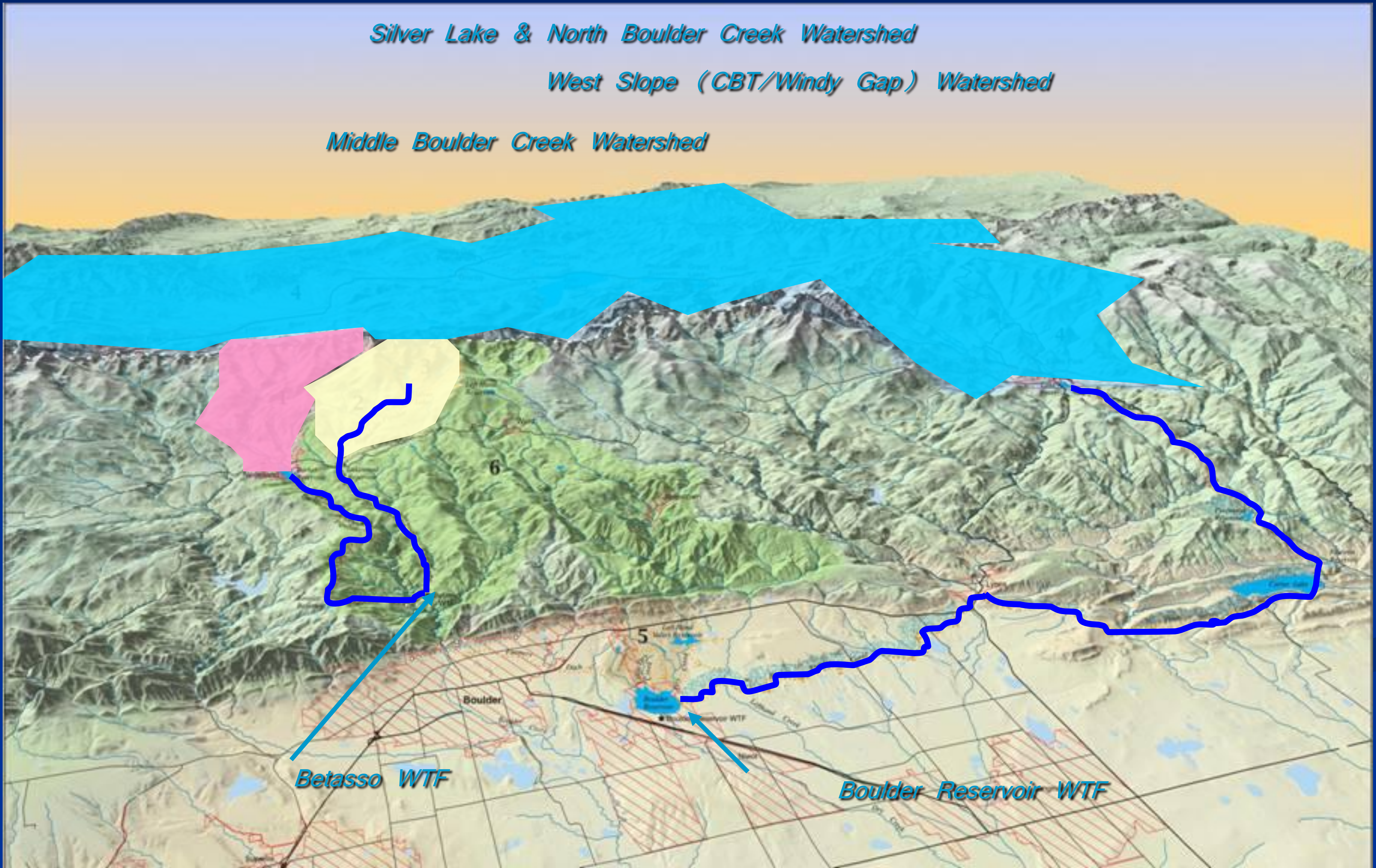
Boulder's Experiences Planning for Drought and Climate Change

