They echoed an observation of the earlier researchers that since precipitation controlled runoff variability, there could not be confidence in estimates of future runoff from climate change modeling until there were reliable estimates of precipitation [103, 104].

They noted that in situations where water supplies were being rather closely matched by water uses, for example, diversions for irrigation, that small increases in temperature with accompanying evapotranspiration could affect flow, drawing supplies below critical levels. While limiting their study only to effects of precipitation and temperature, the researchers acknowledged that there were other factors potentially important to streamflow, including the direct effects of atmospheric carbon dioxide on plant uptake of water, net radiation, changes in land use and cover, and changes in water use [103].

What interacts with flow regime?

Water temperature, species competition, stream connectivity, channel geomorphology, population size, stream size, disease, and disturbance events such as wildfire are important factors that interact with flow regime [73, 74, 94, 105, 106]. While extended drought may cause cutthroat trout to disappear from some streams [93], it may support recruitment success in higher elevation streams as a result of lower flows and warmer temperatures [8, 107]. In the Flathead River system, reduced spring flows together with an earlier spring peak likely have allowed higher rainbow trout recruitment and rapidly increased hybridization with native cutthroat trout [94]. Researchers determined that connectivity, geomorphology, surrounding land use, beaver activity, and habitat complexity appeared to ameliorate the negative effects of drought on Bonneville cutthroat trout in two watersheds [80].

Researchers analyzing data on air temperature, precipitation, and flow data in five drainage areas of the Rocky Mountains for the period from 1950 to 2009, concluded that decreased summer flows, together with increased risk of wildfire, likely will adversely affect trout survival where there is poor connectivity among trout populations [108], as is the case for cutthroat trout populations in Colorado's upper Dolores River watershed [109]. They also cautioned that in headwater streams where trout populations are limited by stream size, declining flows could lower the elevations at which streams become intermittent, or cause perennial reaches to become fragmented by intermittent sections. Further, lower summer flows may decrease macroinvertebrate productivity and thus reduce food supplies trout growth and survival [108].

Using predictive modeling to study the potential effects of climate change on the distribution of brown, brook, rainbow, and cutthroat trout, researchers found that brook trout declines were driven by a combination of increasing temperature and increasing frequency of winter high flows; brown trout declines, primarily by increasing winter high flow frequency; and potential rainbow trout declines due to increasing temperature were mitigated by a positive effect of increased winter high flow frequency. Declines projected for cutthroat trout resulted mainly from increasing water temperature and not from predicted changes in flow regime [74].

What about streambed gradients?

Can high streambed gradients limit trout movement? What are inhabitable bed slopes for trout? For reference, here is how the Oregon Department of Fish & Wildlife makes distinctions in streambed gradient (or slope, which is determined by dividing the difference in elevation by the horizontal distance, expressed as percent): <1-2%, low gradient; 2-8%, moderate slope; 8-16%, steep; and >16%, very steep [110].

Cutthroat trout were observed in steeper-gradient sites than other trout species in Rocky Mountain streams, being present at slopes as high as 27% and abundant at 6-14% [75, 111-113]. A gradient of 10% or more was determined to function as a barrier to the upstream presence of wild cutthroat trout in a study area of 56 perennial streams at elevations of 7,500-10,700 ft (2,300-3,350 m) in Wyoming [114]. Anadromous cutthroat trout were seen in a Washington study area at slopes up to 33% [115]. Brook trout were found to be most abundant at less than 3% gradient and absent at 14% in the Colorado River basin, based on data from Wyoming, Utah, and Colorado streams. It was believed likely that brook trout excluded cutthroat trout presence at lower gradients, the higher gradients and elevations being less suitable for the nonnative species, enabling cutthroat trout to persist [8, 111].

Researchers have reported that streambed gradient had no consequence on the amount of trout biomass measured upstream and downstream at 23 changes in slope, 0.2-7.2%, in 18 Wyoming and Idaho streams [116]. In other research, it was found, however, that gradient effects on trout density were a function of channel size. That is, larger trout densities were at the high (8-20%) and moderate (4-8%) streambed gradients, as compared with the low gradients (2-4% and <2%), when channel sizes were large (having catchment areas >300 ha). At the lowest gradient (<2%), there was no relationship between trout density and stream size. As gradient increased, however, the stream-size (or catchment area-size) effect developed. It was determined that the smaller channels (draining <300 ha) tended to support more fish if the gradients were small; and the larger channels had more fish at the moderate to high gradients [117].

The Washington Department of Fish & Wildlife (WDFW) applies a standardized methodology for evaluating the suitability of stream reaches as fish habitat. It has criteria for identifying fish passage barriers that result from streambed gradient, which it defines as a slope greater than 20% for a continuous length of 525 ft (160 m) or more, or exceeding 16% for streams 3 ft (0.9 m) or less in width. The amount of 525 ft (160 m) is simply what the state considers a minimum length for a stream reach in its assessment protocol [118].

Are there useful slope threshold values?

The WDFW criteria appear to indicate useful slope thresholds (20%, and 16% for smaller streams) for anticipating, in general, high-gradient barriers to upstream movement of trout. These values may be most appropriate and helpful in assessing habitat for anadromous (migrating from salt water to spawn in fresh water), fluvial (migrating from rivers or streams to spawn in tributaries or headwaters), and adfluvial fish (migrating from lakes to spawn in headwater streams), concluded researchers who had set about mapping rules to delineate salmonid distributions in north-central Washington [118]. There may be legacy populations, however, of resident (spawning in the headwaters of streams they inhabit) trout established above the slope threshold values. The researchers suggested, consequently, that the criteria may not always be applicable for resident forms of bull, cutthroat, and rainbow trout [118], for example, if the purpose is anticipating the upper extent of populations.

Where will trout face high bed gradients and the resulting high flow velocities? It may be at naturally steep streambed slopes as may exist in headwaters, perhaps over some distance, or as may occur along the stream channel over shorter length in the form of chutes, for example. It may be at manmade structures, such as culverts, which, if poorly designed and installed, may present trout with elevated flow rates.

How do trout capacities compare with potential stream flow velocities?

How fast can trout swim, and what affects their speed? What water velocities may they confront? Researchers have suggested this classification for the range of speeds that fish may employ: sustained or cruising, which is normal function without fatigue; prolonged, for activities lasting 15 to 200 seconds, which results in fatigue; and burst or sprint, which causes fatigue in 15 seconds or less [119, 120]. Fish may travel at sustained speeds for migrating, prolonged for getting through relatively difficult areas, and burst for feeding or escape. Cutthroat trout are said to have a cruising speed of 2.0 ft/sec (0.61 m/sec); prolonged, 6.4 ft/sec (2.0 m/sec); and burst, 13.5 ft/sec (4.1 m/sec) [119, 121].

The amount of muscle mass increases with body size, so that larger fish may attain higher speeds during prolonged swimming [122, 123]. For under-yearling and yearling fish (juveniles), flow rates of 0.4 ft/sec (12 cm/sec) will not impede upstreaming movement [124, 125]. Large trout, on the other hand, were capable of overcoming flow velocities of 12 ft/sec (3.4 m/sec) over short distances (20 ft or 6.1 m), based on review of literature [125]. Other researchers have described brook and brown trout speeds of 25 body lengths/sec—which is 25 ft/sec (7.7 m/sec) in an adult trout that is 12 in (0.3 m) in length—contending that commonly accepted estimates of trout performance were low. They found, as well, that brook trout showed two burst modes, similar to the change from prolonged to burst, with a shift to the highest speed at 19 body lengths/sec [126].

Water temperature affects swimming performance, with fish stamina highest at 65-75°F (18-24°C) and lowest at 32-40°F (0-5°C) [124, 125]. *Water pH* also can affect performance. While variations in water pH between 6 and 9 had no discernible effect on the maximum swimming speed of rainbow trout in laboratory tests, water pH of 4, 5, and 10 reduced performances by 45, 33, and 39 percent, respectively, as compared with that at the neutral pH of 7. As well, fatigue occurred earlier in fish swum to exhaustion in acidic as compared with neutral waters [127].

Also important is *dissolved oxygen* content. A decrease in dissolved oxygen from a normal concentration of 7 ppm to 3 ppm may reduce sustained swimming speeds by a factor of five [124, 125]. Other research indicated that oxygen levels at one-third saturation may reduce swimming speeds by more than half [120, 125]. Oxygen deficiencies may result from introduction of organic wastes, for example, in discharge from sewage treatment plants or in runoff from grazed land, as bacteria consume dissolved oxygen in decomposing the waste materials.

Where fish must swim against significant but passable velocities for a period of time, fatigue may reduce measurably their capacities to perform further. Researchers have suggested that perhaps several hours or more may be needed to recover before fish may be ready for more exertion [125]. Fish that must swim in water with entrained air, white water, which has lower density than less-turbulent water, may have their capacity for speed reduced because their tail has less propulsive power in that medium [120]. Flow velocities that cause excessive delay or depletion of energy may result in death or prevention of a life stage activity, such as spawning [120].

What high flow velocities may trout attempting to move upstream have to confront? It depends primarily on bed slope at a stream location, velocity increasing with slope. Where flow rates are elevated in nature, for example, at a chute, trout passage may be prevented, particularly following high precipitation events. That may prevail unless mitigation is implemented, such as installation of a fish ladder. Where a manmade structure, such as a culvert, presents high flow rate problems, it can be removed and replaced with one designed to minimize the opportunity for flow velocities to impede trout passage. In general, culvert slopes and the resulting velocities should be compatible with existing stream channel characteristics such that continuity in habitat is enabled. For example, the maximum flow rate at a culvert exit should be consistent with what occurs in the natural channel. A manmade structure should not be the source of flow velocity problems. Detailed culvert design and installation guidance is readily available, for example, from state and federal departments of transportation.

Chapter 3
Stream Morphology as a Limiting Factor

By *stream morphology* is meant stream channel characteristics, including shape and how it changes over time, and, in the context of this document, those features that potentially affect trout population persistence. Attention is directed, in particular, at *segment length* and, consequently, at *barriers*, which establish segment length, and *connectivity*, that is, the opportunity for trout to move among the *habitat components* necessary for population persistence within a segment. Barriers may be naturally occurring, such as waterfalls, or may be manmade, including dams and water diversion structures. They may ensue from flows that have higher velocities than trout can overcome to move upstream, for example, as a result of steep streambed gradients or channel configurations, natural or manmade, such as chutes or culverts, that cause elevated flow rates; and barriers may happen from low or no flows, occurring temporarily or developing permanently, that impede trout passage.

Segment length refers to the portion of a stream, including its tributaries, beyond which trout cannot pass, either upstream or downstream. For a population to persist, that segment, or stream fragment, must contain habitat components sufficient for each of the life stages of the trout.

3.1 How is segment length a limiting factor?

Segment length is determined by barriers that cannot be breached such that trout cannot move beyond them. A segment length is too short for population persistence if it does not contain the *habitat components* required for the life stages of the trout.

What are habitat components?

By habitat components are meant the stream and streamside features that figure in trout needs. They include, for example, food, such as aquatic and nonaquatic insects and animals; structures and substrate for refuge from predators; shallows and substrate for spawning; streamside vegetation and undercut banks for protection from solar radiation; and pools and flows for refuge from dewatering and freezing. While the presence and quality of such components may vary across segments, improvements may be possible on a segment-by-segment basis, potentially enabling population persistence within those segments. This may include, for example, the addition of shading to offset solar radiation in one, or the placement of substrate (boulders) or large woody debris for more refuge and replacement of a poorly designed culvert in another.

Other habitat components may extend across segments, such as water quality, including the nature and extent of pollutants and nutrients, which may affect both trout and its food sources, and the amount of flow, potentially determining connectivity within more than one segment along a stream. Pollutants from mine drainage, for example, or inadequate flow amounts resulting from water diversions, may be preventing population persistence downstream. This may be more difficult to correct than those habitat component issues occurring between *barriers* on a segment-by-segment basis. With the resolution of stream-extensive problems, however, may come the possibility, and economy, of multiple segments being more capable of supporting trout populations, potentially assisted incrementally by subsequent segment-by-segment improvements, as well.

What are barriers to trout passage?

There may be naturally occurring height barriers to trout passage, such as waterfalls that exceed a trout's capacity to jump, including during full flow and flood conditions. It may be manmade structures for impounding or diverting water that prevent trout passage. Debris jams from debris flows following wildfires may develop and block trout movement.

There may be barriers to trout passage from insufficient flow. The dewatering that follows from drought conditions may prevent some (for example, adult) passage under low flows or all trout passage under no flow conditions. Dams and diversion structures may lead to dewatering downstream. Debris and sediment flows from deforestation following wildfires may produce locations of shallow stream flows that are susceptible to freezing, as may result in low-flow situations from other causes. These barriers from dewatering may be temporary, being resolved by precipitation; or they may develop as permanent conditions where there is insufficient water supply from rainfall or snowmelt to compensate.

High flow velocities may block trout passage. This may occur naturally, for example, in chutes, or in manmade structures, such as culverts, resulting in loss of *connectivity*, as may occur with dewatering.

What is meant by connectivity?

Connectivity refers to the opportunity for trout passage among the habitat components necessary for population persistence within a segment. There may be insufficient habitat that results when stretches of a segment are disconnected. Barriers to connectivity may be long-standing, such as dams and diversions, for which removal is a possible response. Or disconnections may be near-term developments, resulting, for example, when debris flows follow wildfires, having temporary impact until further flows may provide relief or becoming long-term blockage pending remediation actions to clear them, which may be very difficult to implement. As well, segments may increasingly experience dewatering due to declining rainfall and snowmelt amounts, potentially further fragmenting them, and with the additional problem that little may be done about it.

3.2 What are relevant segment length thresholds?

What is a minimum segment length?

There cannot be a universal minimum segment length because the extent and quality of habitat components that sustain populations vary within a stream and from stream to stream. Studies, however, shed wisdom on the matter of segment length needs. They indicate, in general, that a minimum of about four miles (7 km) of stream segment length routinely seems necessary for the sufficient presence of habitat components that enable population persistence. This threshold amount is based on research briefly described below. While the possibility of population persistence will be a function of stream conditions within segment lengths on a case-by-case basis, the four-mile estimate is a useful guide for anticipating and subsequently developing an understanding of segment-specific needs.

Researchers have estimated that a trout population needs a minimum stream segment length of 4.5 mi (7.2 km) for a high probability of persistence. They studied cutthroat trout in the Upper Colorado River Basin and used empirical modeling to consider stream temperature, along with geomorphic and landscape variables, and develop conclusions [128]. Theirs was compatible with the work of other researchers who found a segment length of 5.2 mi (8.3 km) necessary for what they called relatively high fish *abundance*, 0.09 fish/ft (0.3 fish/m), in their study of 41 fish populations from four regions in Idaho, Montana, and Utah [129]. A researcher assessing a single, productive stream in California containing redband trout (a distinctive form of rainbow trout) concluded that a minimum segment length of 2.7 – 4.8 mi (4.3 – 7.7 km) was needed to maintain a total population of 2,500 individuals [130]. The effect of segment length on trout population persistence in the face of *stochastic risks* is summarized as follows, based on findings from seven technical sources: for segment lengths <2.2 mi (3.6 km), a trout population is highly susceptible to stochastic risks; 2.2 – 4.5 mi (3.6 – 7.2 km), at variable risk; and >4.5 mi (7.2 km), robust to those risks [128].

How are stochastic risks involved?

Stochastic risks are from random occurrences. Stochastic risks affecting population persistence may be demographic, genetic, or environmental [131, 132]. Wildfires, for example, which would be stochastic environmental disturbances, may result in debris and sediment flows that modify habitat and cause diminishment of food sources or loss of refuge from sedimentation or from predators.

The smaller the stream segment, the more susceptible is its trout population to stochastic risks. That is, small, random environmental occurrences within a small segment may be expected to have greater adverse consequences for a population than equivalently small disruptions within a larger stream segment. Food sources and refuge, for example, may remain sufficient within the larger segment despite random disturbances. It should be noted that risks from stochastic occurrences would be in addition to dangers posed to population persistence from nonstochastic, or chronic, circumstances, such as steadily rising temperatures or dewatering from declining rainfall and snowmelt amounts.

How does segment length affect trout?

As segment length increases, so does the likelihood of greater habitat complexity, which can result in greater trout abundance [77, 129, 133, 134]. Complex habitats may be necessary to meet the life stage needs of trout, including refuge from environmental stresses, chronic and random [135].

Segment length limits a trout population's exposure to the habitat along its extent. The persistence of a population already established within a segment length may be threatened if habitat conditions within that segment degrade. This may occur from steadily rising air temperatures, for example, which may adversely affect both water temperature and, consequently, food supply. It may result from stochastic disturbances such as debris and sediment flows that may follow deforestation from wildfires, which may reduce food supplies and refuges for trout from predators or from rising temperatures.

As previously noted, the opportunity for a population to persist within a segment requires the habitat components necessary for the life stages of the trout. This introduces two possibilities where there is insufficiency. One is the improvement of habitat quality within a segment to meet population needs, such as, for example, increasing streamside shading for adequate trout refuge from the effects of solar radiation or placement of boulders or large woody debris for more shelter from predation. The other is removal of barriers so that the segment is lengthened to include the habitat sufficient for population persistence.

What population size is needed?

What is the population size that researchers consider necessary to maintain within a segment? What do they recognize is evidence of *abundance* within that segment length? Researchers distinguish between *total* (or *actual*) populations and *effective* populations. An *effective* population is an ideal one with discrete cohorts (that is, representing every stage of the life cycle), equal sex ratio, random mating, constant size, and equal reproduction probability [128, 132, 136]. It has the necessary components for propagation of the population. The characteristics of individuals within total populations vary among streams and over time. Researchers consider that a total population must be large enough for the needs of reproduction to be met, so they use the concept of an effective population—a population subset—for hypothetically meeting those needs. Researchers express the ratio of effective (N_e) to total population (N) as N_e/N. Ratio values of 0.15-0.50 are seen in stream-resident salmonid population-related studies [128, 131, 137-139].

Researchers that provided the estimates of 4.5 mi (7.2 km) and 5.2 mi (8.3 km) as minimum segment length for trout population persistence used N_e/N values of 0.20 and 0.25, respectively, for their contemplation of persistence as applied to an effective population size of 500 individuals [128, 129]. These ratio values of 0.20 and 0.25 were conservative within the range of 0.15 – 0.50

cited above. That is, results using these values will tend to overstate, not underestimate, the segment length believed necessary for population persistence.

For studying the potential persistence of an *effective* population, N_e, of 500 within a segment length, the researchers evaluated using for their modeling purposes *total* population numbers, N, of 1,000, 2,500, or 5,000. They concluded that a total population of 1,000 (of individuals >3 in or 7.5 cm in length) probably was insufficient for maintaining N_e=500 because stream-resident cutthroat trout do not mature until 5.5 in (14 cm). Since N_e is a fraction of the actual breeding population size, as indicated above by the 0.15 – 0.50 range of N_e/N values used, they were concerned that a total population size, N, of 1,000 would be too small to assure successful breeding. In contrast, 5,000 individuals would be a preferred total population size (for maintaining N_e=500), but was probably bigger than truly necessary, they concluded. They noted that other researchers recommended N=2,500 individuals per generation for maintaining anadromous Pacific salmonids, approximating a per-generation N_e=500 [131]. So the trout researchers determined that a total population, N, of 2,500 individuals probably was sufficient from which to project persistence for an effective population, N_e, of 500 [129].

On what basis should N_e of 500 individuals be considered a sufficient number for evaluating population persistence? Population isolation can reduce genetic diversity through lack of gene flow (that is, the lack of movement of individuals or the genetic material they contain from one population to another), inbreeding depression (the reduced fitness in a population due to inbreeding), and genetic drift (the random fluctuations in a gene pool over time that are attributed to random chance rather than natural selection) [129, 131,140-142]. Genetic variation is known to decrease with population size [143].

Isolation can occur within a trout population in which segment length is too short. For persistence, a population must be large enough to have sufficient genetic variation for adapting to ecological and evolutionary constraints [128, 131]. It is generally recognized that effective population sizes of 50 to 500 are essential [137]. Populations of fewer than 50 individuals are believed to be in danger of immediate, deleterious inbreeding effects. Those of 50 – 200 are at risk over the short term. Populations of 201 – 500 are buffered from short-term effects, even though at some risk over the long term [128, 131, 137]. As a result, researchers regularly have taken the upper value of 500 as a minimum effective population size [128, 129, 131, 137, 144, 145].

What is evidence of abundance?

What constitutes fish abundance within a segment, according to researchers? The researchers citing a minimum segment length of 5.2 mi (8.3 km) called 0.09 fish/ft (0.3 fish/m) evidence of relatively high abundance. They observed mean abundances of 0.06 – 0.11 fish/ft (0.2 – 0.35 fish/m) [with mean densities of 0.007 – 0.012 fish/ft^2 (0.08 – 0.13 fish/m^2)] in 41 trout populations from four regions in Idaho, Montana, and Utah. In addition to the relatively high fish abundance of 0.09 fish/ft (0.3 fish/m)—considered by them as a *best-case* scenario—they characterized average abundance as 0.06 fish/ft (0.2 fish/m) and low abundance as 0.03 fish/ft (0.1 fish/m) [129].

Researchers found that as segment length increased, so did adult cutthroat trout (>5 in or 12.5 cm) length and density, along with juvenile (≤5 in or 12.5 cm) length, but not juvenile density. Habitat complexity along with adult trout density increased significantly with segment length. Adult trout densities were highest at locations with large substrate particles (boulders) and a high percentage of undercut banks [135].

How do trout respond to fragmentation?

Researchers assessed eight cutthroat trout populations detached for 25 – 44 years above water diversion structures in headwater streams in Wyoming, and concluded that such isolated populations may persist for decades, but are vulnerable to eventual loss of genetic variability and to extinction [146]. Other researchers used population viability analysis to model dispersal, growth, and survival in both connected and naturally-isolated, stream-dwelling brook trout populations, and determined that increasing fragmentation—independent of habitat loss—threatened population persistence [147]. They concluded that connectivity likely was particularly important to persistence in branching stream systems [147, 148].

The researchers who performed the viability analysis noted their modeling showed, however, that sometimes small populations detached as a result of stream fragmentation may persist. They surmised that localized adaptation may play an important role. They observed higher early survival and reproduction rates at smaller body sizes in an isolated population of brook trout, as compared with trout in non-isolated systems [147]. Other researchers observing cutthroat trout in isolated populations noted higher survival rates early in life, smaller sizes for their age, and reproduction as smaller, younger individuals [149]. Size distribution in the isolated populations were skewed toward smaller individuals. The researchers recognized that smaller fish were more important in isolated populations. This may be a phenotype phenomenon, that is, an adjustment in response to genetic and environmental effects [147, 150]. Changes in size distributions of isolated populations are well documented in scientific literature [147, 151].

The researchers found that based on life history theory, higher early survival and earlier maturation rates were important factors in resistance to stochastic extinction [147, 152]. Important is whether populations will evolve the demographic characteristics, for example, the early survival and reproduction, that enable persistence instead of extinction [147, 153]. The researchers did determine from population viability modeling that blocking access to tributaries increased the likelihood of extinction in the main stem, which in turn increased the likelihood of extinction throughout the system [147]. Other researchers concluded from their individual-based modeling (in which demographic and movement rates resulted from habitat dynamics and individual behavior) that trout passing over non-blocking barriers had little effect on the downstream populations, but reduced the abundance and persistence in the upstream populations from which they departed [149].

What is too high?

What constitutes a barrier in height such that trout passage is blocked? That is, what height is necessary, and what figures in besides height? Researchers measuring trout-jumping performance under laboratory conditions determined that the most important factors affecting the ability of trout to jump over barriers were height, plunge pool depth, and fish size. They ruled out fish condition, that is, intact fins, because the scientists had no control over it. They found that jumping trout could not exceed 3 ft (0.9 m) in barrier height. They could jump just over 1 ft (33.5 cm) if the plunge pool (the pool at the base of the barrier) depth was less than 4 in (10 cm) [154].

They observed, specifically, that brook trout approximately 8 – 12 in (about 20 – 30 cm) in length had a maximum jumping height of 29 in (73.5 cm). They concluded that brook trout 4 – 6 in (10 – 15 cm) in length could jump 25 in (63.5 cm), or 4.7 times body length; and brook trout 6 – 8 in (15 – 20 cm) and those >8 in (20 cm) in length could jump 29 in (73.5 cm), or 2.9 – 4.0 times body length for the 6 – 8 in (15 – 20 cm) group. When plunge pool depth was less than 4 in (10 cm), the smaller trout, those 4 – 8 in (10 – 20 cm) in length, were defeated by a height of just over a foot (33.5 cm); and the larger trout, >8 in (20 cm) in size, were limited at 17 in (43.5 cm) in height [154].

In other studies, a mass acceleration formula was used by researchers to estimate by calculation that adult brown and cutthroat trout could jump maximum heights of 30 in (76 cm) and 34 in (85 cm), respectively. The muscle mass of adult trout would enable them to jump higher than juveniles. Sufficient plunge pool depth would be necessary for the adult trout to build speed to accelerate over the barrier. For those calculations, the plunge pool depths assumed greatly exceeded the 4 in (10 cm) cited above [154, 155].

On the other hand, where fish passage was an objective, researchers recommended preventing apparent barriers from exceeding 16 in (40 cm), along with ensuring plunge pools depths greater than 4 in (10 cm) [154, 156].

Can streambed gradients and flow velocities be barriers?

Can high streambed gradients limit trout movement? Can stream flow velocities be too great for trout to pass? At what velocities can trout swim, and what affects their speeds? Does water temperature influence their capacities? These and related matters are taken up in this document in *Chapter 2, Flow Regime*.

3.3 What influences and interacts with this limiting factor?

What is meant by habitat complexity?

Habitat complexity influences segment length as a limiting factor. Trout abundance and body length tend to increase, which is favorable indication of population health, as habitat complexity increases [77, 129, 133-135]. What is meant by habitat complexity?

The notion of habitat complexity follows from recognition that the life stage needs of trout require a variety of habitat components. Here are variables that some researchers used in characterizing habitat complexity: *pool* depth (percent, as a function of surface area), residual pool depth, percent undercut bank, extent of *large woody debris* (in number of pieces), particle size, and hydraulic retention. They partitioned segments into pools, riffles, or runs as part of identifying differences in flow velocity and depth and in substrate particles sizes, which, along with the other variables cited, affect a segment's suitability in supporting trout life stages [135]. They developed a complexity index to quantify habitat quality and assist them in comparing it among segments and streams [135, 157].

How do pools figure in?

Pools are key in habitat complexity. With pools, trout may obtain resting areas, refugia, where flow rates are slower, and they may acquire food supply and some relief from predators [158]. Pools may bring cooler water at depth, as well, away from surface water temperatures that are more directly affected by solar radiation. While the presence of large woody debris (LWD) in the stream channel also is important in habitat complexity, providing shelter from aquatic and terrestrial prey, fish use the deep water in pools more than any other cover type, even when LWD is available [159, 160].

Researchers found on average 10 – 40% of rainbow trout within thermal refugia, having 3 – 33 ft^2 (1 – 10 m^2) surface area, during midday maximum water temperatures in 12 Oregon stream reaches. They noted that refugia in the study area likely were too small and too infrequent to sustain high densities of trout over prolonged high water temperature conditions [161].

Researchers concluded from a summertime study at a 5 ft (1.5 m) deep pool on a creek in California that the rainbow trout population faced a trade-off between cooler water having possibly lethally low dissolved oxygen (DO) concentrations versus water with high DO but lethally high temperatures. The cooler water was at the base of the pool, which was judged to be supplied by low-oxygen groundwater seeps. The warmer water was at the surface, of course, affected by solar radiation, where contact with the air maintained adequate DO concentrations [162]. From studies conducted at five pools during drought conditions, researchers reported that brown trout preferred lower temperatures near the bottom rather than higher DO near the surface. They noted, not surprisingly, that some trout moved towards the surface at night when pool temperatures cooled slightly [163].

From their review of literature and synthesis of current knowledge, researchers linked the necessity of fish to reside in low-flow refugia to increasing mortality, decreasing birth, and increasing migration rates. They observed that refuge size, disturbance intensity, and mobility of organisms would play a large part in population persistence. They proposed using modified source-sink dynamics to model drought effects on population [164]. Concerning potential development of low-flow conditions in mountain streams, researchers have classified areas at about 8,800 – 10,500 ft (2,690 – 3,190 m) in elevation to be at moderate risk of future drought, and watersheds above 10,500 ft (3,190 m) at low risk [165].

In mountain streams—typical trout habitats—that is, for bed slopes greater than 3%, *step pools* are the predominant bedform [166-169]. They develop under conditions of high stream flows and sediment transport [170]. Step pools (pools being the deepest locations in reaches, where the slopes of the water surfaces are near zero) occur in regular intervals along a stream channel, followed by glides (where the bed slopes are negative and the water surface slopes are positive), then riffles (having the steepest bed slopes and the shallowest depths of flow), and subsequently runs (between riffles and pools, where the depths of flow are greater than at riffles and the bed slopes are less; and which, unlike riffles, often have well-defined thalwegs, that is, indications of low-flow conditions that show the natural path, or profile, of the watercourse) [171].

Intervals of larger rocks extending across the channel, like ribs, are effectively step risers that result in scouring and pool formation, with flows becoming supercritical (shallow and fast with a high-energy state) approaching the step crest, falling to subcritical (deep and slow with a low energy state) upon tumbling into the pool; and becoming supercritical again with acceleration over the next step [170]. That is, the periodically occurring steps dissipate stream energy, resulting eventually in minimized erosion effects on channel morphology, in general, and on pools, in particular [172-173]. Spacing between pools is typically about one-half to four channel widths [158, 172-175], with the spacing increasing as channel slope decreases [158, 176].

The vertically rhythmic occurrence of step pools dissipating the energy of mountain stream flows is analogous to the familiar horizontal meandering of rivers channels in environments having lower bed gradients [174, 175]. Pools as sanctuary for trout, including refuge from warmer surface water temperatures at other locations, results, in part, because the two turbulent eddy currents that are dominant in a step pool's flow dynamics, called inward and outward interactions, tend to leave surface water separate from, that is, unmixed with, water at the bottom of the pool [169].

What are other influences and interactions?

Food supply, for example, the presence and abundance of aquatic and nonaquatic insects and animals, is a factor in habitat complexity, bringing more variables that pertain to trout life stage needs. Sedimentation, which can adversely affect aquatic biota, may be part of habitat complexity as a result of human-initiated activities like road building and maintenance, cattle grazing, logging, and mining. The extent of riparian vegetation, potentially shading the stream from solar radiation, figures in habitat complexity. While not easily characterized, and not having standardized measurement methods, habitat complexity has singular importance in the capacity of a segment length to support population persistence.

Water temperature, *water flow*, and *water quality* also affect segment length as a limiting factor and are part of habitat complexity. Increases in water temperature may increase segment length needs so that more and perhaps deeper pools may be included for more refuge from solar radiation and predation. Decreases in water flow may result in temporary or permanent loss of connectivity within a segment. This can cause reduction in habitat availability, loss or alteration of food production, deterioration of water quality, and damage to interspecies interactions, plus increased adverse effects of river ice during the winter [177, 178]. Other causes of water quality degradation, for example, introduction of pollutants, or increases in their amounts or toxicity, which may affect trout directly or their food supplies, may threaten population persistence.

Changes in *species competition* may affect predation and food supply, with increased competition potentially requiring greater segment length for population persistence. In segments with complex habitats, predation risk may be slower to increase, however, due to predator inefficiency [135, 179].

Stochastic environmental disturbances may affect segment length needs. Debris and sediment flows following deforestation from wildfires, for example, may reduce the adequacy of food sources and refuges from predators. They may leave barriers to adequate water flows, further fragmenting segments and undermining population persistence.

Chapter 4
Pollutants and Nutrients as Limiting Factors

Pollutants, for example, dissolved heavy metals, are substances in the water environment, as considered in this document, that can damage the health and survival of trout, and thereby endanger their population persistence. They can threaten trout food supplies, as well. For the most part, pollutants enter streams from human activity, for example, from mining, including those no longer active, that release heavy metals and other pollutants through surface water and groundwater discharges. Additionally, substances that are *nutrients* to trout and their food sources, like nitrogen and phosphorus, can be pollutants at elevated concentrations. This is only rarely a problem, however, the occurrence of excessive nutrients in the streams, or ponds and lakes, that may be trout habitats and strongholds.

4.1 How are pollutants and nutrients limiting factors?

Pollutants in stream water are toxic to trout directly from exposure and ingestion, including through consumption of pollutant-contaminated food. They are indirectly so by being toxic to the biological community upon which trout depend for food.

Nutrients in stream water are necessary for trout and its food supplies. Problems can occur where nutrient concentrations exceed healthful levels, for example, causing eutrophication in static water, ponds and lakes, which can lead to depletion of dissolved oxygen that is otherwise necessary for fish and for the aquatic biological community, in general.

But, inclinations for concern about nutrients should make way, instead, for attention to pollutants, which are much more likely to be problems for trout populations. After all, the predominant media for trout are the flowing waters of relatively high-elevation streams, which are not candidate bodies for eutrophication. As well, the static or slow-moving waters (ponds and lakes) that also may host trout tend to be at elevations above significant, human-induced nutrient inputs, for example, agricultural runoff or municipal non-point and wastewater point source discharges, so nutrient excesses in these waters are uncommon.

4.2 What are relevant pollutant and nutrient thresholds?

Which pollutants are of concern?

What pollutants are present in streams? What concentrations should not be exceeded for trout habitats to exist, and persist? Discharges from hard rock mining activity, conveyed to streams through surface water and groundwater, particularly from abandoned sites that have little or no water management, are the most significant sources of pollutants, in nature and extent, adversely affecting trout habitat. The pollutants in these discharges derive from the geologic material disrupted.

There commonly are metal sulfides, in particular, pyrite, FeS_2, at mined sites such that contact with water yields sulfuric acid (which is given favorable kinetics by the ready presence of the bacteria *Thiobacillus ferrooxidans*) sufficient to leach and transport heavy metals from the disturbed geologic material. Discharges typically contain, in addition to sulfuric acid, dissolved iron and heavy metals, and sometimes aluminum, arsenic, and cyanide, which are conveyed to streams in surface water runoff and groundwater flows.

A stream's *cleaning* functions, such as they are, include dilution from mixing of inputs with greater flow volumes; plus, neutralization of acidity, primarily by carbonates, but potentially including other buffering substances also occurring naturally in the stream water; and oxidation and complexation of the dissolved metals, which reduces toxicity, with oxidation resulting in some precipitation of metals, as well, also lowering toxicity in the water column.

The length of stream necessary for cleaning depends, logically, on the amount of pollutants discharged and the amount of flow and neutralizing materials present in the stream. In fact, the pollutants—the metals, in particular, for example—don't *go away* but instead are modified in form such that they are less toxic to aquatic life, with some remaining in the sediments, pending further natural flushing, while the rest is passed downstream.

Trout habitat is susceptible, as well, to sediment that is transported by surface water runoff from other types of watershed disruptions, such as logging, road construction and maintenance, and grazing. Significant amounts of sedimentation also can result from runoff following deforestation from fires. Sedimentation as a limiting factor is considered separately from pollutants and nutrients in this document.

Potential effects from municipal runoff and from municipal and industrial wastewater treatment discharges are not particularly relevant because trout habitat, including, candidate stronghold locations, are at higher elevations in the watershed than normal occurrences of such discharges. Mining site releases, on the other hand, are an existing and substantial concern, and the pollutants that they can deliver to streams are given considerable attention in this document.

Dissolved iron and heavy metals can enter surface waters that receive drainage from the *hydrothermal alteration* of geologic material in contact with intensely hot water circulating in the earth's crust, as documented to be occurring in some Colorado streams [180]. Where hydrothermal alteration happens to include historic mine sites, there can be severe downstream water quality problems [180]. Absent thermal water and mine site involvement, however, natural (or background) weathering of hard-rock geologic material produces only dissolved iron and aluminum, for the most part. Other metals that formerly were present, in relatively smaller amounts, were leached out long ago [181].

Are there pollutant threshold values?

Studies give some indication of what trout can tolerate, including at various life stages. No pollutant limits exist, however, specifically for trout population persistence, mostly, perhaps, because the matter is complex. Stream conditions that affect pollutant toxicity to trout vary, chemically and physically, spatially and temporally. As well, trout susceptibilities to pollutants differ at life stages and among species. Further, aquatic biota that are key for trout populations as food supplies, which typically include small organisms, for example, benthic macroinvertebrates, tend to have even less tolerance to pollutants than their predators.

What pollutant concentrations should not be exceeded? Are there threshold values available to judge water quality for habitat health, in particular, heavy metals concentrations, which seem distinctively problematic to potential trout population persistence? The answer is yes. The Aquatic Life Criteria established by the U.S. Environmental Protection Agency (EPA) can serve and are appropriate for that purpose [182]. They are described below in the section "What are relevant pollutant limits?"

What about nutrients?

While pollutants receive much greater attention for their potential effects on trout habitats and strongholds, nutrients do warrant some mention. The activity of the aquatic biological community, plants and animals, removes nutrients from solution. Terrestrial transfers and the breakdown of biological material bring nutrients back into the stream water. Nutrient concentrations have been found to be patchy and highly variable in streams from spatial patterns in nutrient delivery and instream processing [183-185].

So, net nutrient source or sink conditions may exist along a stream, depending on location and time [184]. Some researchers contend that riparian groundwater inputs control nutrient concentrations because in-stream gross uptake and release tend to balance each other most of the time [184-186].

In general, in streams that are existing or potential trout habitats or strongholds, the situations of flowing water and mobile trout minimize potential problems of nutrient insufficiency. It is similar for susceptibility to consequences of nutrient excess, which could manifest as eutrophication (high concentrations of nutrients resulting in extravagant plant growth, for example, algae blooms) in waters that are static or slow-moving, unlike streams, with subsequent dissolved oxygen deficiencies resulting from death and decomposition of the plant growth that could adversely affect fish and other aquatic biota populations. As well, the usual contributors to nutrient excess, such as, rainfall runoff containing agricultural fertilizers and municipal or industrial point-source discharges having nitrogen and phosphorus materials are, as already mentioned, not typically present at watershed elevations in which there are potential trout habitats or strongholds.

How do pollutants affect trout?

Gills, having large surface areas in contact with water, provide the primary uptake route in trout for toxins, including heavy metals. The toxins are transported in the bloodstream to the rest of the body, accumulating in the liver and kidneys. These are the organs responsible for processing, detoxifying, storage, and excretion [187-188].

A trout's metal homeostasis system (which ensures an adequate supply of essential metals—in trace amounts) changes with exposure to increased metals concentrations. It appears that metallothioneins and glutathione, cell enzymes, have an affinity for most metals and act as buffers for metal ions entering cells, reducing the effect of exposure to metals. Metals also can disrupt the balance of ions in the body, causing oxidative damage. Researchers found cells modifying to maintain ion balance. That is, trout exhibit some capacity to develop tolerance to metals pollutants. Metal- and ion-homeostasis mechanisms appeared most likely to account for the metals tolerance observed in brown trout in mining-metals-contaminated streams, based on testing of embryo stages and adults [188].

What are relevant pollutant limits?

Studies have shown that, in addition to iron, the heavy metals cadmium, copper, lead, nickel, and zinc, and sometimes aluminum, arsenic, and cyanide, are typical pollutants entering streams from mine drainage [189-197]. Scientists tend to hold that the uncomplexed ion is the toxic form of dissolved metals. For cadmium, for example, that would be Cd^{+2}; for zinc, Zn^{+2}. Most of the heavy metals have a +2, or divalent, dissolved ion form. In the presence of dissolved carbonates, as would be indicated directly by measured alkalinity concentrations, or indirectly by water hardness determinations, most metals also can form dissolved carbonate complexes, in addition being present in their uncomplexed form.