Lee Rozaklis
AMEC Earth & Environmental
Boulder, Colorado
lee.rozaklis@amec.com

Water System Overview



Boulder's Water Use

- 113,000 people, 102,000 jobs in service area
- 65% indoor use, 35% outdoor use
- 63% residential, 27% commercial/industrial, 3% municipal, 7% losses
- System-wide use of 154 gpcpd (average of 2003-2007)

Planning Evolution

- 1988: Comprehensive model (the Boulder Creek Model)
- 1989: Water supply reliability criteria
- 2001: Tree ring data used in model
- 2002: Drought plan, incorporated into model
- 2006: NOAA-supported climate change study

Water Supply Reliability Criteria

Boulder does not plan to satisfy all of its customers' water demands in all droughts

- Reliability criteria adopted by Council in 1989, with much public input
- Struck a balance between costs of supply development and effects of restrictions
- Water deliveries based upon drought severity
- Goal: meet all water needs in 19 of 20 years

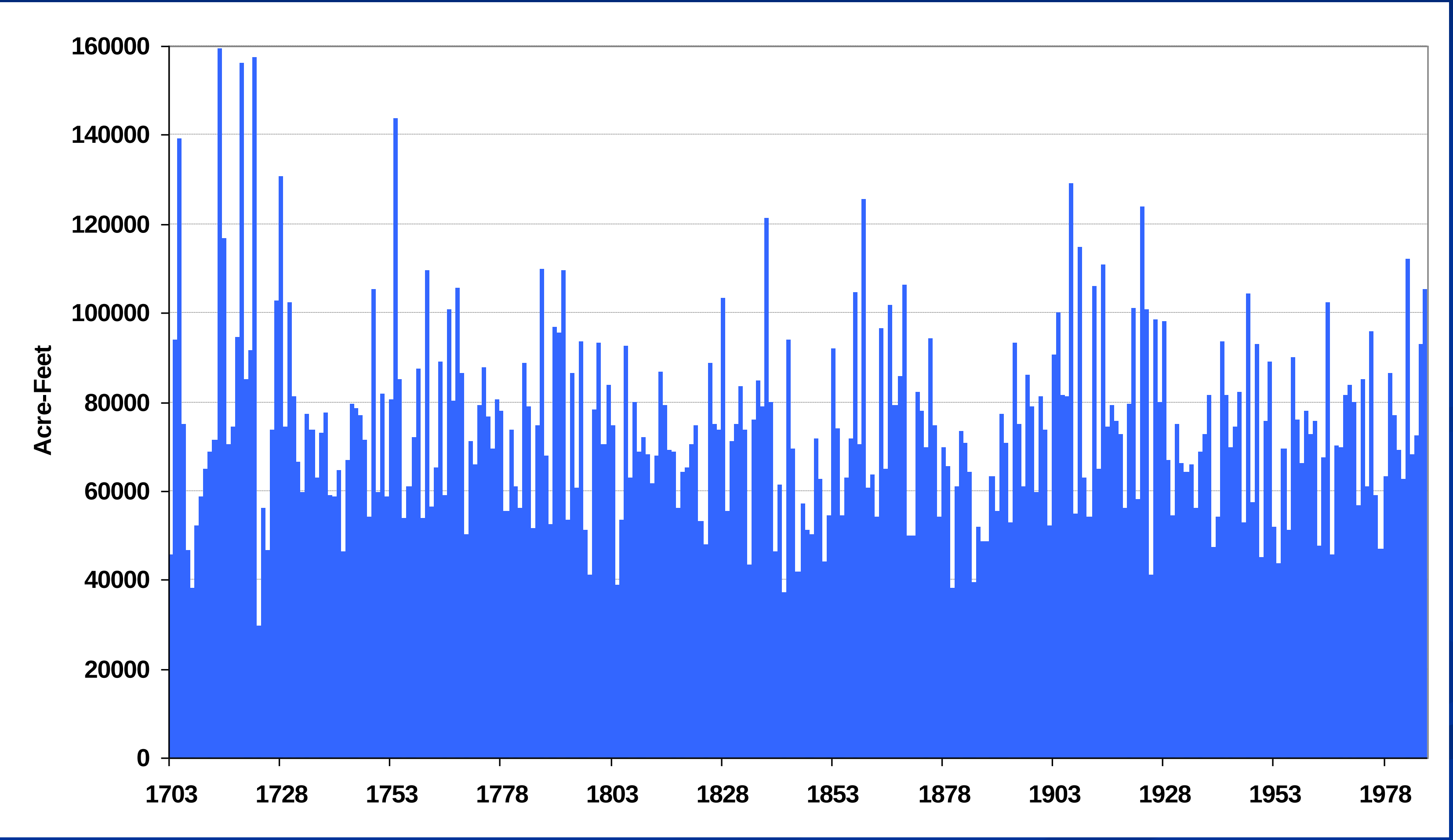
Water Supply Reliability Criteria

- Up to 1-in-20 year severity: satisfy all water needs
- 1-in-20 year to 1-in-100 year severity: minor to significant demand reductions, but maintain viability of landscaping
- 1-in-100 year to 1-in-1000 year severity: supply "essential uses" (indoor domestic, commercial, industrial, fire fighting), but may lose landscaping

Advantages of Reliability Criteria