This means that the amount of dissolved metal ions measured in the water may be expected to be higher when the water has hardness, which is dissolved calcium and magnesium, or more to the point, contains the dissolved carbonates associated with hardness [198-206]. In such settings, that is, in waters having measurable hardness and alkalinity, which is common in streams, metals would exist in *both* uncomplexed divalent ion *and* complexed ion forms. The particularly relevant result is that threshold values for heavy metals toxicity are higher in harder than in softer waters, which have lower hardness or alkalinity.

Hardness is the sum of dissolved calcium and magnesium ions (and other ions, to a lesser extent) in solution. It follows from the contact of rainwater, which is soft, that is, contains few ions, with calcium- and magnesium-containing sedimentary carbonate rock, such as, limestone (composed of the minerals calcite and dolomite, predominantly). The rainwater's dissolved carbon dioxide content, effectively, carbonic acid, makes it aggressive enough to dissolve calcium and magnesium (and other constituents occurring in lesser amounts) as it percolates through the geologic material. Becoming surface water runoff or groundwater, it flows to streams, bearing dissolved calcium, magnesium, and carbonates (HCO_3^- and CO_3^{+2}, which make up alkalinity). Water with dissolved calcium and magnesium concentrations below 60 mg/L is considered *soft*; above 60 mg/l, *hard*.

If the geologic sources of calcium and magnesium are carbonates, as described above, then the resulting water hardness and alkalinity are equal. Less than 20 mg/L alkalinity is considered low. Alkalinity anions may form complexes with metal cations and, also, may provide some buffer against changes in stream water pH, for example, from entry of metals-bearing, low-pH mine drainage discharge.

Therefore, metals toxicity is said to decrease with increasing water hardness (or alkalinity) [204, 207]. That lowering of metals toxicity seems to result from the formation of metals complexes in solution, as mentioned. But it also may be because calcium and magnesium in solution, also as divalent ions like the metal ions, may attach to some cell receptor sites, for example, at trout gill surfaces, instead of the metal ions, such that the metal ions have a reduced opportunity to adversely affect the organism [208]. There is some evidence that calcium plays a more important role than magnesium in lowering the toxicity of metals [209]. This reduction in toxicity of the heavy metals ions by the hardness cations (Ca^{+2} and Mg^{+2}) is referred to as an antagonistic effect—the hardness cations being antagonistic to the metal ions finding open receptor sites. Perhaps most likely is that a mix of both mechanisms causes the decreasing metal ion toxicity [7, 208].

What can be done about this? Are there threshold values available to judge water quality for habitat health, in particular, the relationship of heavy metals concentrations to potential trout population persistence, with adequate consideration given to water hardness conditions? Would they, as well, be relevant to the larger aquatic environment, since portions of the biotic community constitute trout food supply? Again, the answer is yes, as already noted. It is the U.S. Environmental Protection Agency's (EPA's) National Recommended Water Quality Criteria for Aquatic Life, or Aquatic Life Criteria. EPA presents these criteria values as the "highest concentrations of specific pollutants or parameters that are not expected to pose a significant risk to the majority of species" in a body of water [182].

Adjustment for water hardness. Because it can be a significant factor, the criteria include adjustment for the effects of water hardness on metals toxicity. That is, EPA has enabled heavy metals toxicity to be determined, both acute and chronic concentrations, as a function of water hardness conditions. Examples of the criteria are shown in Table 1, with toxicities calculated for 10, 50, 100, and 200 mg/L water hardness [182, 210-215]. The *formulas* for making the calculations are shown in Table 2 [182].

Table 1. EPA Aquatic Life Criteria for Heavy Metals, with Adjustments for Water Hardness

Metal & Type Toxicity		**EPA Aquatic Life Criteria, µg/L**			
Heavy Metal	**Toxicity**	**10 mg/L Hardness**	**50 mg/L Hardness**	**100 mg/L Hardness**	**200 mg/L Hardness**
Cadmium	*Acute*	0.19	0.99	2.0	4.0
	Chronic	0.17	0.55	0.92	1.5
Copper	*Acute*	1.7	7.7	15	28
	Chronic	1.6	6.3	11	21
Lead	*Acute*	2.9	23	55	132
	Chronic	0.047	0.36	0.88	2.1
Nickel	*Acute*	47	184	331	595
	Chronic	7.3	29	52	93
Zinc	*Acute*	15	57	102	184
	Chronic	15	57	103	186

Table 2. EPA Formulas for Calculating Heavy Metals Toxicities as a Function of Water Hardness

Heavy Metal	**Acute Toxicity**	**Chronic Toxicity**
Cadmium	(exp(1.0166[*ln*Hardness - 3.924)) x CF	(exp(0.7409[*ln*Hardness) - 4.719)) x CF
Copper	(exp(0.9422[*ln*Hardness - 1.700)) x CF	(exp(0.8545[*ln*Hardness - 1.702)) x CF
Lead	(exp(1.273[*ln*Hardness - 1.460)) x CF	(exp(1.273[*ln*Hardness - 4.705)) x CF
Nickel	(exp(0.8460[*ln*Hardness + 2.255)) x CF	(exp(0.8460[*ln*Hardness) + 0.0584)) x CF
Zinc	(exp(0.8473[*ln*Hardness + 0.884)) x CF	(exp(0.8473[*ln*Hardness + 0.884)) x CF

Conversion for dissolved solids. The formulas in Table 2 for calculating heavy metals toxicities as a function of water hardness include a *conversion factor* (CF) for expressing the hardness-adjusted toxicity as dissolved metal concentrations, both acute and chronic. The conversion factors are given in Table 3, with *formulas* for cadmium and lead, indicating they are functions of water hardness; single values, or *constants*, for nickel and zinc; and no conversion for copper [182]. The formulas indicate that the conversion is a function of water hardness for certain metals; the constants, that hardness does not figure in for those metals.

The conversion factors are necessary because EPA's Aquatic Life Criteria for metals were developed and presented as *total recoverable* concentrations, of which dissolved solids are commonly a major component, but not the only one. Total recoverable concentrations also include particulate material and any dissolved ions attached, adsorbed, to the particulates. Since the primary mechanism for metals toxicity in trout is uptake across the gills, and this physiological process requires metals in the dissolved form, the total recoverable concentrations should be corrected to remove consideration of non-dissolved metals, some or all of which may be unavailable biologically, in order to identify toxic concentrations [216].

EPA's policy now is that "the use of dissolved metal to set and measure compliance with water quality standards is the desired approach [217]." So, as a result, the Aquatic Life Criteria for metals should be converted for expression as dissolved solids concentrations. As well, their comparisons should be against analyses of water containing only dissolved solids, which is defined operationally as that which passes a 0.45 µm filter.

The metals conversion factors shown in Table 3, as applied in the equations presented in Table 2, enables expression of the criteria as dissolved metals values and the calculations displayed in Table 1 for the four, hypothetical water hardness scenarios, 10, 50, 100, and 200 mg/L. It may be noticed that, compared to water hardness effects, the dissolved solids corrections have much smaller consequence on the toxicity calculations. For example, the dissolved solids conversion factors of 0.978 and 0.986 for zinc only slightly affect the metal's toxicity values.

Table 3. EPA Conversion Factors (CF) for Calculating Dissolved Heavy Metals Toxicities

Heavy Metal	Acute Toxicity	Chronic Toxicity
Cadmium	1.136672 - [*ln*Hardness(0.041838)]	1.101672 - [*ln*Hardness(0.041838)]
Copper	0.960	0.960
Lead	1.46203 - [*ln*Hardness(0.145712)]	1.46203 - [*ln*Hardness(0.145712)]
Nickel	0.998	0.997
Zinc	0.978	0.986

Usual hardness and alkalinity. What water hardness or alkalinity values can be anticipated in the mountains streams that may be candidates for trout habitats and strongholds? That is, what is usual? Researchers reported water hardness concentrations of 16 – 110 mg/L at nine sites along a 22-mile (35-km) stretch of Middle Boulder Creek in the Boulder Creek watershed in central Colorado, at approximately 5,400 – 9,800 ft (1,700 – 3,000 m) in elevation [218].

From examination of nine basins in Rocky Mountain National Park, CO, having areas of 445 – 25,700 acres (180 – 10,400 ha), researchers cited annual volume-weighted mean alkalinity concentrations of 25 – 151 mg/L. Closer study of one of the basins, incorporating tundra, talus, forest, and subalpine meadow environments, yielded median alkalinity results of 23 – 315 mg/l [219]. The city of Thornton, CO, elevation 5,400 ft (1,700 m), the water source for which "originates as snow melt from the Rocky Mountains of South Platte Basin," reported from analysis of more than 2,500 samples in 2011 water hardness values of 116 – 276 mg/L [220].

For a study area described as central Colorado, ranging from Wyoming to New Mexico, approximately 13.3 million acres (54,000 km^2) in size, including most of the Rocky Mountains in Colorado, and representing approximately 20 percent of the Colorado's land area, samples taken from sites at 7,600 – 11,600 ft (2,300 – 3,500 m) in elevation during 2004 – 2007 showed hardness values of 5 – 163 mg/L, having a median of 41 mg/L, and alkalinity concentrations of 0 – 141 mg/L, with a median of 25 mg/L [197].

Noting that hardness can greatly exceed alkalinity where gypsum ($CaSO_4$) dominates the geology, instead of limestone ($CaCO_3$), researchers examined the effect of hardness on cadmium's toxicity to rainbow trout, using in the laboratory, as representative for potential application to naturally occurring waters, hardness values of 50, 200, and 400 mg/L, with an alkalinity concentration of 30 mg/L [208]. Studying the acute toxicity of zinc to rainbow and brook trout, researchers, anticipating the extension of results to natural waters, tested with hardness values of 44 – 179 mg/L and alkalinity concentrations of 42 – 170 mg/L [206].

Acute and chronic toxicities. The *acute* toxicity value, what EPA calls the criterion maximum concentration, or CMC, is the maximum one-hour average concentration, which addresses short-term exposure. The *chronic* toxicity value, EPA's criterion continuous concentration, or CCC, is the maximum four-day average concentration, representing concern for long-term exposure. The purpose of these thresholds is to ensure there are no *unacceptable* effects on the aquatic community. That is not the same as no *adverse* effects, however. Some adverse effects, such as small reductions in growth, reproduction, or survival, *may* occur at the threshold values. What is expected is that unacceptable effects *will* occur if concentrations remain above these values [221].

A difficulty in evaluating water quality conditions using thresholds is that their constant values must be compared with the fluctuating concentrations that usually occur in the real world. Expressing thresholds in terms of average concentrations, as done for acute and chronic toxicities, is part of managing the problem. That is, for excursions above, there can be compensating periods of time during which concentrations are lower than the threshold value; hence, the averaging, including a suggested use of the arithmetic and not the geometric mean. The one-hour averaging period for acute toxicity is judged appropriate because death can occur in one to three hours from toxic exposures. The four-day averaging for chronic toxicity is deemed likely to prevent increased mortality at sensitive life stages [221].

Additionally, EPA recognizes that a period of recovery is important following situations in which acute or chronic concentrations are exceeded. Accordingly, it considers that sensitive organisms in the aquatic community "should not be affected adversely" if the acute (CMC) and the chronic (CCC) toxicity concentrations are not exceeded more than once every three years on the average [7].

Other parameters and substances. In Table 4 are EPA Aquatic Life Criteria for acute and chronic toxicities that apply for other parameters and dissolved solids concentrations typically relevant for water quality characteristics in mine-drainage-affected stream water [182, 222-224].

Table 4. EPA Aquatic Life Criteria for Other Parameters and Substances

Parameter or Substance	Type Toxicity	EPA Aquatic Life Criteria, μg/L
pH	*Acute*	No criterion
	Chronic	6.5 – 9.0
Aluminum (pH 6.5-9.0)	*Acute*	750
	Chronic	87
Arsenic	*Acute*	340
	Chronic	150
Cyanide	*Acute*	22
	Chronic	5.2

4.4 What influences and interacts with this limiting factor?

Are there combination effects?

Researchers found that environmentally relevant concentrations of both dissolved, divalent lead and cadmium ions (in soft, pH 6.0 water) appeared to be toxic to rainbow trout synergistically, or additively. That is, based on the examination of gill-binding effects, they found combinations more toxic than the same concentrations of the metals exposed separately to the trout [225]. The researchers suggested that, as a result, it may be necessary to re-evaluate water quality criteria for consideration of exposure to mixtures of pollutants, which is more normal for trout and others in the stream biotic community than contact with a single pollutant, such as, the unlikely exposure to only one heavy metal from mine disturbance drainage.

What about other constituents?

Inorganic and organic ligands (ions or molecules that bond to others) control the ability of natural water to tie up metals [208]. This means that ligands regulate the forms of metals and, thereby, their bioavailability for adversely affecting aquatic life. Because, however, heavy metals react with water quality parameters (and cell sites) differently, there is not a universal way to quantify bioavailability and consequent toxicity of these pollutants [197].

The complexing to metals by inorganic ligands is controlled in natural water ecosystems primarily by carbonate alkalinity, that is, the dissolved carbonates HCO3- and CO3+2, and by pH. In such systems, alkalinity and hardness are similar. EPA's Aquatic Life Criteria enable adjustment for water hardness conditions in determining heavy metal toxicities, as already described. The opportunity for metals complexation by organic ligands depends on the presence of organic material, which normally is low in waters like mountain streams.

What are pH effects?

Lower pH tends to favor the simple, divalent ion form of heavy metals in solution, for example, Cd^{+2}, Pb^{+2}, Zn^{+2}. This makes the toxicity of heavy metals more available to aquatic life. That is to say, it is generally expected that the toxicity of heavy metals increases as stream water pH decreases, even despite the influence of other water quality parameters [187, 211].

The EPA Aquatic Life Criteria for pH are 6.5 – 9.0 for evaluating chronic exposure [182]. Researchers determined that, at a constant water hardness and alkalinity, the lethal concentration for 50% mortality (LC50) for trout increased by a factor of approximately two for each unit decrease in pH [206].

Researchers have reported opposite effects, as well. That is, steelhead trout were found to be more tolerant of dissolved cadmium, copper, and zinc at the lowest pH value, 4.7, as compared with the higher values, 5.7 and 7.0, in tests in soft water. The researchers cited hydrogen ion interference with metals uptake, that is, a variation of the antagonistic effect mentioned earlier, as potentially accounting for the best tolerance of metals at the lowest pH of the three considered. They noted that during snowmelt trout may have exposure to low pH water [226].

Differences among trout species in the effects of decreasing stream water pH on metal toxicity can be expected. For example, rainbow trout were found to be more susceptible to zinc pollution than brook trout when pH decreased, measured as the lethal concentration of zinc for 50% mortality (LC50) [206].

Is there short-term variation?

Researchers have shown that some heavy metals concentrations in mining-affected streams varied *substantially* and *consistently* over a diel (24-hour) period [227]. They cited two important characteristics in the variation, those being the time within that period in which the maximums and minimums occurred and the magnitude of the changes. For example, dissolved cadmium, nickel, and zinc concentrations were found to increase during the night and reach maximums shortly after sunrise, after which they decreased to lowest concentrations during mid to late afternoon. Zinc concentrations changed by as much as 500 percent; nickel, as much as 170 percent; cadmium, 120 percent. This occurred across wide metals concentration levels in the streams, ranging from approximately 80 to 1,000 μg/L for zinc, for example. The researchers discerned no diel cycle, however, in dissolved copper concentrations [227].

The metals concentration cycling reported was in waters with neutral to slightly alkaline pH, which is typical for mountain streams. The data were collected in gravel-bed, headwaters in the northern Rocky Mountains, having flows of 0.5 – 270 ft^3/s (0.014 – 7.65 m^3/s) at sampling times [227].

Water temperature in streams depends on air temperature and incident solar radiation. Researchers reported a strong link between dissolved zinc concentrations and water temperature, stronger than for any of the other field parameters measured, which were pH, dissolved oxygen, specific conductance, and streamflow. The maximum zinc concentrations and minimum temperatures occurred generally at the same time. It suggested that temperature played an important role in those concentrations. The results for the other heavy metals corresponded generally to those for zinc. In contrast, dissolved arsenic concentration cycles were opposite, with maximums in the late afternoon and minimums in the early morning [227].

There are likely other factors besides temperature that figure into diel cycling of heavy metals concentrations. For example, waters with high biological productivity typically have substantial increases in pH and dissolved oxygen concentrations during the day, with decreases at night. This results from changes in relative rates of aquatic photosynthesis and respiration [228]. Both pH and dissolved oxygen affect the concentrations of metal ions and their distribution in complexed forms, for example, as carbonates and hydroxides, which determines toxicity, as previously mentioned. For example, as pH increases, and in the presence of dissolved oxygen, metal precipitates are more readily formed, such as ferric hydroxide, to which metal ions can attach, that is, adhere or adsorb, which reduces metals toxicity.

Researchers have cited in mining-affected streams the daytime photo-reduction of Fe^{+3} to Fe^{+2} (Fe^{+2} being the predominant dissolved form of iron at naturally occurring pHs and dissolved oxygen concentrations), and, subsequently, the re-oxidation of Fe^{+2} back to Fe^{+3}, which readily forms a solid; and the temperature-dependent precipitation of the solid ferric hydroxide, also referred to as hydrous ferric hydroxide or yellow boy, and its hydrolysis, or re-dissolving. This means that ferric hydroxide surfaces to which dissolved ions can adhere are formed and then themselves dissolved over the course of 24-hour periods, alternately acquiring and releasing adsorbed ions, for example, heavy metals, and likely influencing the diel cycling observed in their concentrations [229].

Adsorption to photosynthetic biofilms and desorption from them also was considered likely to contribute to the cycling of dissolved zinc concentrations in a mine-drainage-affected Montana stream [230]. Perhaps to remind that interactions among factors are complex and results can vary as a function of particular details, researchers also have laboratory study results showing, more importantly than temperature, that the diel concentration cycling of zinc followed changes in pH, increasing as pH did, while the diel cycling of arsenic was negatively correlated with pH [231]. Taken together, these observations about diel cycling of concentrations have considerable potential implications for stream sampling practices that might be used for conclusions about heavy metals in waters that are candidates for trout habitats and strongholds.

Chapter 5
Biotic Interactions as a Limiting Factor

What is the role of competition, predation, or interbreeding in limiting the presence or abundance of a trout in a stream?

5.1 How are biotic interactions a limiting factor?

The species of trout or other fish present in a stream can play a major role in limiting the presence, abundance and genetic purity of a given trout species or subspecies. The primary mechanisms behind this limiting factor are competition and predation, which can lead to replacement of one species by another, and hybridization [232]. These interactions are particularly important to understand and take into account where the goal is to protect remaining, or reintroduce, native trout populations of high genetic purity [233]. Studies have found that widespread introductions of non-native trout since the 1880's may be the primary cause of decline for the Colorado River cutthroat trout [8, 74, 232].

Competition for scarce habitat or resources, for example, lower velocity resting habitat near feeding habitat, between fish species or subspecies can occur even at early life stages [74, 234, 235], and can result in replacement of one species by another [74, 236]. Similarly, predation by one species on another can limit the recruitment or survival of the prey species and lead to replacement by the predator species in a reach or system [237].

Hybridization happens when interbreeding between species or subspecies produces fertile offspring [232]. Some studies have found that hybridization between non-native and native trout species can result in rapidly reduced fitness [94, 238]. Due to their reproductive biology coupled with the common practice of introducing non-native trout species, hybridization is quite common in salmonids [94].

5.2 What are relevant biotic interaction thresholds?

What about replacement?

Brook trout are known to replace native cutthroat trout when present in the same streams, particularly in lower gradient and low elevation habitats [232]. The mechanisms for this replacement are not well understood, but appear to be due to low recruitment of native cutthroats when brook trout are present [8, 237].