- Help to address questions of water supply adequacy (how much is enough?)
- Allowable non-municipal uses of municipal supplies (i.e. instream flows, ag leasing)
- A more useful water supply planning approach (reliability assessment rather than firm yield modeling)

Tree Ring-Based Hydrology



Advantages of Using Tree Ring Data

- More robust examination of water supply reliability
- More sophisticated system operating rules
- More realistic perspectives for citizens and decision makers

Boulder's Drought Plan

- Guidance for drought response
- Related to water supply reliability criteria
- Drought recognition and response based on drought severity
- Drought alert stages, invoked by drought response triggers

Drought Alert Stages

Drought Alert Stage	Description	Annual Water Use Reduction Goal	Irrig. Season Water Use Reduction Goal
I	Moderate	8%	10%
II	Serious	14%	20%
III	Severe	22%	30%
IV	Extreme	40%	55%

Drought Response Triggers

- Specific, objective determinations
- Made on May 1 of each year
- “Projected Storage Index”, based upon:
  - storage in Boulder Creek reservoirs
  - Boulder’s current CBT supply (quota, carryover)
  - Boulder Creek snowpack readings
  - Boulder’s unrestrained demand

Projected Storage Index

Projected Storage Index	Drought Alert Stage
Greater than 0.8	None
Between 0.8 and 0.7	I
Between 0.7 and 0.55	II
Between 0.55 and 0.4	III
Less than 0.4	IV

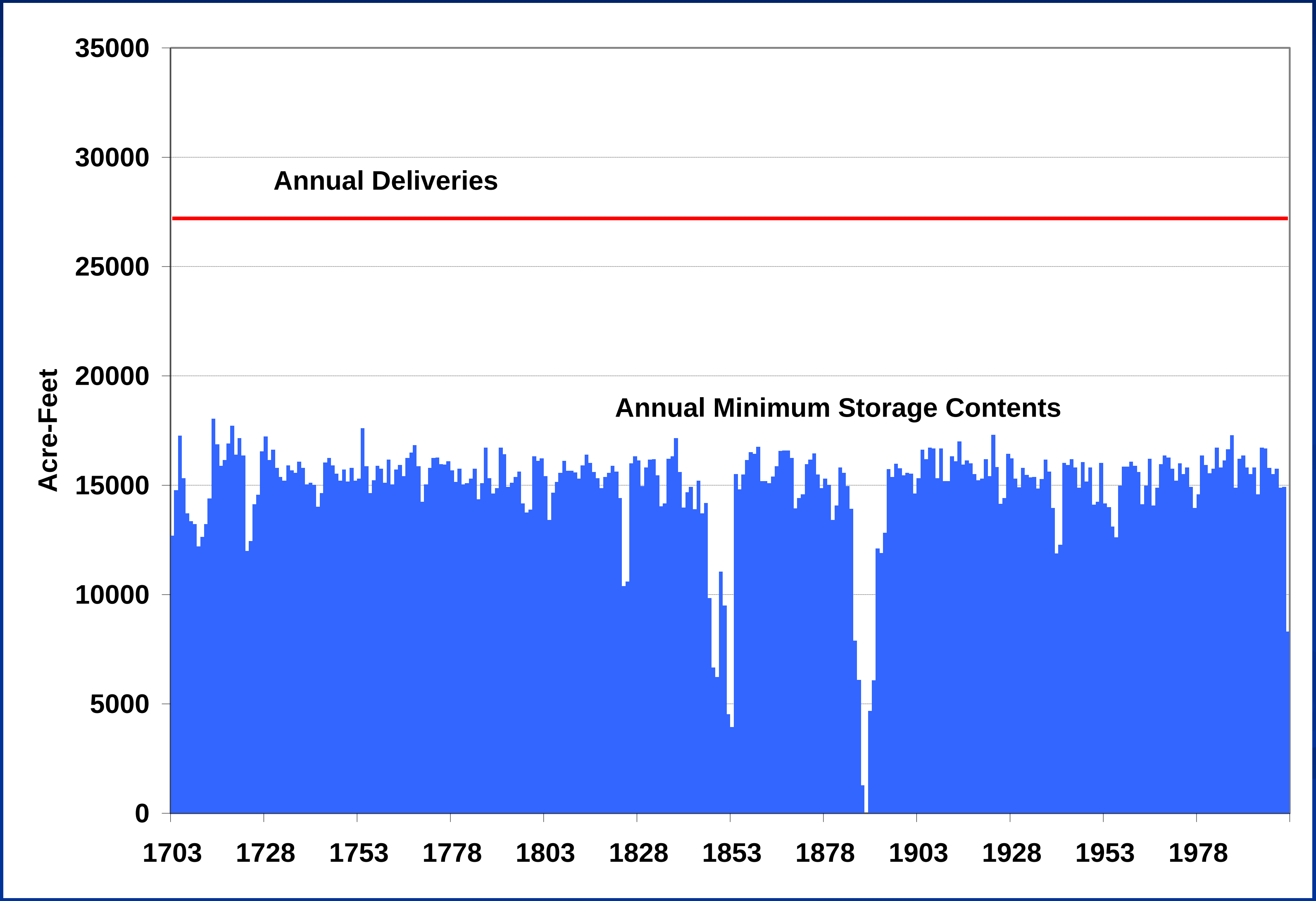
Derivation of Drought Response Triggers

- Projected storage index and demand reduction responses built into model

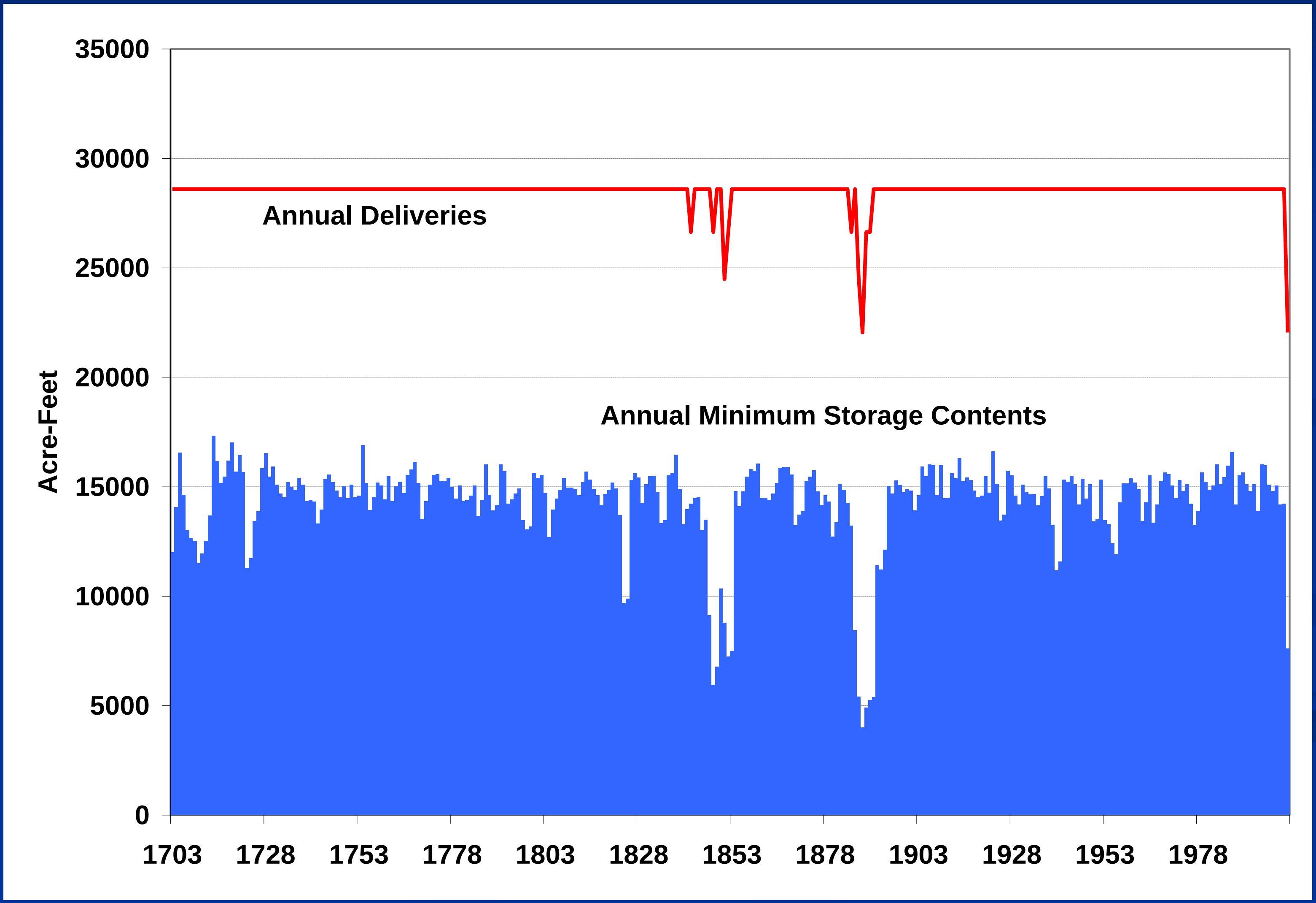
- Iterative model runs
  - build-out demand + 10% safety factor
  - tree ring-based hydrology and demands
  - adjusted storage index parameters and relationships to Drought Alerts to minimize demand reductions