Brown trout consume a similar diet to cutthroat trout and therefore may compete with cutthroats. In addition, brown trout have the potential to prey on smaller cutthroat trout [239]. However, there is little documentation of brown trout replacing Colorado River cutthroat trout

[8]. The fact that brown trout do not currently occupy many of the smaller, higher tributaries where cutthroat trout spawn may minimize the opportunities for competitive or predatory interactions of brown trout on young cutthroat [8].

Brown trout have been documented to replace brook trout, through both competition and predation, in some streams they occur together [236]. The presence of brown trout may limit the foraging of brook trout outside of refugia, particularly where upwelling groundwater has provided refuge for brook trout in warming streams, thereby by limiting the success and expansion of brook trout populations [240].

What about hybridization?

Rainbow trout and non-native subspecies of cutthroat trout hybridize with Colorado River cutthroat trout and produce fertile offspring [232]. While non-native introductions do not always produce hybridization [94], more introductions tend to increase the risk of hybridization [8]. If hybridization continues over a number of generations, non-native genes can be found in all trout within a given area. In the absence of migration barriers, hybridized populations may eventually occupy most upstream habitat [8]. Brown trout have been documented to hybridize with brook trout in some streams where they occur together [241].

5.3 What influences and interacts with this limiting factor?

The presence of more than one species or subspecies of trout, the presence of adult age classes of one species with juvenile age classes of another species, the distance to a source population, and the number of non-native introductions appear to increase the risk of biotic interactions to limit trout populations in a given stream [8, 94, 232]. The presence of natural or installed barriers influences the ability of species to co-occur.

Elevation and gradient appear to increase the risk of replacement of cutthroat trout by brook and brown trout [232]. Climate shifts, including changes to precipitation, temperature or flow regime, may drive changes to the distribution of one trout species that can result in changes to other trout species [16, 74, 94]. Trout introductions can also introduce diseases into existing populations of native or non-native trout [232].

Chapter 6
Sedimentation as a Limiting Factor

Chronic accumulation of fine sediments and acute high sediment load and deposition events, for example, post-fire debris flows, can be antagonistic to trout population persistence. Together with water flows, the flow of sediments, including all particle sizes from silt and clay to cobbles and boulders, within a stream play a critical role in determining the amount and quality of trout habitat. For the purposes of this document, sedimentation is the deposition of a range of particle sizes, critically including sand and silt, within the channel. In addition, acute stochastic events such as post-fire debris flows that can deliver geologic and vegetative material in great amounts, and some of it very large, such as boulders and trees, to the stream channel can severely damage habitats and force trout populations to try adapting, which may not be possible.

6.1 How is sedimentation a limiting factor?

Both chronic accumulation of fine sediments and acute high sediment load and deposition events, including post-fire debris flows, can have short-term and long-term effects on trout populations by adversely affecting their reproduction (hatching and emergence success) [242-245] and survival (loss of food sources and increased predation from loss of concealment) [246, 247].

How does sedimentation affect reproduction?

The adverse effects of sedimentation on reproduction are most consequential where trout spawn, at redds, which are hollows scooped out in the sand or gravel of a river bed [247]. The eggs incubate within the interstitial spaces of the substrate. For hatching, water must flow around the eggs, delivering dissolved oxygen and carrying away metabolic wastes. Therefore, if fine sediments clog these interstitial spaces, the embryos can suffocate [245, 246]. Following hatching, the alevins remain briefly in the substrate, and then emerge through these spaces, which requires that they remain unblocked by sediments [246-248].

How does it influence survival?

Deposition of fine sediments, covering or embedding the larger bed material of a stream, that is, gravels, cobbles, and boulders, can result in the smothering macroinvertebrates and the reduction of habitat complexity. This can diminish the diversity and density of the macroinvertebrate community and decrease the food supply for trout [247, 249-251].

Post-fire debris flows are stochastic disturbances resulting from high-intensity rainfalls at burned areas, delivering sediment and woody debris to stream channels. In the short term, this may limit or eliminate trout presence within the affected reach by scouring stream reaches to bedrock, especially in small headwater streams, removing food and damaging other necessary habitat features, such as cover and connectedness [252-257]. Over the longer term and extending further downstream, it can result in reconfigured stream morphology [253, 258-261], including reduced channel stability and increased sediment loads, adversely affecting habitat and potential trout population persistence throughout the stream [262, 263].

6.2 What are relevant sedimentation thresholds?

What determines spawning success?

Table 1 shows substrate particle sizes that rainbow, cutthroat, and brown trout used for spawning, based on research findings [242, 264]. While the sediments for all were larger than about 0.6 cm, the range of particle sizes preferred by cutthroat trout was greater than for rainbow and brown trout.

Table 1. Preferred Particle Sizes for Trout Spawning, with Water Depth and Velocity

Trout Species	Substrate Particle Size, mm	Water Depth, mm	Water Velocity, cfs
Cutthroat	6 – 102	≥6	11 – 72
Rainbow	6 – 52	≥18	48 – 91
Brown	6 – 76 6.9, mean	≥24 25.5, mean	21 – 44 46.7, mean
Brook	5.7, mean	24, mean	17.6, mean

Deposition of fine sediments in spawning beds can damage both incubation and emergence success. It can diminish the flow of water through the beds and over the eggs, and block the pathways for fry to emerge. Researchers found that sediments <1 mm in size limited the permeability of the spawning bed, which adversely affected incubation. For spawning success, they estimated that particles <1 mm should not exceed 12 – 14 percent of the sediment size distribution [245, 265-267]. Somewhat coarser sediments, between 1 and 10 mm, were found by other researchers to block emergence of salmonids [245, 268-270].

Thresholds expressed as particle size and percent fines for trout spawning success are shown in Table 2, along with endpoint criteria for the evaluations [247]. An additional recommendation is that <20 percent of the spawning area have particle sizes >8 mm [247]. The Table 2 thresholds accommodate protection of both incubation and emergence for cutthroat, rainbow, brook, and brown trout by using the larger particle sizes from the ranges reported by researchers, and the middle values from their percent fines ranges [245, 247].

Table 2. Particle Size and Percent Fines Thresholds for Trout Embryo Survival and Emergence, with Evaluation Endpoints

Trout Species	Thresholds, Particle Size, mm	Thresholds, Percent Fines	Endpoints Evaluated
Salmonids	<2 3 6.3	10 19 25	Embryo survival, 80%
Brook, brown, cutthroat, and rainbow trout	3	5 – 30	Embryo survival and emergence
Cutthroat trout	6.3	20	Embryo emergence
Cutthroat trout Brook trout Rainbow trout Rainbow trout	6.35 ? 6.35 0.83	20 10 30 12	Embryo emergence, 50%
Brook trout	1 – 3	20	Embryo survival and emergence
Brook and brown trout	2	<20	Embryo survival and emergence
Coho salmon Chinook salmon Rainbow trout	0.85 6 6 – 12	20 2 10	Embryo survival
Rainbow trout	2	25	Embryo survival

What provides macroinvertebrate protection?

Researchers have reported that particles <2 mm in size have the greatest adverse impact on benthic macroinvertebrates, which are necessary food supply for trout [247, 271]. What is the percentage of fines <2 mm in the sediment at which survival is endangered, that is, what is the threshold value? The Water Quality Control Division of Colorado uses those shown in Table 3 for primary indication of sedimentation risk to macroinvertebrates, specific for lower through upper watershed characteristics. These thresholds portray an increasingly negative effect as elevation increases, that is, increasing threat to the macroinvertebrate community [247].

Table 3. Thresholds as Percent Fines <2 mm for Macroinvertebrate Protection, as a Function of Watershed Characteristics

Watershed Characteristics	Thresholds, Percent Fines <2 mm
Low mountains, mid-elevation hills, ridges, and foot slopes, unglaciated, woodland and shrub land	41.0
Mid-elevation mountains, partially glaciated, mid-elevation forests	29.3
High mountains with steep slopes, glaciated, alpine and subalpine forest	27.5

The density and diversity of the macroinvertebrate community can be biological indicators of sedimentation effects. The Water Quality Control Division of Colorado uses measurement of them as secondary, biological indication of the sedimentation risk to macroinvertebrates. It determines both the reduction in relative abundance of sediment-sensitive taxa and the increase in relative abundance of sediment-tolerant taxa [247], an approach that is based on methods recommended by the National Water Quality Assessment Program [272]. Macroinvertebrate density may be a more sensitive indicator of sedimentation effects than diversity, according to studies [247, 273].

What anticipates debris flows?

Researchers developed a spatially explicit model that uses four topographic features—hillslope gradient, flow accumulation pathways, channel gradient, and valley confinement—for estimating the risk of post-fire debris flows in first-order headwater streams [253, 263, 274]. They concluded that the following conditions were indications high probability for such flows:

- Slopes ≥30 percent, and that are at least 90 m in length or adjacent to ravines [253, 275, 276].
- Reaches having a mean gradient >7 percent [277] and classified as confined [278].

Other researchers found the majority of post-fire debris flows occurred in drainages having areas <640 acres (<2.6 km^2) and slopes >20 percent [279]. While the likelihood of debris flows depended primarily on fire severity [280], the post-fire timing, duration, and magnitude of precipitation events and topographic features, the criteria described above may help with the identification of headwater reaches that are most at risk for post-fire debris flows [8, 253].

6.3 What influences and interacts with this limiting factor?

What are causes and additional factors?

Naturally occurring highly erosive soils are sources of fine sediment transport to streams. High intensity storms, unusually high stream flows, and landslides can dramatically increase sediment load. Land use that disturbs soils and vegetation, such as, mining, logging, farming, grazing, road and trail installation and maintenance, off-road recreation, and stream channelization activities can contribute significantly to sedimentation [8].

What interactions may affect trout?

Low fry densities due to sedimentation may lead to lower competition, resulting in higher survival and recruitment among salmonid populations [281]. Researchers have suggested that there may be other spawning habitat characteristics that offset damage caused by sedimentation [248, 282]. Where there is naturally high sedimentation, trout populations may develop adaptations, for example, increased fecundity, egg size, egg depth, which buffer the adverse effects of sedimentation [248, 283].

The intermediate host worm (*Tubifex tubifex)* for the parasite that causes whirling disease favors habitats with high amounts of fine sediments. Therefore, whirling disease, which reduces survival in juvenile trout, may exacerbate the adverse effects of sedimentation on trout populations in infected reaches [284].

Tributaries flowing to a reach and connectedness among the trout populations may help reduce the effects and speed the recovery from sedimentation events [257, 285]. The probability and intensity of post-fire debris flows decline as vegetation regrows [8, 286].

Researchers noted differences in resilience to post-fire debris effects among trout species [8, 248, 257, 287]. For example, they found that brook trout populations declined more severely than those of cutthroat trout in reaches experiencing debris flows. They hypothesized that brook trout may be less adaptable to lower channel stability or higher sediment loads than the native trout [257, 262].

Chapter 7
Disease as a Limiting Factor

Disease in trout is caused by bacterial, viral, and parasitic pathogens, which can adversely affect trout populations. Pathogens may exist naturally in the environment, may be introduced through formal or informal fisheries management actions, and may be accidental consequences of fishing and other water-related, recreational behavior. Trout populations may decline or be asymptomatic in the presence of pathogens. The role of disease as a limiting factor is highly specific to interactions of the pathogen, the habitat, and the host species [288].

7.1 How is disease a limiting factor?

Disease may be present in a trout population without limiting it. The factors that determine the severity of a pathogen's effects on a population are genetic traits in the affected trout or pathogen and environmental factors in the habitat, including, substrate and temperature characteristics [288-290]. For example, pathogens have optimal temperatures for growth [291].

The U.S. Fish & Wildlife Service National Wild Fish Health Survey has identified the pathogens shown in Table 1 as endangering fish populations [292].

Table 1. Pathogens Endangering Fish Populations

Pathogens
Viruses
Infectious pancreatic necrosis virus
Viral hemorrhagic septicemia virus
Oncorhynchus masou virus
Spring viremia of carp virus
Bacteria
Aeromonas salmonicida, furunculosis
Yersinia ruckeri, enteric redmouth
Renibacterium salmoninarum, bacterial kidney disease
Parasite
Myxobolus cerebralis, whirling disease

Infection can be acute and dramatic for some illnesses, such as whirling disease. For others, such as, bacterial kidney disease, acute outbreaks are rare, and chronic weakening and eventual mortality are the norm [293]. Whirling disease has caused high concern for wild trout stocks in western states, having resulted in large declines in some wild trout populations in Colorado and Montana in the 1990s [8, 289, 294, 295]. It affects the cartilage of young fish, causing skeletal deformities and swimming in circles, that is, whirling, as well as nerve damage and sometimes death [296].

7.2 What are relevant disease thresholds?

Environmental factors can influence the likelihood and severity of a disease outbreak. Factors increasing whirling disease's infectivity are conductivity [297, 298]; high stream productivity; high percent fine sediments and fine organic material; slow flows; cold water temperatures; proximity to places with severe infections; and high percent cover of the invasive diatom known as didymo or rock snot (Didymosphenia geminate) [8, 289, 290, 299].

How susceptible are trout?

Not all salmonid fish are highly affected by whirling disease; some are resistant. Table 2 indicates the susceptibility of trout species to whirling disease, based on laboratory or field exposure at the vulnerable juvenile life stages [289, 300].

Table 2. Trout Susceptibility to Whirling Disease

Trout Species	Susceptibility to Whirling Disease
Brown	Partially resistant; clinical disease rare and develops only when exposed to very high parasite doses
Brook	Susceptible; clinical disease common at high parasite doses, but greater resistance to disease at low doses
Cutthroat, Colorado River	Susceptible; clinical disease common at high parasite doses, but greater resistance to disease at low doses
Rainbow	Highly susceptible; clinical disease common

What are substrate thresholds?

The parasite that causes whirling disease depends on two hosts to complete its life cycle, which are the fish and a common benthic worm, Tubifex tubifex. A dead trout that was infected releases hard whirling disease spores, known as myxospores, in large numbers. These spores can stay viable for many years and are resistant to freezing and drought. When they are taken in by a T. tubifex worm, the worm is parasitized and eventually releases water-borne whirling disease spores, known as triactinomyxons [296].

Researchers have found that both the risk and severity of infection by whirling disease increase with the presence of fine sediments in the stream. This is partly due to the preference of T. tubifex to silt and clay substrates [284, 289, 301, 302]. Researchers determined that worm survival and the production of triactinomyxons were significantly higher in silt, having 92 percent of particles that were <0.125 mm in size, as compared with sand, in which 67 percent of particles were 0.25 - 2mm or were organic debris having an average size 2.8 x 1.2 mm [303]. The presence of worms was found to be significantly greater in sediments with a 70 – 100 percent ratio of clay-to-silt content than in sediments with lower clay-to-silt mixes [301].

From 150 dry-sieved sediments collected in a Colorado stream study, samples with median particle sizes >1.0 mm had lower maximum densities of oligochaetes, the taxonomic class of worms that includes T. tubifex. The highest abundance of oligochaetes occurred in samples having the smaller particle sizes, that is, with mean sizes <0.3 mm [304].

What are temperature effects?

Water temperatures of 50 – 59°F were optimal for the release of whirling disease spores from T. tubifex worms and the subsequent infection of young trout, according to researchers. The development of whirling disease in worms appeared to peak at 59°F. Release began to slow after 10 days at 68°F in worms producing spores [289, 305-308]. Similarly, infection rate and severity in fish were highest between 50 – 59°F [289, 308-312].

7.3 What influences and interacts with this limiting factor?

The whirling disease parasite may have arrived in the United States in a shipment of frozen rainbow trout from Europe [8, 284], and appears to have been introduced to Colorado through imported trout from a private hatchery [296]. Any pathway that transports infected fish, infected host worms, or the parasite's spores can transmit whirling disease. Examples are mud from cars and boats, waders, and fishing equipment; water from boats, coolers, and bait wells; live fish; dead fish or entrails; and aquatic plants [296].

The genetics of both pathogen and hosts can affect the course of disease in trout. With whirling disease, the genotype of the worms influences the severity of the infection [8, 313]. Researchers have found that trout populations can develop resistance to the parasite [312, 314, 315].

Land management practices that cause sediment transport to streams, that is, the deposition of fine particles, can facilitate the occurrence of favorable habitat for the host worms of whirling disease [299].

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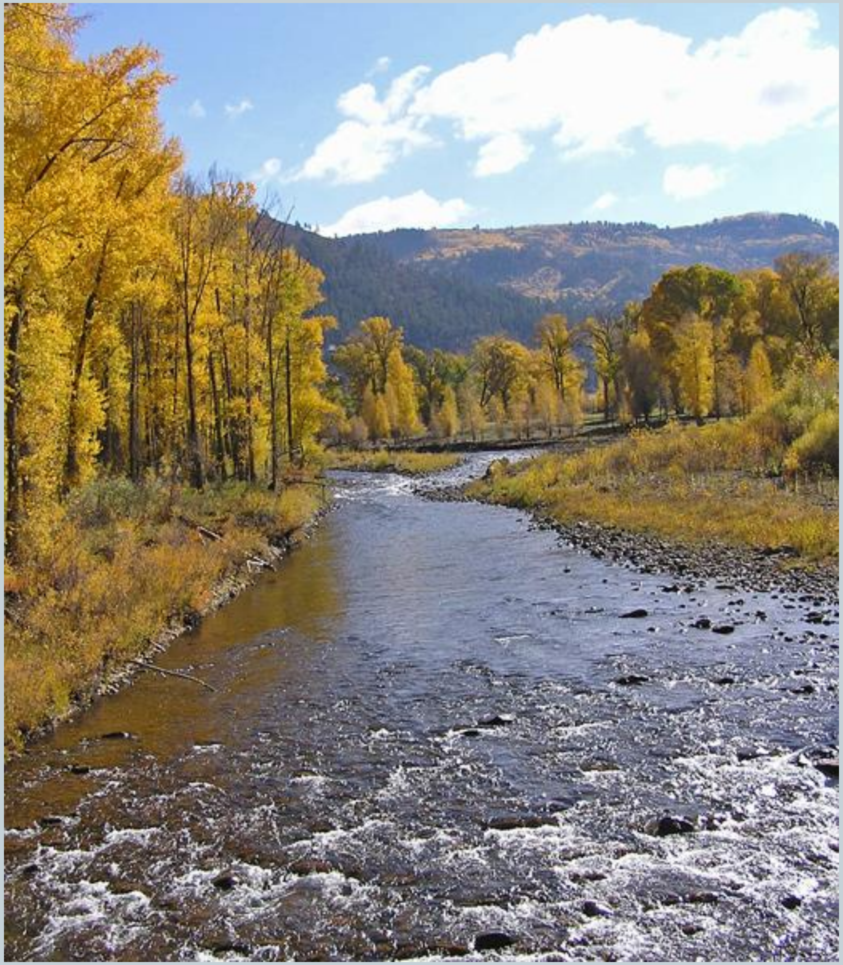
CAMF – Coldwater-fisheries Adaptive Management Framework

TROUT HABITAT IN THE UPPER DOLORES WATERSHED AND HOW IT IS LIKELY TO CHANGE WITH A CHANGING CLIMATE

Intro: Overview of CAMF – What and Why?