- Input from water utility managers and operators

Before: Firm Yield Modeling



Now: Incorporating Drought Response into Modeling

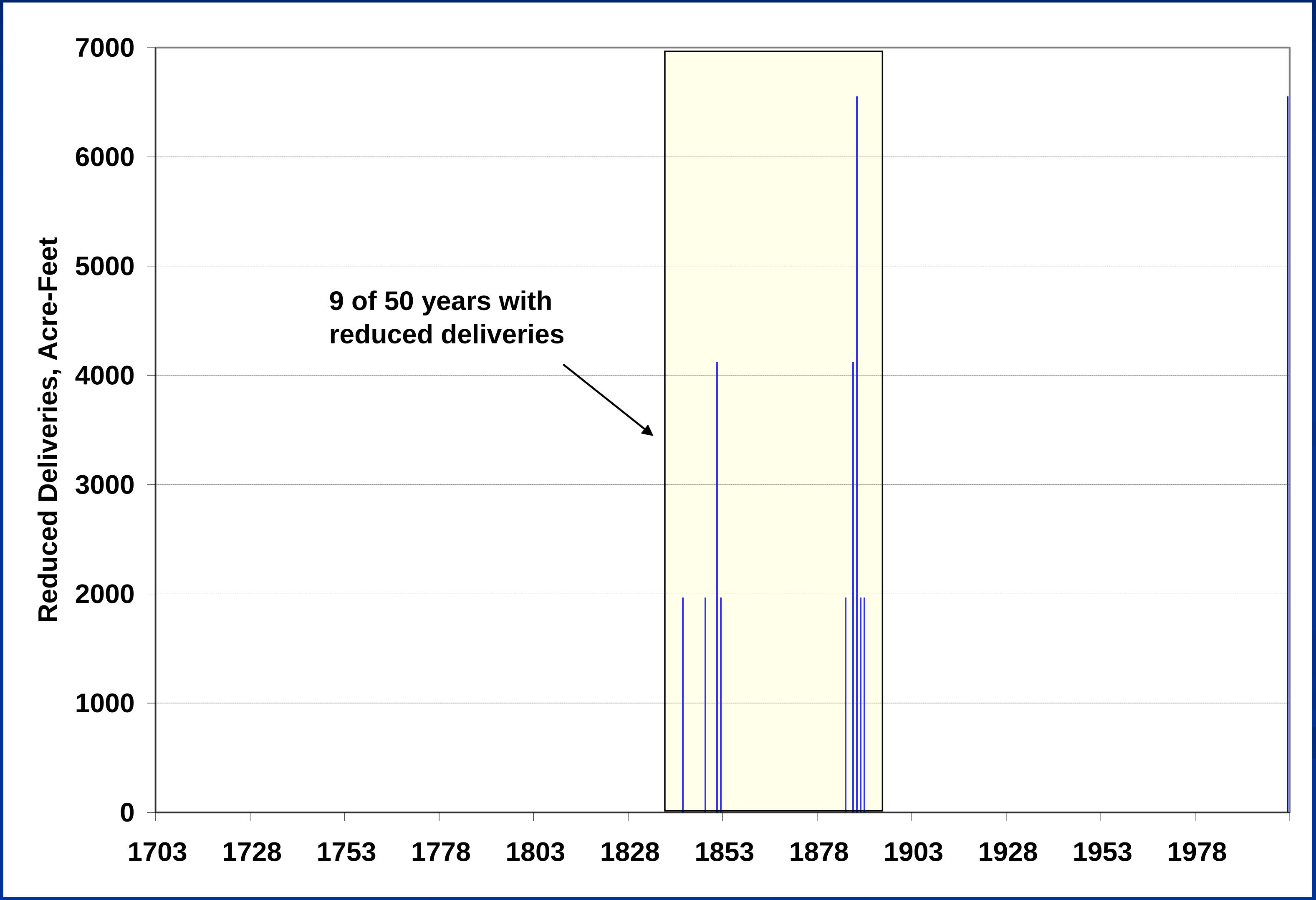


Drought Plan Finding:

- "Boulder's water supply system is capable of meeting its projected build-out demands plus a safety factor in a manner consistent with Boulder's adopted reliability criteria"

Drought Alert Stage	Number of Years
Full demand met	290
Level I	6
Level II	2
Level III	2
Level IV	0

But, drought impacts are not evenly distributed



Sensitivity of Boulder's Water Supply to Climate Change

Study Team

- Joel Smith (Stratus) project coordination, climate scenarios
- Ken Strzepek (University of Colorado) and KC Hallett (Stratus) developed runoff model, applied paleoclimate data and estimated runoff changes
- Lee Rozaklis, AMEC (formerly Hydrosphere) estimated changes in demand and ran Boulder Creek Watershed Model
- Carol Ellinghouse, City of Boulder representative and advisor
- Advisors
  - Tom Wigley, NCAR on climate change scenarios
  - Connie Woodhouse provided paleoclimate scenarios
  - Rajagopalan Balaji (CU) advised on applying paleoclimate data