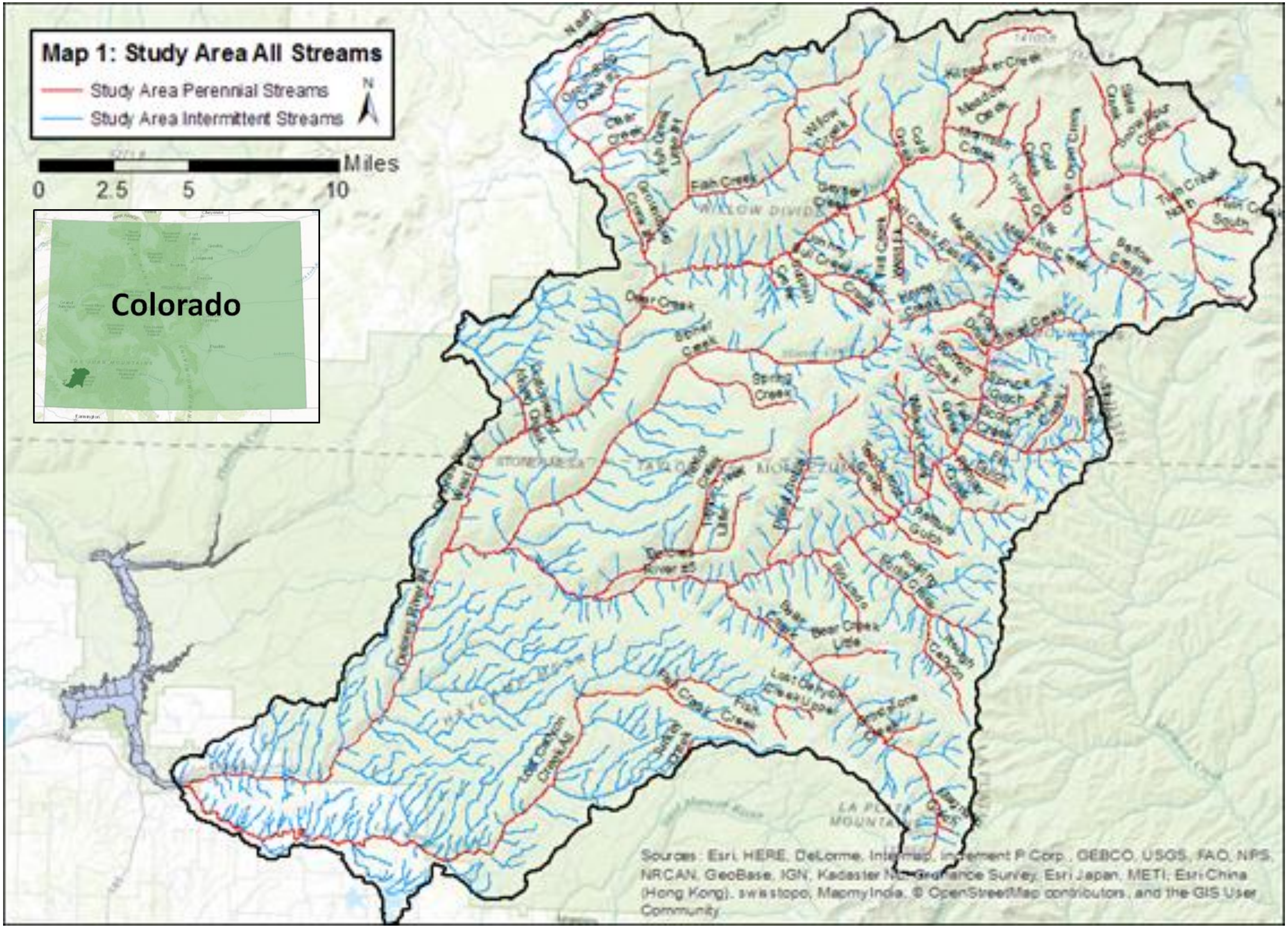
What Is the Purpose of CAMF?

- CAMF is a multi-year effort to systematically identify and map *native and wild trout strongholds within the context of climate change.*
- This effort is specifically focused over a long timeframe (to 2100) on the upper Dolores watershed, situated in the Four Corners area of southwestern Colorado.
- Lying at the abrupt transition between high desert and alpine mountains, southwest Colorado is a "canary in the mine" for assessing the impact of climate change on coldwater-fishery habitat.



Our Core Organizational Question

"Given increasingly limited private, state and federal resources, and in the face of substantial habitat change, where should our Chapter, working with and through local public and private partners, focus its in-stream and near-stream efforts most cost effectively over the long run?"


Map 1: Study Area All Streams
Study Area Perennial Streams
Study Area Intermittent Streams
N
Miles
0
2.5
5
10
Colorado
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

What Is the Expected Benefit?

- Identifying trout strongholds within the context of long-term climate change should provide a useful operational framework
- which, working with and through Colorado Parks and Wildlife staff, National Forest staff and local land owners,
- assists in identifying and investing in appropriate best management practices (BMPs)
- to "Protect, Reconnect, Restore, and Sustain" the diminishing coldwater resources of the area.

Mapping our Journey Through CAMF

- How is climate change likely to affect our trout fisheries? Where are our strongholds?

Which habitat ecological factors, with their associated threshold values, limit the viability and survivability of trout populations?

How are these thresholds likely to be adversely affected by climate change as it impacts the Southwest, Colorado

Which streams in the Upper Dolores watershed are likely to provide viable trout populations through the end of the 21st century (our "strongholds")?

What strategic management strategies emerge as most relevant?

Mapping our Journey Through CAMF

- How is climate change likely to affect our trout fisheries? Where are our strongholds?

Trout habitat limiting factors
"state of the science"

Climate change modeling,
esp. for Southwest,
Colorado

Downscale to San Juans,
vulnerability analysis

Adaptive management
considerations

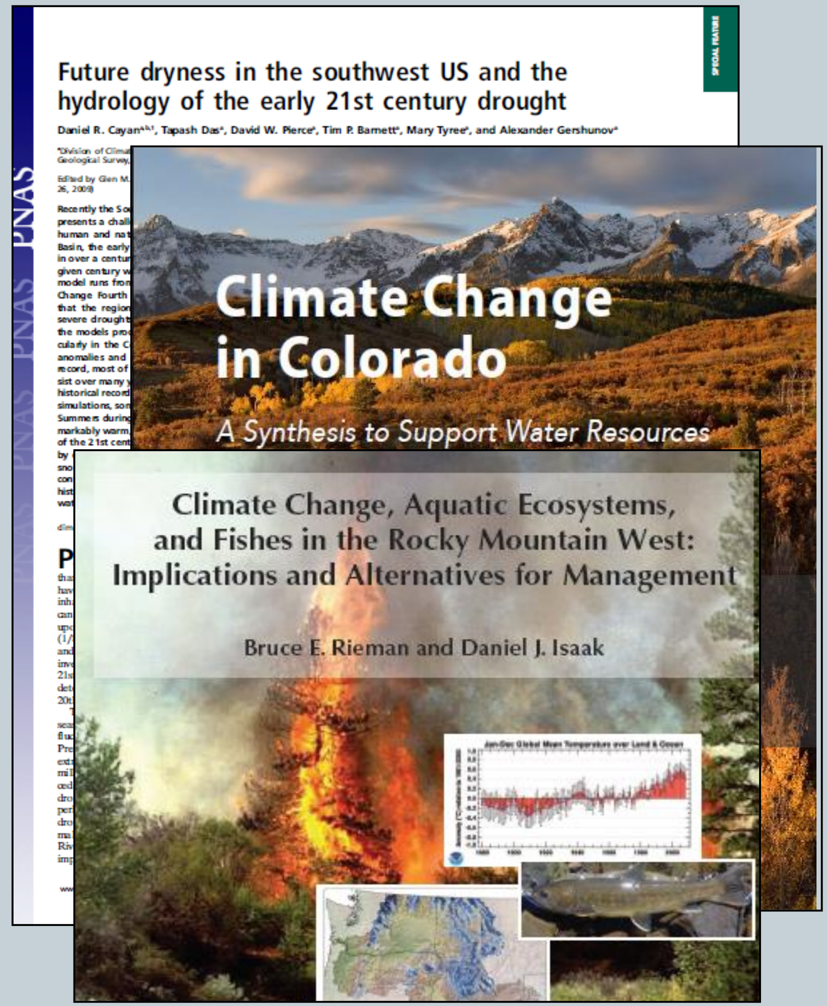
Summary of Findings

Summary of findings (1)

- With very few exceptions, *current* coldwater-fisheries in the Study Area are healthy; populations are viable.
  - There are 46 identified trout streams containing approximately 295 stream miles of viable trout habitat in the Study Area, with flow derived from over 1430 square miles of contributing watershed.
  - Four species of trout (cutthroat, rainbow, cutbow and brown), one of char (brook) and one species of salmon (kokanee) inhabit the area.
  - At least one stream in the Study Area has a reach with a very pure strain of "Greenback" Cutthroat.
  - Virtually every long-term perennial stream has a viable trout population.
  - If there were no systemic changes on the horizon, there is little reason to suspect that this state would change substantially in the foreseeable future.

SUMMARY OF FINDINGS (3)

- However, highly credible science indicates that substantial systemic changes are already underway, thought to be due largely to the greenhouse effects driving climate change.
  - What the exact nature of these changes will be in our area cannot yet be precisely determined.
  - Instead, sophisticated science can give us a pretty solid characterization of the expected change.
  - This is accomplished through the development of several major climate change scenarios for the Study Area over the timeframe from now to 2100.
- Our review of on-point climate change research for the Southwest indicates that climate change will increasingly affect our Study Area between now and 2100. The major impacts fall in two dimensions: *temperature and precipitation.*



Summary of Findings (2)

- Our careful review of mountain stream ecological systems and trout habitat research identified the following as limiting factors for such habitat:
  - Stream temperature
  - Flow regime (includes volume, rate, depth and periodicity)
  - Stream morphology (includes segment length, connectivity, gradient, refugia and barriers)
  - Pollutants (includes nutrients)
  - Biotic competition (wild vs native, cold vs warm water, food stock)
  - Sedimentation (includes risk of impact from wildfire)
  - Salmonid disease
- Limiting factor analysis identifies those ecological factors and their associated critical threshold values, beyond which, for any given factor, a selected habitat is likely to deteriorate to the point of dissipation.
- These factors are detailed in a separate companion document also developed by the study team entitled *Mountain Stream Trout Habitat Limiting Factors – A State of the Science Review*.

Mountain Stream Trout Habitat Limiting Factors – A State of the Science Review

In Support of Guidelines for Developing a Coldwater-Fisheries Adaptive Management Framework and Plan

Prepared in collaboration with Trout Unlimited, Colorado Parks and Wildlife, San Juan National Forest, and Dolores River Anglers Chapter of Trout Unlimited (DRA)

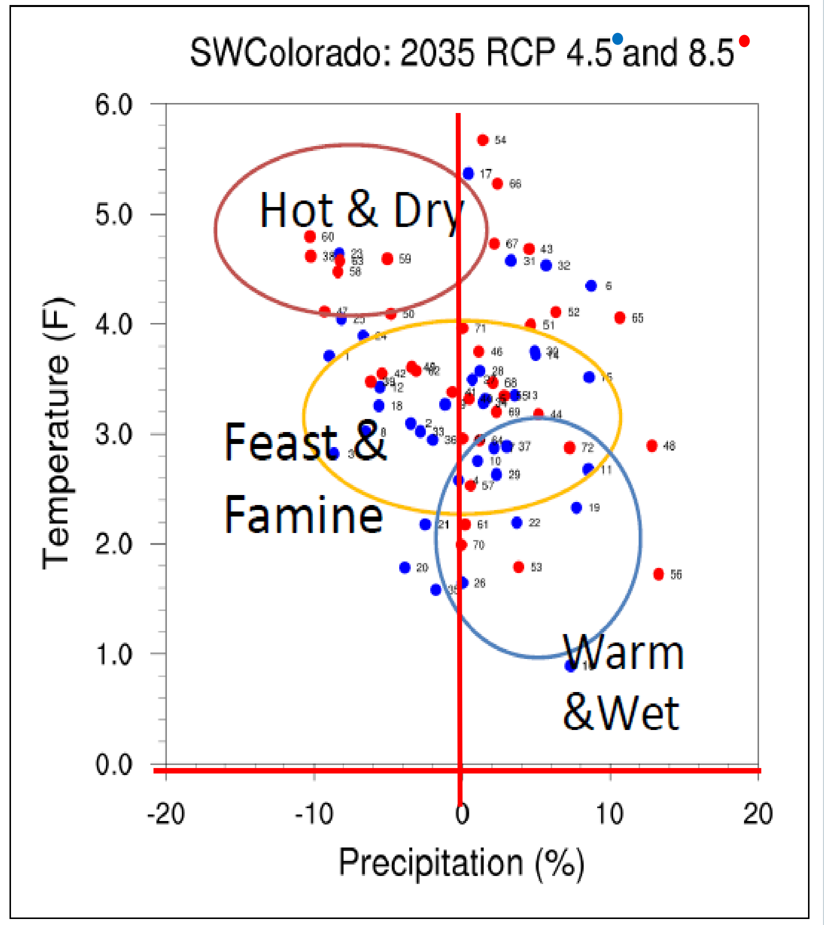
Project Directors:
Matt Clark and Duncan Rose, Trout Unlimited, DRA

Authors:
Raymond Rose, Ann Oliver, Duncan Rose, and Chris Rasmussen

Draft August 10, 2016

SUMMARY OF FINDINGS (4)

- Downscaled research that specifically models climate change in the San Juan mountains identifies three “clusters” found within 72 modeled scenarios that characterize the impact on the Study Area:
  - Warm and Wet,
  - Hot and Dry and
  - Feast and Famine.
- Of the three, two (Hot and Dry and Feast and Famine) pose the most serious challenges to trout habitat. Drought is the underlying force for both. In these scenarios, simulations show drought to steadily increase in both intensity and duration through the study period.
- While reflecting less intense impact on our area, Warm and Wet could still pose challenges through increased flow velocity, changed flow timing and increased inter and intra aquatic-specie competition (fish and food).



Scenarios	Hot and Dry	Feast and Famine	Warm and Wet
Temperature	Annual temperature increases by 5F; At lower elevations: summer days with temperature above 77F (25C) increases by 1 month, and nights with temperature above 68F = 10	Annual temperature increases by 3F; At lower elevations: summer days with temperature above 77F (25C) increases by 2 weeks, and nights with temperature above 68F = 20	Annual temperature increases by 2F; At lower elevations: summer days with temperature above 77F (25C) increases by 1 week
Precipitation	Annual precipitation decreases by 10%; less frequent and more intense individual rain events; summer monsoon rains decrease by 20%	Annual precipitation does not change but much greater fluctuations year to year (leading to more frequent feast or famine conditions); El Nino of 1982/83 strength occurs every 7 years	Annual precipitation increases by 10%; more intense individual rain events; summer monsoon rains increase by 10%
Runoff	Runoff decreases by 20% and peak runoff occurs 3 weeks earlier	Runoff decreases by 10% and peak runoff occurs 2 weeks earlier	Runoff volume does not change but peak runoff earlier by 1 week
Heat Wave	Severe and long lasting; every summer is warmer compared to 2002 or 2012 (5F above normal)	Hot summers like 2002 and 2012 occur once every 3 years	Hot summers like 2002 and 2012 occur once every decade
Drought	More frequent drought years like 2002/2012 - every 5 years	Drought years like 2002/2012 occur once every decade	No change in frequency but moderate increases in intensity; fewer cases of multi-year drought
Snowline or Freezing Level	Snowline moves up by 1200ft	Snowline moves up by 900ft	Snowline moves up by 600ft
Wildfire	Fire season widens by 1 month; greater fire frequency (12x) and extent (16x) in high elevation forest	Fire risk during dry years is very high at all elevations b/c of large fuel build up from wet years; on average fire frequency increases 8x, and area burnt increases 11x	Increases in fire frequency (4x) and extent (6x)
Dust Storms	Extreme spring dust events like 2009 every other year; causing snowmelt and peak runoff to be six weeks earlier	Frequency of extreme dust events increases from current but tied to extreme dry years	Same as current
Flood Risk	Flood less frequent but risk increases for big summer rain events	Risk increases substantially during the wet years	Flood frequency increases substantially as well as the overall risk
Growing Season	Increases by 3 weeks	Increases by 2 weeks	Increases by 1 week

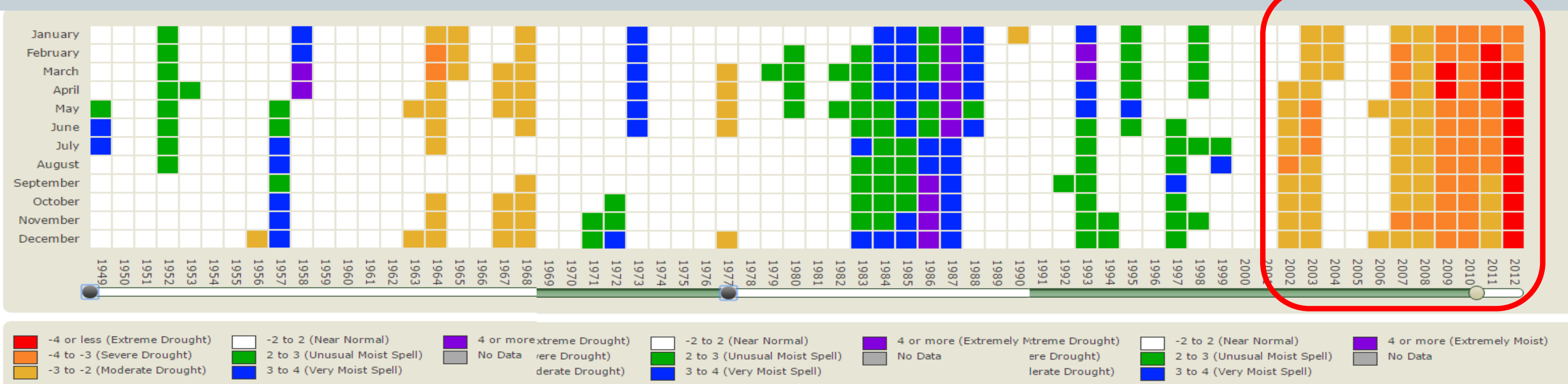
MSI: Three Climate Scenarios for the San Juan Basin Region by 2035

Projected mid-late century drought in Southwest

- All substantial climate change studies for the Southwest which we have been able to locate project substantially increasing severe drought across the Southwest, especially from mid century on.
- The studies indicate drought will increase from periodic drought of 2 to 5 year duration by 2035, through decadal drought by 2070, to perhaps multi-decadal drought by the end of the century.
- Such drought is beyond the experience of post Ancient Puebloan culture, and not seen since the late 13th century, if ever.
- "Our results point to a remarkably drier future that falls far outside the contemporary experience of natural and human systems in Western North America, conditions that may present a substantial challenge to adaptation." (Unprecedented 21st century drought risk in the American Southwest and Central Plains. Cook et al. *Science Advances* 12 Feb 2015: Vol. 1, no. 1, e1400082 DOI: 10.1126/sciadv.1400082)

SUMMARY OF FINDINGS (5)

- In all 72 modeled scenarios, temperatures are likely to increase steadily over the analysis period (2016 – 2100).
- Precipitation may well stay close to current levels (models are inconclusive), but will change "phase proportions" (less snow, more rain) and timing (snow starting later and ending earlier). This will reduce available *effective* (trout habitat "beneficial") precipitation.
- If Hot and Dry and Feast and Famine prevail, drought will likely increase in both intensity and duration, with potentially very substantial drought becoming prevalent between 2070 and 2100.



Summary of findings (5)

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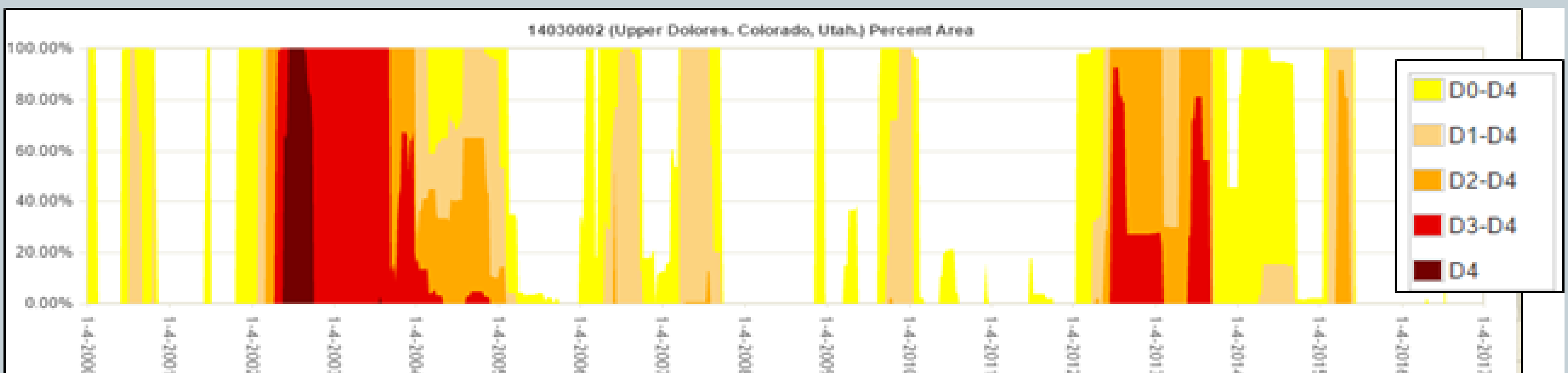
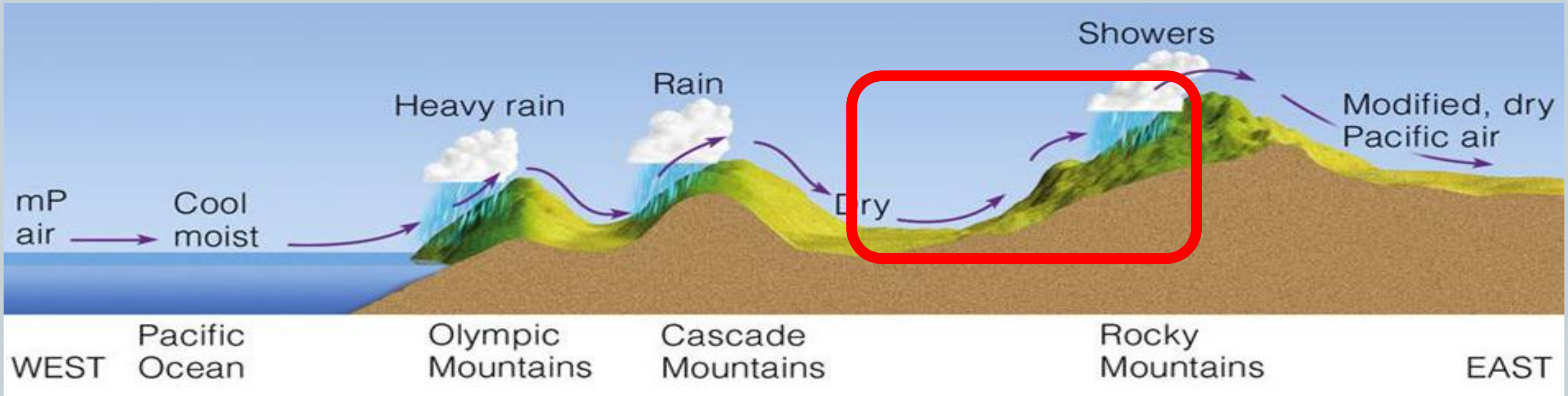


SUMMARY OF FINDINGS (6)

- Climate change is expected to modify a key driver of climate in our area, namely the Southern Oscillation (El Nino, La Nina and "Normal" weather cycles). These changes, coupled with a warming desert terrain, will directly impact the Study Area.
- Offsetting these impacts is the effect of our surrounding high mountains, which will continue to add precipitation through orographic effects in an otherwise increasingly challenging climate.



Summary of findings (7)

- As air temperatures rise, water temperatures will follow. Elevation, stream shade, flow rate, volume, and depth and timing and amount of precipitation will affect how substantially each stream will be affected.
- Lower, slower, non-shaded streams may be so significantly impacted by 2070 that they no longer support cold-water species.
- Warmer water temperatures cause trout to expend more energy to survive, reducing both growth and fertility. Warmer waters also reduce disease resistance.
- As high headwaters warm, more high-elevation habitat opens up for trout migration (while lower is lost to temperature),
- However, that additional higher habitat, being smaller, is more vulnerable to reductions in flow during drought periods and an increase in flash flooding.

Summary of findings (8)

- Trout habitat, then, will become increasingly challenged through 2100, largely through stream drying and low flow caused by drought and phase changes in precipitation, followed (in terms of impact) by increasing stream temperatures, periodic flash flooding, and increased sedimentation due to an increasing numbers of wildfires.
- Effective stream flow will be reduced - some permanently, some periodically - on an increasingly substantial basis, with habitat on smaller and lower tributaries experiencing the greatest impact.
- Habitat will likely be substantially and continually reduced over the analysis period.

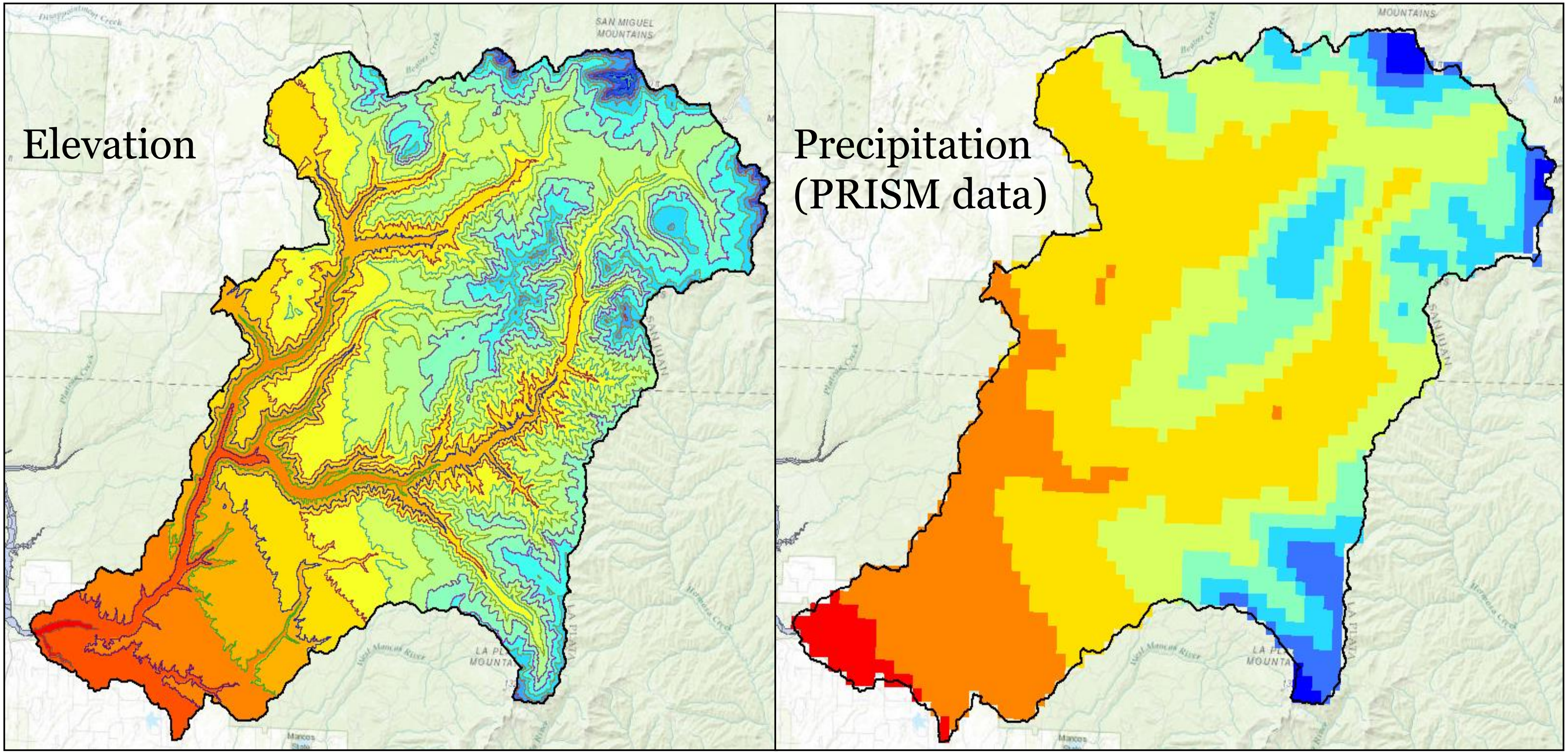
Identifying and Mapping Vulnerability to Climate Change by Stream – Strongholds!

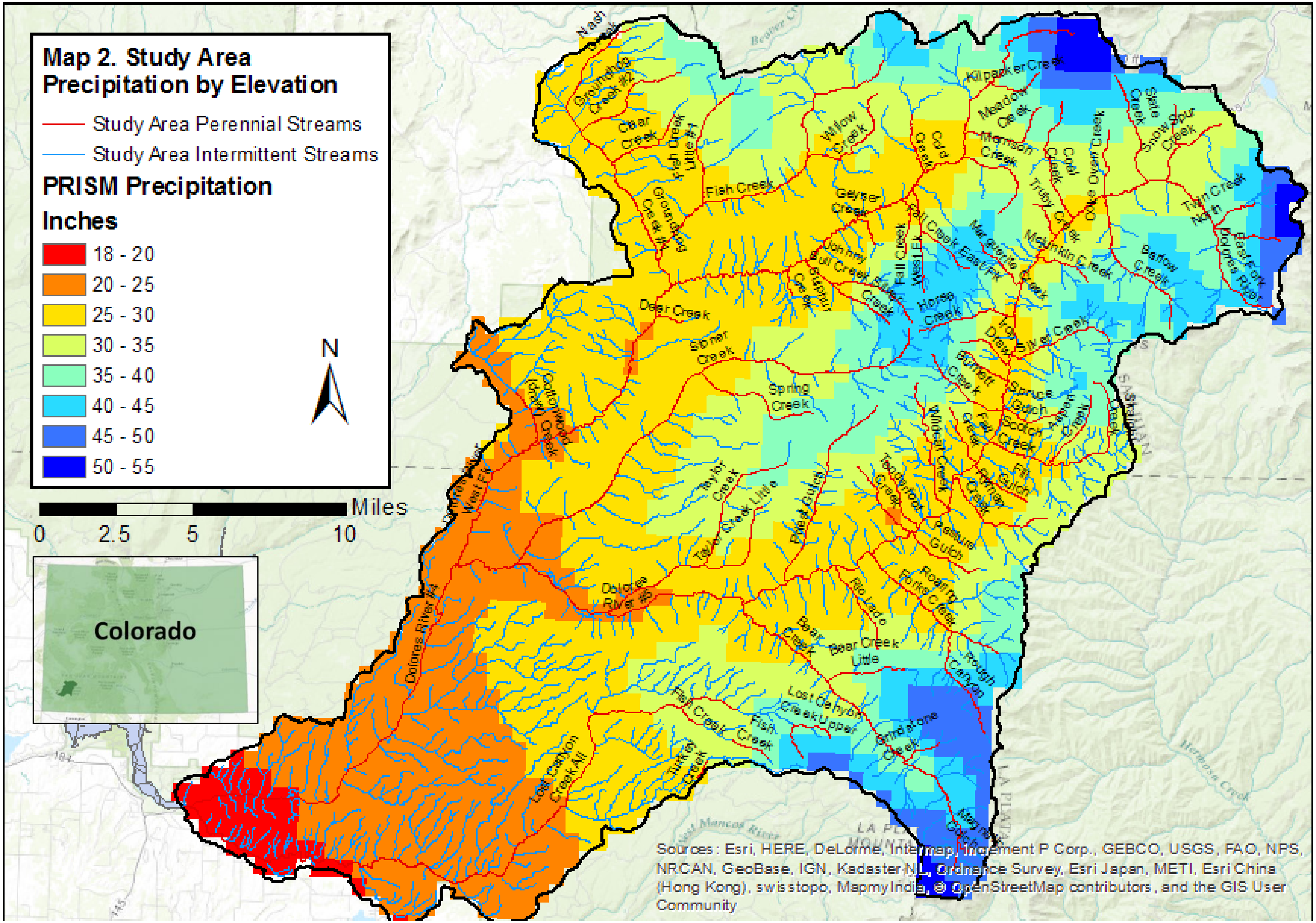
Downscaling to the Study Area

- Two sites (StreamStats and PRISM) aggregate local field-derived data (4 Snotel sites) reflecting the state of threshold values for the seven limiting factors for the Study Area.
- Two flow meters exist (only one – just below Rico – collects flow data *above* the various irrigation diversions that support agricultural use).
- Comparison of daily average flow for each day of 2002 with the 62 year average for that day indicates an average drop of 44% flow per day in 2002.

Comparison of daily mean flow for year 2002 with daily mean flow for 62 years															
site_no	Month	Day	begin_yr	end_yr	count_nu	max_va_yr	max_va	min_va_yr	min_va	mean_va	Actual Flow 2002	Mean all Data	Difference (N-M)	% Diff
9165000	1	1	2013	2015	3	2014	29	2013	9.9	23	22	20	-2	-10%
9165000	1	2	2013	2015	3	2014	29	2013	9.7	22	21	19	-2	-11%
9165000	1	3	2013	2015	3	2014	29	2013	9.8	22	24	19	-5	-26%
9165000	1	4	2013	2015	3	2014	29	2013	9.8	22	24	19	-5	-26%
9165000	1	5	2013	2015	3	2014	28	2013	9.8	22	23	19	-4	-21%
9165000	1	6	2013	2015	3	2014	28	2013	9.8	22	22	19	-3	-16%
9165000	1	7	2013	2015	3	2015	33	2013	9.8	24	24	19	-5	-26%
9165000	1	8	2013	2015	3	2015	35	2013	9.8	25	26	19	-7	-37%
9165000	1	9	2013	2015	3	2015	34	2013	9.9	24	27	19	-8	-42%
9165000	1	10	2013	2015	3	2015	33	2013	10	24	22	19	-3	-16%
9165000	1	11	2013	2015	3	2015	31	2013	10	23	22	19	-3	-16%
9165000	1	12	2013	2015	3	2015	29	2013	9.9	22	22	19	-3	-16%
9165000	1	13	2013	2015	3	2015	29	2013	9.9	22	20	19	-1	-5%
9165000	1	14	2013	2015	3	2015	29	2013	9.8	22	22	19	-3	-16%
9165000	1	15	2013	2015	3	2014	28	2013	9.7	22	25	19	-6	-32%
9165000	1	16	2013	2015	3	2015	29	2013	9.7	22	25	19	-6	-32%
9165000	1	17	2013	2015	3	2015	30	2013	9.7	22	20	19	-1	-5%
9165000	1	18	2013	2015	3	2014	28	2013	9.7	22	16	19	3	16%
9165000	1	19	2013	2015	3	2014	28	2013	9.8	22	19	19	0	0%
9165000	1	20	2013	2015	3	2015	28	2013	9.9	22	19	19	0	0%
9165000	1	21	2013	2015	3	2014	27	2013	9.9	21	20	18	-2	-11%
9165000	1	22	2013	2015	3	2014	27	2013	10	20	22	18	-4	-22%
9165000	1	23	2013	2015	3	2014	26	2013	10	20	20	18	-2	-11%
9165000	1	24	2012	2015	4	2014	26	2013	9.9	19	20	18	-2	-11%
9165000	1	25	2012	2015	4	2014	26	2013	9.7	19	21	18	-3	-17%
9165000	1	26	2012	2015	4	2014	27	2013	9.8	20	22	18	-4	-22%
9165000	1	27	2012	2015	4	2015	28	2013	9.9	20	23	19	-4	-21%
9165000	1	28	2012	2015	4	2015	28	2013	9.8	20	23	18	-5	-28%
9165000	1	29	2012	2015	4	2015	27	2013	9.6	19	23	18	-5	-28%
9165000	1	30	2012	2015	4	2014	26	2013	9.6	19	20	18	-2	-11%
9165000	1	31	2012	2015	4	2014	27	2013	9.6	20	18	18	0	0%
9165000	2	1	2012	2015	4	2014	27	2013	9.7	19	21	18	-3	-17%
9165000	2	2	2012	2015	4	2014	26	2013	9.8	19	19	18	-1	-6%
9165000	2	3	2012	2015	4	2014	26	2013	9.7	19	19	18	-1	-6%
9165000	2	4	2012	2015	4	2014	26	2013	9.7	19	19	18	-1	-6%
9165000	2	5	2012	2015	4	2014	26	2013	9.7	19	17	18	1	6%
9165000	2	6	2012	2015	4	2015	26	2013	9.8	19	18	18	0	0%

Precipitation Is Closely Tied to Elevation

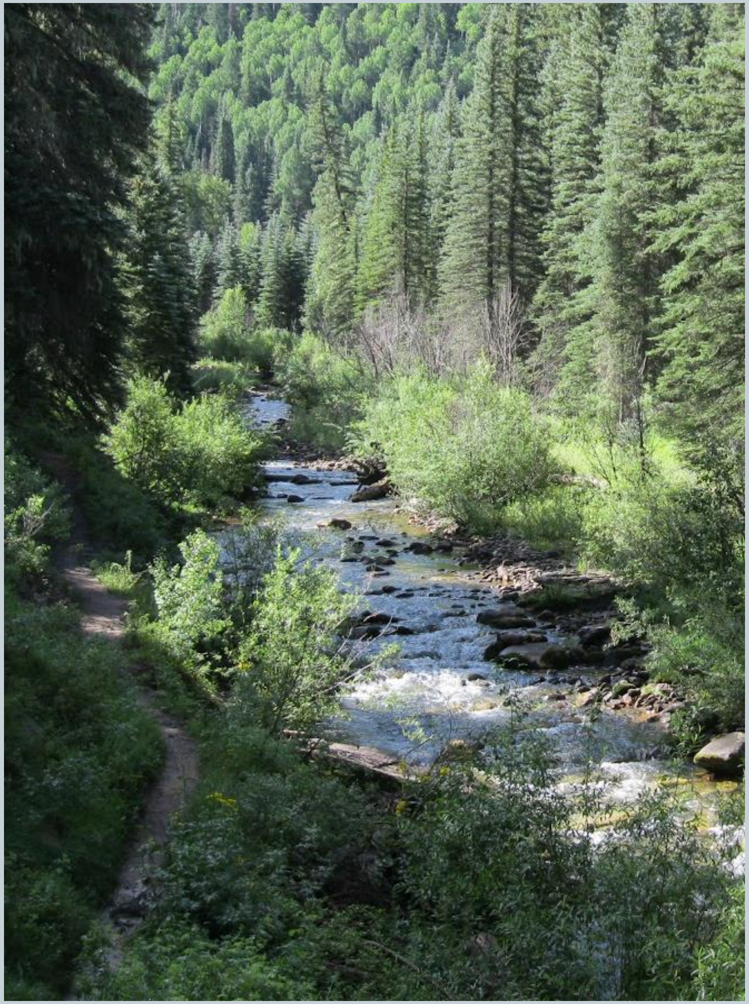




Map 2. Study Area Precipitation by Elevation
Study Area Perennial Streams
Study Area Intermittent Streams
PRISM Precipitation
Inches
18 - 20
20 - 25
25 - 30
30 - 35
35 - 40
40 - 45
45 - 50
50 - 55
N
Miles
0 2.5 5 10
Colorado
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Where Trout Habitat Will Likely Persevere

- Those streams that will be the most likely candidates for sustained habitat and populations to 2100:
  1. Have headwaters that reach to the highest elevations,
  2. Have the largest watersheds
  3. Have watersheds with large areas at high elevations,
  4. Have moderate gradient,
  5. Have many feeder streams and fens/wetlands at higher elevation, and
  6. Are shaded through riparian cover, north facing aspect and narrower valley "walls".
- Conversely, populations in streams with low reaching headwaters and low elevation feeder streams, smaller and lower elevation watersheds, high gradient and with wide valley walls and substantial east-west aspect will likely struggle to survive extended drought due to drying and increasing water temps reaching limiting thresholds.

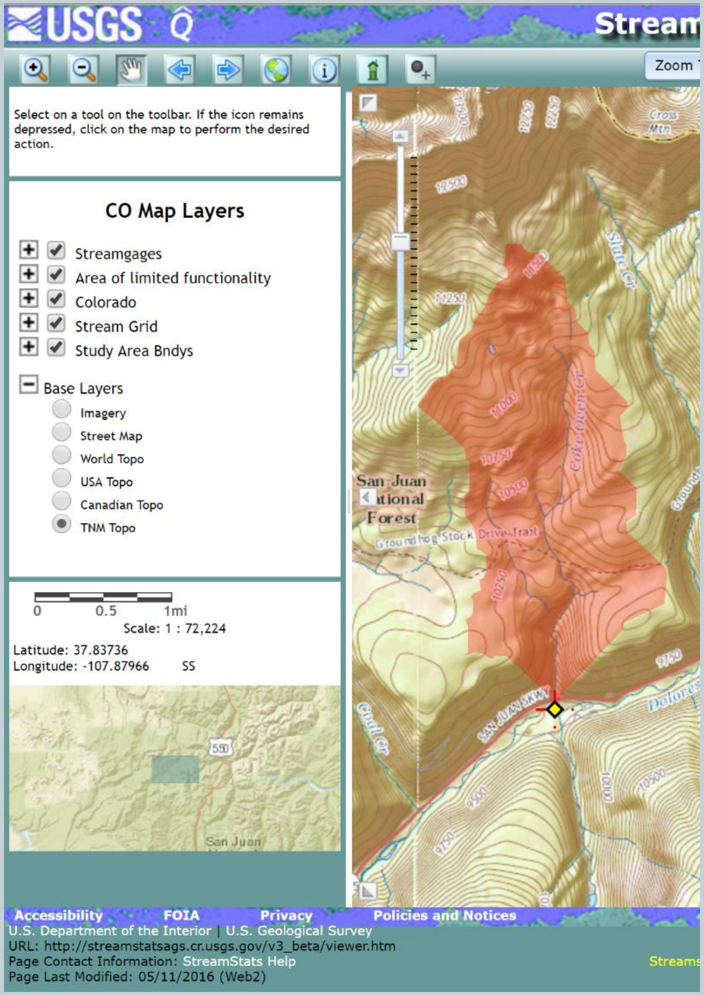


Ranking Vulnerability to Climate Change

- Vulnerability is ranked by
  - Geophysical/hydrological features (streamflow)
  - Temperature (elevation)
- Geophysical/hydrological features include:
  - Watershed size in square miles
  - M7D10Y Low Flow ("Mean 7 day, 10 year low-flow")
  - Mean annual precipitation
  - Mean basin elevation
  - Mean basin wall slope
  - % watershed above 7500 feet
  - Elevation of stream mouth
  - Headwaters elevation
  - Average gradient
- Primary data sources:
  - PRISM
  - StreamStats
  - GIS (National map, National Hydrographic Dataset)

StreamStats: Key Analytic Tool

- StreamsStats, an online hydrologic modeling web site from USGS, does contain modeled data for all streams in the watershed. Since no site specific data are collected from within the Study Area, all precipitation and flow values available through StreamStats are derived from regression equations based on data from other (similar) Colorado watersheds where such data are available.
- PRISM, a federally supported source of mapped weather data from Oregon State University, is incorporated into the StreamStats modeling.



Removed: Problematic "Perennial" Streams

	Problematic Streams
81	Aspen Creek
89	Cold Creek
99	Fall Creek West Fk
41	Cottonwood (draw) Creek
25	Deer Creek
73	Dipping Vat Creek
94	Eagle Creek
55	Estes Draw
49	Fill Gulch
104	Geyser Creek
36	Iron Draw
110	Johnny Bull Creek
106	Lower Groundhog Creek (#1)
80	Magnetic Gulch
26	Mcjunkin Creek
19	Pasture Gulch
43	Spruce Gulch
39	Sulfur Creek
28	Sulphur Creek
138	Truby Creek
76	Turkey Creek
48	Fall Creek (Rico)

Problematic Streams:

Streams listed as "perennial" on the National Hydrographic Dataset but with known issues for long-term trout habitat viability based on local knowledge (observed intermittent flow in drought, extensive irrigation draw, extensive canalization, very small, no trout, excessive mineralization, etc.).

Table 8.1: Ranking of Existing Trout Streams in Study Area by Long-Term Vulnerability to Climate Change (Low to High)

OBJ ECT ID	STREAM NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
	Quintile 1: Lowest Vulnerability													
142	East [illegible]	[illegible]	11	6.35	1	1	1	1	2	1	1	1	2	
82	Barlo[illegible]	[illegible]	15	5.53	2	1	1	1	3	1	2	2	[illegible]	
87	Coal [illegible]	[illegible]	18	4.44	2	2	2	2	2	1	2	2	[illegible]	
16	Slate [illegible]	[illegible]	18	3.98	3	2	[illegible]	1	4	1	1	2	[illegible]	
127	Snow [illegible]	[illegible]	18	3.02	2	2	3	2	2	1	1	4	[illegible]	
125	Silver [illegible]	[illegible]	19	3.78	2	2	1	1	5	1	2	4	[illegible]	
139	Twin Creek North	1	20	1.68	4	5	1	1	4	1	1	1	[illegible]	
83	Bear Creek	1	21	13.71	1	1	2	3	4	1	5	3	[illegible]	
101	Fish Creek @ SWA	1	21	12.95	1	1	4	3	3	1	4	3	[illegible]	[illegible]
	Quintile 2: Lower Vulnerability													
93	Dolores River West Fk	2	22	34.84	1	1	4	5	3	1	5	1	[illegible]	
15	Lizard Head Creek	2	22	1.45	5	5	2	1	2	1	1	3	[illegible]	
116	Meadow Creek	2	22	3.45	3	3	3	3	1	1	2	3	[illegible]	
1[illegible]	[illegible]	[illegible]	22	17.99	1	1	5	5	2	1	5	1	[illegible]	
[illegible]	[illegible]	[illegible]	22	2.37	5	5	1	1	3	1	1	1	[illegible]	
1[illegible]	[illegible]	[illegible]	23	3.56	4	5	2	2	1	1	2	3	[illegible]	
121	Roaring Forks Creek	2	23	5.74	1	1	3	4	3	1	4	4	[illegible]	
122	Rough Canyon	2	23	3.95	2	2	2	3	3	1	3	3	[illegible]	
98	Fall Creek East Fk	2	24	2.06	5	5	1	1	4	1	1	1	[illegible]	
108	Horse Creek	2	24	3.40	3	2	1	2	5	1	3	2	[illegible]	
113	Lost Canyon (above Dipping Vat Creek)	2	24	1.50	5	5	2	3	1	1	1	3	[illegible]	
92	Upper Dolores (#5)	2	24	35.20	1	1	3	4	3	1	5	5	[illegible]	[illegible]
	Quintile 3: Moderate Vulnerability													
88	Coke Oven Creek	3	25	2.39	4	5	3	2	1	1	2	3	[illegible]	
96	Fall Cr[illegible]	[illegible]	25	1.47	3	3	1	2	3	1	3	5	[illegible]	
102	Fish Cr[illegible]	[illegible]	25	4.18	2	2	3	3	3	1	4	4	3	
111	Kilpack[illegible]	[illegible]	25	2.00	5	5	1	1	5	1	1	3	3	
1	Nash C[illegible]	[illegible]	25	4.72	2	3	4	5	1	1	3	5	1	
128	Spring Creek	3	25	4.58	3	3	4	4	1	1	3	3	3	
107	Upper Groundhog Creek (#2)	3	25	4.27	3	3	4	4	1	1	3	4	2	
141	Willow Creek	3	25	4.31	3	3	4	4	1	1	3	4	2	27.93
	Quintile 4: Higher Vulnerability													
124	Scotch Creek	4	26	4.46	2	2	4	3	4	1	4	1	5	
131	Straight Creek	4	26	2.58	5	5	2	1	5	1	1	1	5	
[illegible]	[illegible]	[illegible]	[illegible]	14.68	1	1	5	5	2	2	5	5	1	
1[illegible]	[illegible]	[illegible]	[illegible]	8.71	1	2	5	5	2	1	5	4	2	
1[illegible]	[illegible]	[illegible]	[illegible]	1.43	5	5	2	2	4	1	2	5	2	
119	Priest Gulch	4	28	6.97	2	2	4	4	4	1	5	2	4	
84	Bear Creek Little	4	29	2.69	4	5	3	3	2	1	3	4	4	
85	Burnett Creek	4	29	3.28	4	5	3	2	5	1	3	1	5	
17	Marguerite Creek	4	29	2.10	5	5	2	2	5	1	2	2	5	46.90
	Quintile 5: Highest Vulnerability													
112	Lost Canyon Creek (All)	5	30	26.15	1	4	5	5	1	5	5	3	1	
18	Silver Creek (Johnny Bull)	5	30	2.41	5	5	3	3	5	1	2	1	5	
140	Wildcat C[illegible]	[illegible]	30	4.85	3	3	4	4	5	1	4	1	5	
123	Ryman Cr[illegible]	[illegible]	32	4.30	3	3	5	4	5	1	4	3	4	
86	Clear Cre[illegible]	[illegible]	33	2.87	4	5	5	5	1	1	4	5	3	
135	Taylor Creek Little	5	33	3.46	4	5	5	4	2	1	4	4	4	
120	Rio Lado	5	37	3.29	4	5	5	5	4	1	5	4	4	
136	Tenderfoot Creek	5	37	2.95	4	5	5	5	4	1	4	4	5	50.28
	Total Miles			296.1										296.1

1: Lowest Vulnerability

2: Moderately Low

3: Moderate

4: Moderately High

5: Highest

Composite Worksheet: Ranking by Geophysical/ Hydrological Vulnerability (Streamflow) [Low (Green) to High (Red)]

1: Lowest Vulnerability Streams: Strongholds!

OBJ ECT ID	DOW_NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
142	East Fork Dolores River	1	11	6.35	1	1	1	1	2	1	1	1	2	
82	Barlow Creek	1	15	5.53	2	1	1	1	3	1	2	2	2	
87	Coal Creek	1	18	4.44	2	2	2	2	2	1	2	2	3	
16	Slate Creek	1	18	3.98	3	2	1	1	4	1	1	2	3	
127	Snow Spur Creek	1	18	3.02	2	2	3	2	2	1	1	4	1	
125	Silver Creek (above Rico pond)	1	19	3.78	2	2	1	1	5	1	2	4	1	
139	Twin Creek North	1	20	1.68	4	5	1	1	4	1	1	1	2	
83	Bear Creek	1	21	13.71	1	1	2	3	4	1	5	3	1	
101	Fish Creek @ SWA	1	21	12.95	1	1	4	3	3	1	4	3	1	55.43

142	East Fork Dolores River	1	11
82	Barlow Creek	1	15
87	Coal Creek	1	18
16	Slate Creek	1	18
127	Snow Spur Creek	1	18
125	Silver Creek (above Rico pond)	1	19
139	Twin Creek North	1	20
83	Bear Creek	1	21
101	Fish Creek @ SWA	1	21

2: Moderately Low Vulnerability Streams

OBJECT ID	DOW_NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
93	Dolores River West Fk	2	22	34.84	1	1	4	5	3	1	5	1	1	
15	Lizard Head Creek	2	22	1.45	5	5	2	1	2	1	1	3	2	
116	Meadow Creek	2	22	3.45	3	3	3	3	1	1	2	3	3	
130	Stoner Creek	2	22	17.99	1	1	5	5	2	1	5	1	1	
23	Twin Creek South	2	22	2.37	5	5	1	1	3	1	1	1	4	
117	Morrison Creek	2	23	3.56	4	5	2	2	1	1	2	3	3	
121	Roaring Forks Creek										4	4	2	
122	Rough Canyon										3	3	4	
98	Fall Creek East Fk										1	1	5	
108	Horse Creek										3	2	5	
113	Lost Canyon (above Dipping Va										1	3	3	
92	Upper Dolores (#5)										5	5	1	115.52

93	Dolores River West Fk	2	22
15	Lizard Head Creek	2	22
116	Meadow Creek	2	22
130	Stoner Creek	2	22
23	Twin Creek South	2	22
117	Morrison Creek	2	23
121	Roaring Forks Creek	2	23
122	Rough Canyon	2	23
98	Fall Creek East Fk	2	24
108	Horse Creek	2	24
113	Lost Canyon (above Dipping Vat	2	24
92	Upper Dolores (#5)	2	24

3: Moderately Vulnerable Streams

OBJECT ID	DOW_NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
88	Coke Oven Creek	3	25	2.39	4	5	3	2	1	1	2	3	4	
96	Fall Creek (Dunton)	3	25	1.47	3	3	1	2	3	1	3	5	4	
102	Fish Creek Little (#1)	3	25	4.18	2	2	3	3	3	1	4	4	3	
111	Kilpacker Creek	3	25	2.00	5	5	1	1	5	1	1	3	3	
1	Nash Creek	3	25	4.72	2	3	4	5	1	1	3	5	1	
128	Spring Creek	3	25	4.58	3	3	4	4	1	1	3	3	3	
107	Upper Groundhog Creek (#2)	3	25	4.27	3	3	4	4	1	1	3	4	2	
141	Willow Creek	3	25	4.31	3	3	4	4	1	1	3	4	2	27.93

88	Coke Oven Creek	3	25
96	Fall Creek (Dunton)	3	25
102	Fish Creek Little (#1)	3	25
111	Kilpacker Creek	3	25
1	Nash Creek	3	25
128	Spring Creek	3	25
107	Upper Groundhog Creek (#2)	3	25
141	Willow Creek	3	25

4: Higher Vulnerability Streams

OBJECT ID	DOW_NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
124	Scotch Creek	4	26	4.46	2	2	4	3	4	1	4	1	5	
131	Straight Creek	4	26	2.58	5	5	2	1	5	1	1	1	5	
91	Lower Dolores (#4)	4	27	14.68	1	1	5	5	2	2	5	5	1	
134	Taylor Creek	4	27	8.71	1	2	5	5	2	1	5	4	2	
105	Grindstone Creek	4	28	1.43	5	5	2	2	4	1	2	5	2	
119	Priest Gulch	4	28	6.97	2	2	4	4	4	1	5	2	4	
84	Bear Creek Little	4	29	2.69	4	5	3	3	2	1	3	4	4	
85	Burnett Creek	4	29	3.28	4	5	3	2	5	1	3	1	5	
17	Marguerite Creek	4	29	2.10	5	5	2	2	5	1	2	2	5	46.90

124	Scotch Creek	4	26
131	Straight Creek	4	26
91	Lower Dolores (#4)	4	27
134	Taylor Creek	4	27
105	Grindstone Creek	4	28
119	Priest Gulch	4	28
84	Bear Creek Little	4	29
85	Burnett Creek	4	29
17	Marguerite Creek	4	29

5: Highest Vulnerability Streams

OBJECT ID	DOW_NAME	Quintile	Composite Score	Stream Length Miles	Watershed Size Sq Miles	M7D10Y Low Flow	Mean Annual Precip	Mean Basin Elevation	Mean Basin Wall Slope	% Area watershed above 7500ft	Elevation of Stream Mouth	Headwtrs elevation	Average Gradient	Miles by Category
112	Lost Canyon Creek (All)	5	30	26.15	1	4	5	5	1	5	5	3	1	
18	Silver Creek (Johnny Bull)	5	30	2.41	5	5	3	3	5	1	2	1	5	
140	Wildcat Creek	5	30	4.85	3	3	4	4	5	1	4	1	5	
123	Ryman Creek	5	32	4.30	3	3	5	4	5	1	4	3	4	
86	Clear Creek	5	33	2.87	4	5	5	5	1	1	4	5	3	
135	Taylor Creek Little	5	33	3.46	4	5	5	4	2	1	4	4	4	
120	Rio Lado	5	37	3.29	4	5	5	5	4	1	5	4	4	
136	Tenderfoot Creek	5	37	2.95	4	5	5	5	4	1	4	4	5	50.28

112	Lost Canyon Creek (All)	5	30
18	Silver Creek (Johnny Bull)	5	30
140	Wildcat Creek	5	30
123	Ryman Creek	5	32
86	Clear Creek	5	33
135	Taylor Creek Little	5	33
120	Rio Lado	5	37
136	Tenderfoot Creek	5	37

Ranking by Temperature Vulnerability

- Stream temperature measurements taken during the typical seasonal late-July/early August peak period in late afternoon at the Fourth Street Bridge in Dolores suggest that streams in lower and even mid elevations in the Study Area would likely be subject to approaching and even exceeding limiting thresholds for trout habitat as air temperatures warm over the next decades.
- How high up the watershed might warming issues reach?

Impact of Projected Warming by Elevation

Stream Temp: Degrees F at Elevation (feet) Dolores River/Snow Spur					
Date	**7000**	**8000**	**9000**	**10000**	
21-Jul-16	66	61	58	56	Partly cloudy and just after three days monsoon rain
27-Jul-16	76	66	66	65	Sunny and after four days sun
03-Aug	64	60	58	56	Raining @ 9 & 10k and just after 3 days monsoon rain
13-Aug-16	70	63	63	63	Clear afer three days no rain

	Increase ° F	7000 Ft	8000 Ft	9000 Ft
Baseline Temp °F		76	66	66
Hot and Dry				
2035	5.0	79.1	69.1	69.1
2070	9.0	81.5	71.5	71.5
Feast and Famine				
2035	3.0	77.8	67.8	67.8
2070	5.5	79.4	69.4	69.4
Warmer and Wetter				
2035	2.0	77.2	67.2	67.2
2070	3.5	78.1	68.1	68.1

Species	Chronic F°	Acute F°
Cutthroat	62.6	71.8
Brook	64.9	71.1
Rainbow	64.8	74.8
Brown	67.3	76.3

Impact of Projected Warming by Elevation

Stream Temp: Degrees F at Elevation (feet) Dolores River/Snow Spur					
Date	7000	8000	9000	10000	
21-Jul-16	66				soon rain
27-Jul-16	76				
03-Aug	64	60	58	56	Raining @ 9 & 10k and just after 3 days monsoon rain
13-Aug-16	70	63	63	63	Clear afer three days no rain

Baseline° by elevation

	Increase ° F	7000 Ft	8000 Ft	9000 Ft
Baseline Temp °F		76	66	66
Hot a				
				9.1
				71.5
Feast				
				7.8
				9.4
Warn				
2035	2.0	77.2	67.2	67.2
2070	3.5	78.1	68.1	68.1

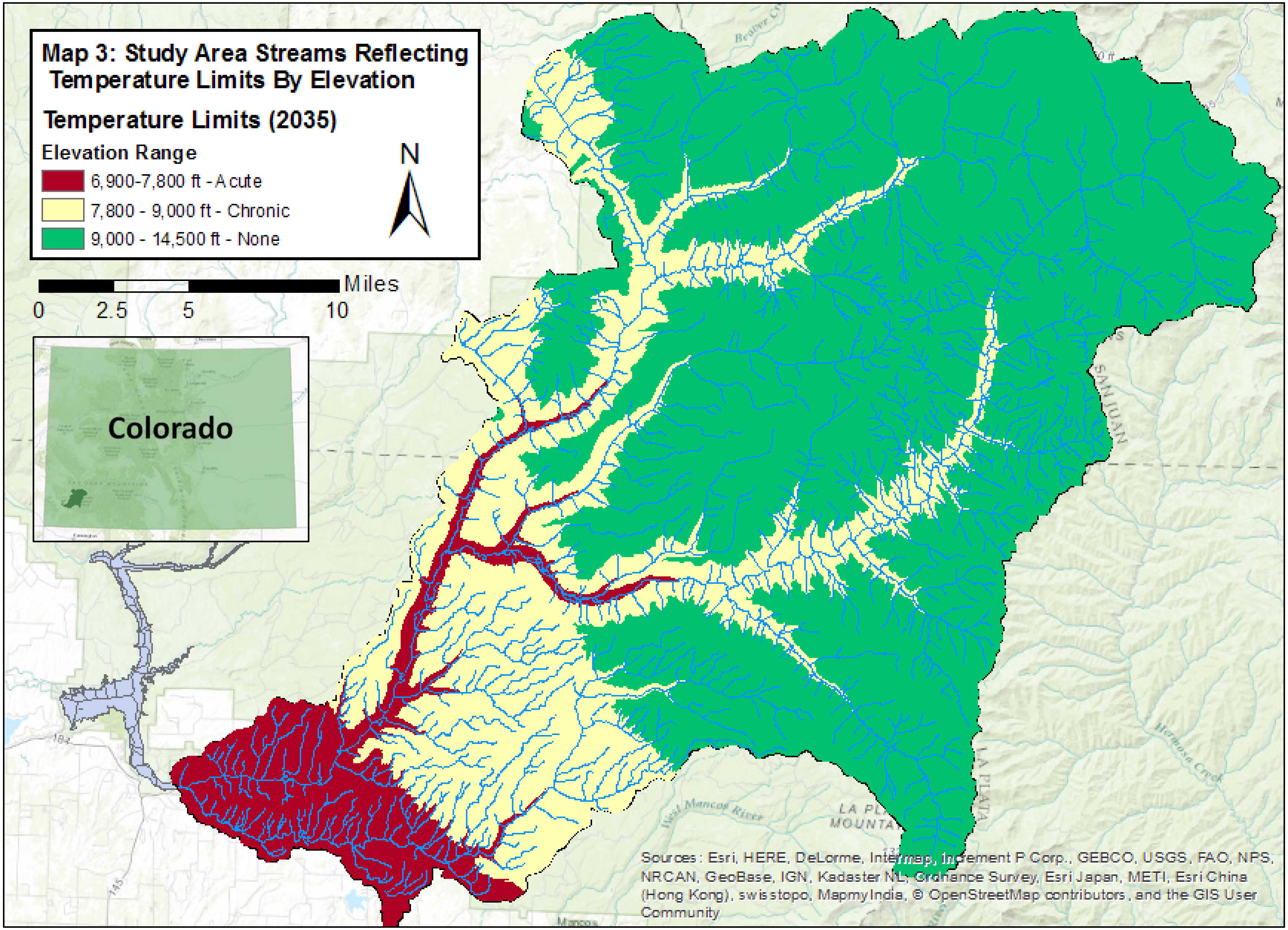
Projections° by elevation

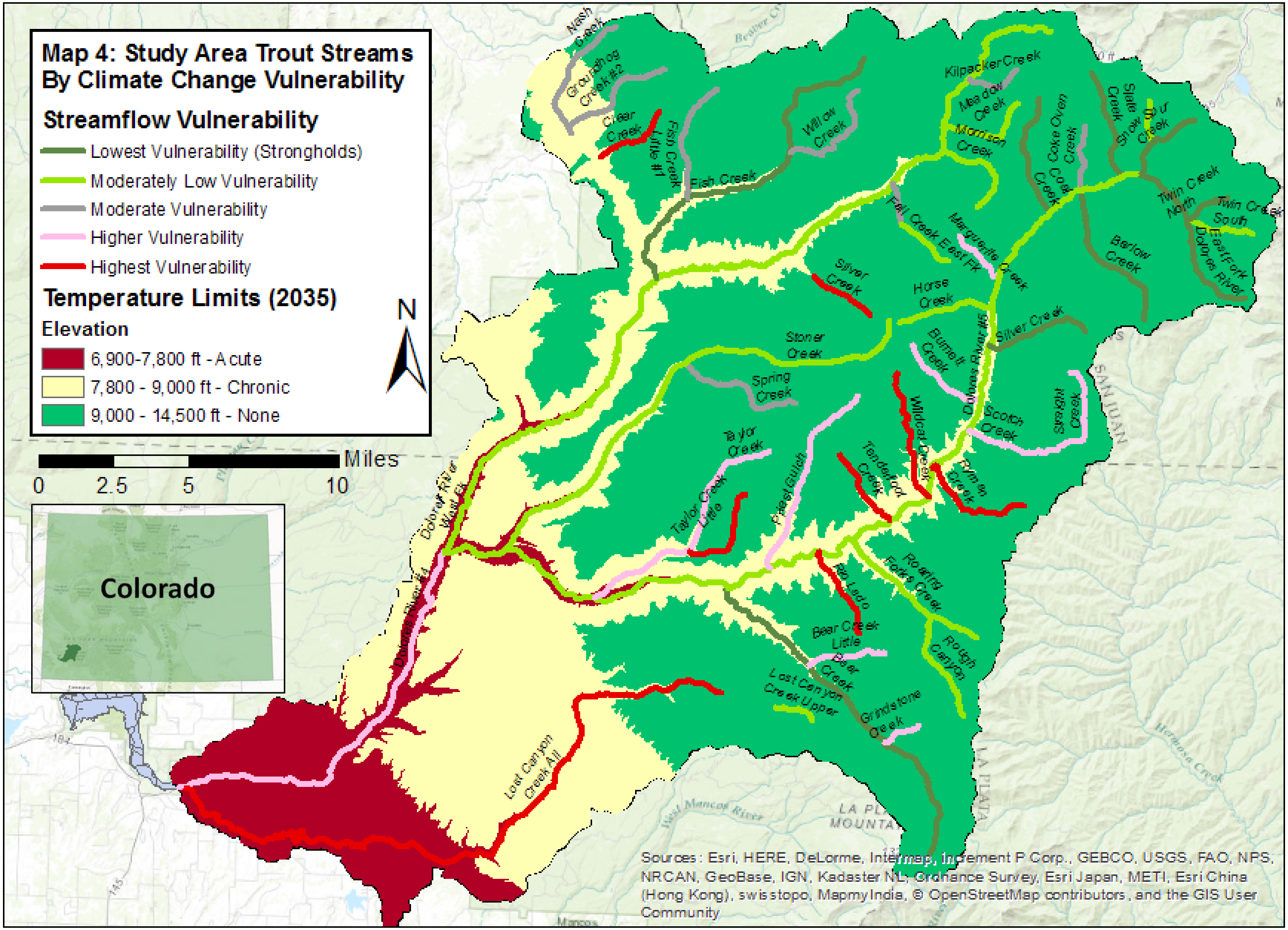
Species	Chronic F°	Acute F°
Cutthroat	62.6	71.8
Brook		71.1
Rainbow	64.8	74.8
Brown	67.3	76.3

Limits°

Observations: Temperature Vulnerability

- Dolores River
  - Sampling indicates that chronic limits are already being reached on hot summer days in July up to about 7600 feet.
  - Going up-river, initial projections indicate that water temperatures could well reach acute limits by the bridge at Hillside Drive (8000 feet) and may well reach as high as just above Rico (9000 feet).
  - Much of the lower reach of the Dolores (especially below the confluence with the West Dolores) lacks cover and can be quite shallow during the late summer/fall period, making that reach particularly susceptible to rapid temperature rise on clear days with high temperatures, especially so during periods of sustained high temperatures.
  - With increasingly prolonged drought (and associated clear skies), low flows would increase the rate, extent and duration of daily warming.
- West Dolores
  - There are reaches on the West Dolores around and below Dunton that, while at higher altitude, experience sluggish flow, have shallow depth and are highly exposed to direct sunlight. No temperature data exist for these reaches. These reaches likely will have issues, too.


Map 3: Study Area Streams Reflecting Temperature Limits By Elevation
Temperature Limits (2035)
Elevation Range
6,900-7,800 ft - Acute
7,800 - 9,000 ft - Chronic
9,000 - 14,500 ft - None
N
Miles
0
2.5
5
10
Colorado
SAN JUAN
LA PLATA
West Mancos River
Hermosa Creek
Sources: Esri, HERE, DeLorme, Intermap, Increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community


Map 4: Study Area Trout Streams By Climate Change Vulnerability
Streamflow Vulnerability
Lowest Vulnerability (Strongholds)
Moderately Low Vulnerability
Moderate Vulnerability
Higher Vulnerability
Highest Vulnerability
Temperature Limits (2035)
Elevation
6,900-7,800 ft - Acute
7,800 - 9,000 ft - Chronic
9,000 - 14,500 ft - None
N
Miles
0 2.5 5 10
Colorado
Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

What strategic management strategies emerge as most relevant?

Mapping our Journey Through CAMF

- How is climate change likely to affect our trout fisheries? Where are our strongholds?

Trout habitat limiting factors "state of the science"

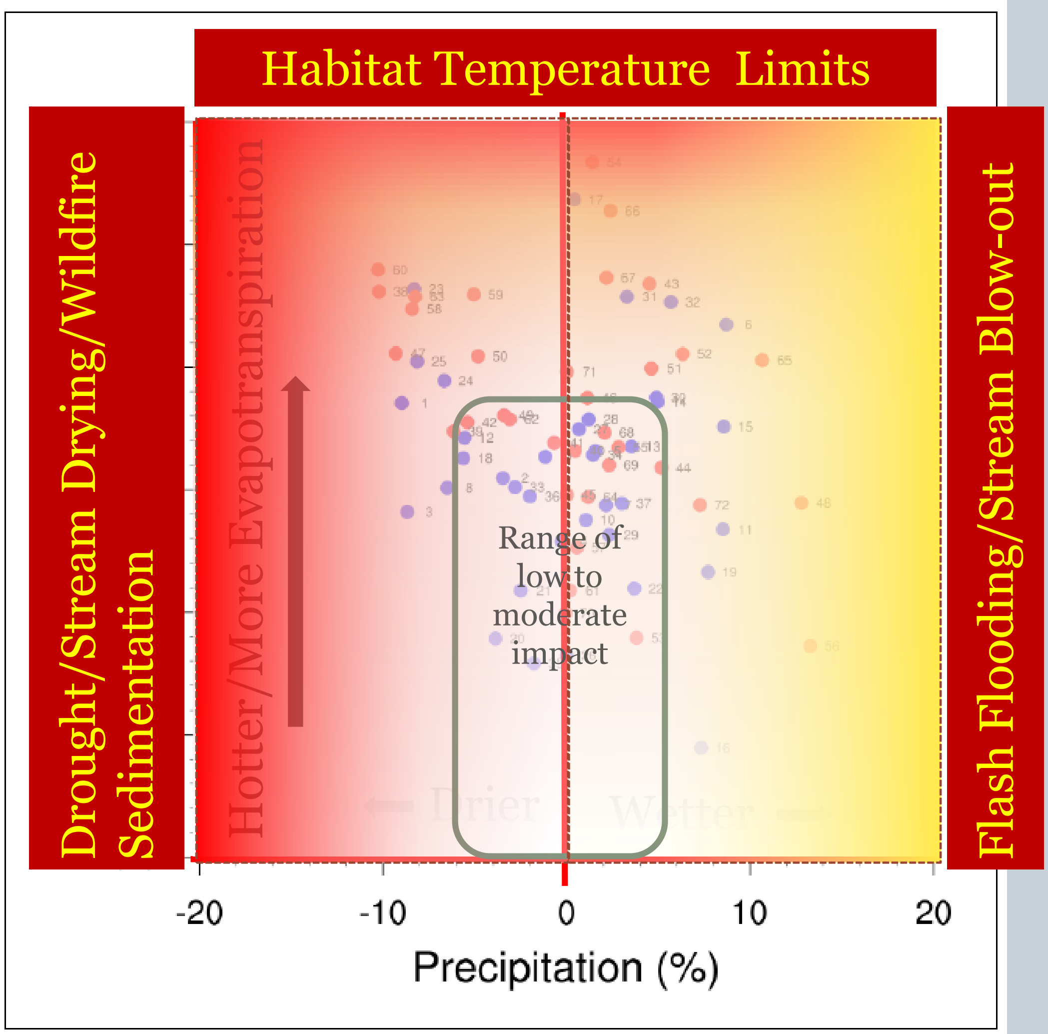
Climate change modeling, esp. for Southwest, Colorado

Downscale to San Juans, vulnerability analysis

Adaptive management considerations

Vulnerability>Adaptability: Integrated Framework

Key to managing ecological vulnerability is managing habitat resistance (capacity to withstand disturbances) and resilience (capacity to recover from disturbances).



Resistance (1)

- The key to resistance is "refugia."
  - Refugia requires:
    - A sustained appropriate temperature range for the entire food chain
    - Protective cover from predators, UV
    - Respite from flow, especially during periods of intense high flow
    - Continuous sufficient depth (minimum of ~ 10")
  - Refugia usually takes the form of pools in larger streams and pockets in smaller streams.
  - Enhancing refugia is an obvious management strategy; unfortunately, due to the heavy equipment often required for major enhancements and the "back country" nature of the Study Area, streams other than those lying next to a road could be very challenging to access.
  - Field-crew-type Best Management Practices (pool/pocket enhancements) are highly relevant, but at smaller scale, for our many miles of back country streams.

Classic Pocket Refuge on Upper Fish Creek

Resistance (2)

Resistance can be strengthened by:

- Modifying stream morphology to compensate for periods of increased intensity in stream flow can protect spawning grounds.
- Installing barriers to upstream passage can reduce competition from warmer water species and protect native trout reaches from non-native.
- Targeting forestry pre-treatment to reduce the probability of wildfires for key stream reaches can reduce the risk of associated sediment flow.
- Restoring/protecting riparian cover, especially in lower elevations, reduces the impact of temperature rise.
- Restoring riparian areas quickly after fire enhances recovery of habitat.
- Treating mine waste at a level that anticipates concentration of pollutant loads as water volume decreases due to drought can preserve fishable reaches.

Resilience

- The very good news: our watershed – and its associated trout habitat - has survived three substantial droughts in the past 15 years (each greater that two years).
- While some streams did become seasonally intermittent (and some completely dry) and all reduced substantially in size and flow, *all seem to have recovered with currently viable trout populations.*
- Likewise, paleoclimate studies indicate several 25+ year droughts in the past 1000+ years, yet trout populations still thrive locally.
- Research indicates that trout can show substantial DNA adaptation in as little as 10 - 20 generations – about 40 - 80 years*.
- What is unknown is over how many drying cycles and of what intensity habitat and populations can recover from over the long run.

*Climate Change, Aquatic Ecosystems & Fishes in Rocky Mtns.pdf

Potential Management Strategies

- In stream construction: Consider carefully-selected in-stream and near-stream morphological modifications where cost effective (focusing larger investments on long range strongholds). Protecting, enhancing and creating pools/pockets is essential as is sustaining and providing riparian cover.
- Increased regulation: As more fishermen become concentrated within a steadily reducing habitat range, more regulation such as strictly catch and release, reach closure/rotation, barbless (dry?) flies only, and even sign up periods for specific reaches may have to be introduced. More wildlife officers will likely be required.
- Integrated management: As the forests become dryer and ecosystems and habitats change, coordination between Colorado Parks & Wildlife, National Forest Service and National Park management teams across disciplines (hydrology, fire management, road and trail maintenance, etc.) becomes vital.
- Coordination with water users : Coordination with local water districts, irrigation companies, etc. becomes critical as flow diminishes and irrigation increases.
- Low impact philosophy: Public outreach to inculcate a value of low impact use of all lands, but especially public lands, becomes increasingly important.

Wrap-up

Key Take-Away Points (1)

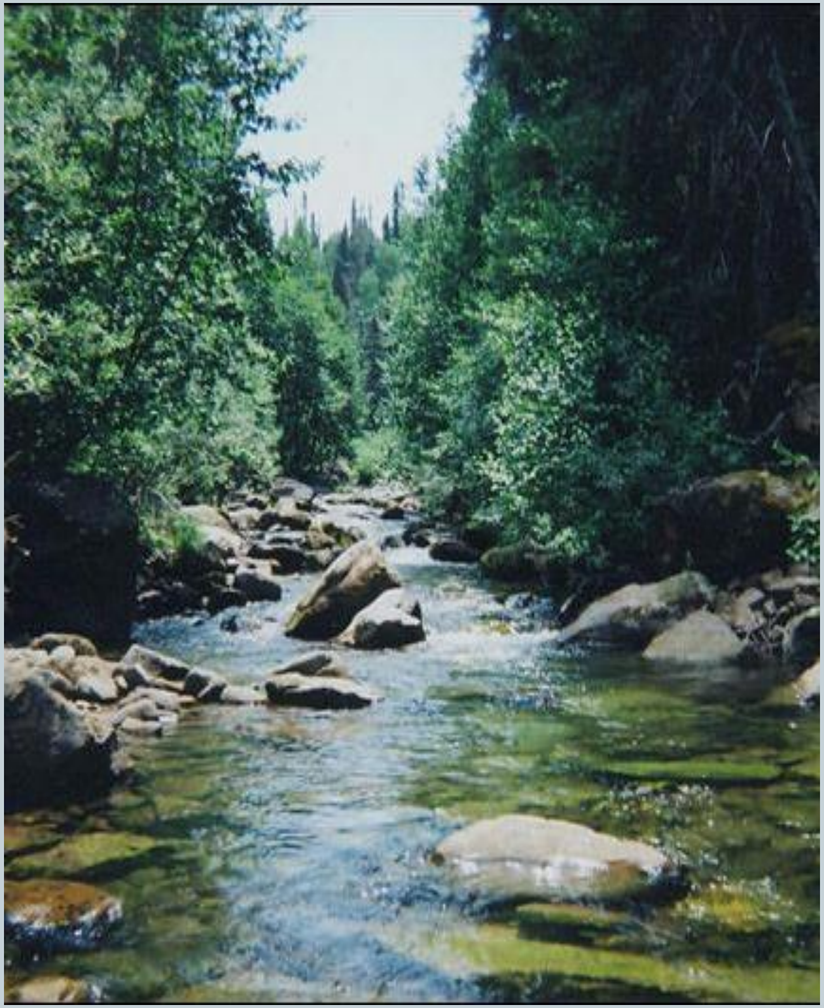
- If drought intensity and duration increases and stream temperatures rise through 2100 as simulated:
  - Many quintile 4 and 5 streams (highest and higher vulnerability) could become supra-annually intermittent, some by 2035; then annually intermittent by late mid century.
  - Many quintile 3 streams (moderate vulnerability) could become supra-annually intermittent by mid-century, then could become annually intermittent by late century depending on the severity of the actual climate change pathway.
  - Quintile 1 and 2 streams [lowest (stronghold) and lower vulnerability] could reduce in flow as feeders reduce in flow or dry up, and base flow and soil moisture reduces.
- If precipitation increases substantially, stream velocity and volume become substantial challenges to habitat by scouring stream channels and wiping out refugia, especially should extreme storm events coincide with key spawning stages (spring and early summer for cutthroat and rainbow and fall for brook and brown).

Key Take-Away Points(2)

- Temperatures in lower, more exposed reaches could rise, with seasonal peak periods likely approaching limiting levels in the lower Dolores from Fourth Street bridge up to perhaps as high as Hillside Bridge and even Rico, and in slow, shallow, open reaches of the West Dolores around and below Dunton.
- The rate and degree of impact will depend largely on the extent to which greenhouse gasses are mitigated.
- Aggressive climate change mitigation will likely lead to only modestly worse conditions than what has been experienced since the turn of this century.
- However, worst case scenarios, those where virtually no effective action is taken (leading to 25 year super-droughts with high 8 to 10 degree air temperature increases), could see an extensive elimination of all but the most resistant/resilient fisheries by 2100 (from ~295 miles of currently viable fisheries to perhaps as little as 80).

Ending Thoughts…

- The engines driving climate change are massive. Many streams/reaches in our Study Area will face very serious challenges as they approach 2100.
- Some will respond well to carefully selected mitigation efforts.
- Many, though, may well be outside the range of cost effective management over the long-run and will either become warmer-water fisheries or will simply dissipate.
- To paraphrase Reinholt Neibuhr's famous Serenity Prayer, "may we have the wisdom to know the difference".



Questions & Discussion

Thanks!