Approach

1. Develop scenarios of temperature and precipitation change

2. Generate hydrology, apply to tree ring reconstructions

3. Use Boulder Creek Model to incorporate water demands, water rights and facilities.

4. Assess likelihood of exceeding Boulder’s reliability criteria in 2030 and 2070

5. Work with Boulder to review results and consider appropriate responses

Climate Change Scenarios

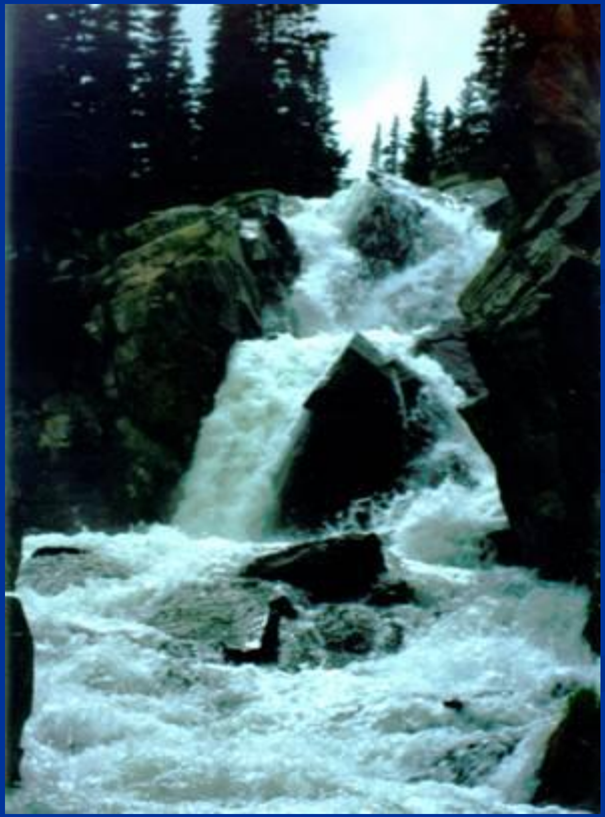
- 4 global climate models
- 3 greenhouse gas emission scenarios
- 2030 and 2070 climate conditions

Summary of Scenarios

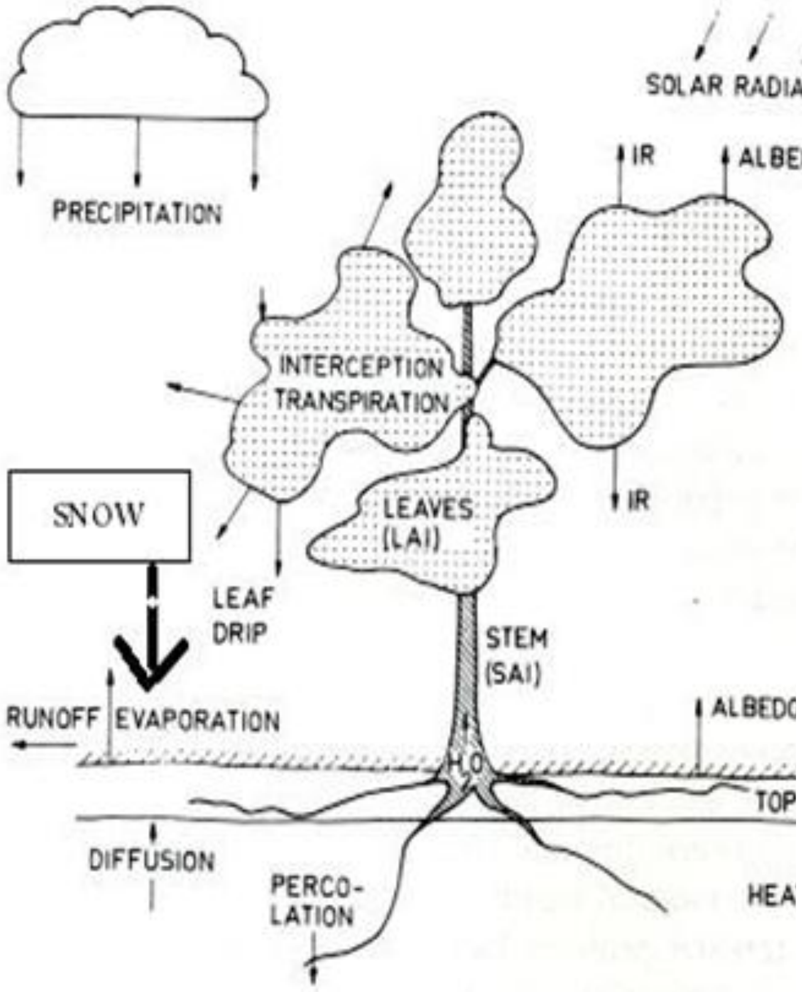
- Temperatures virtually certain to rise

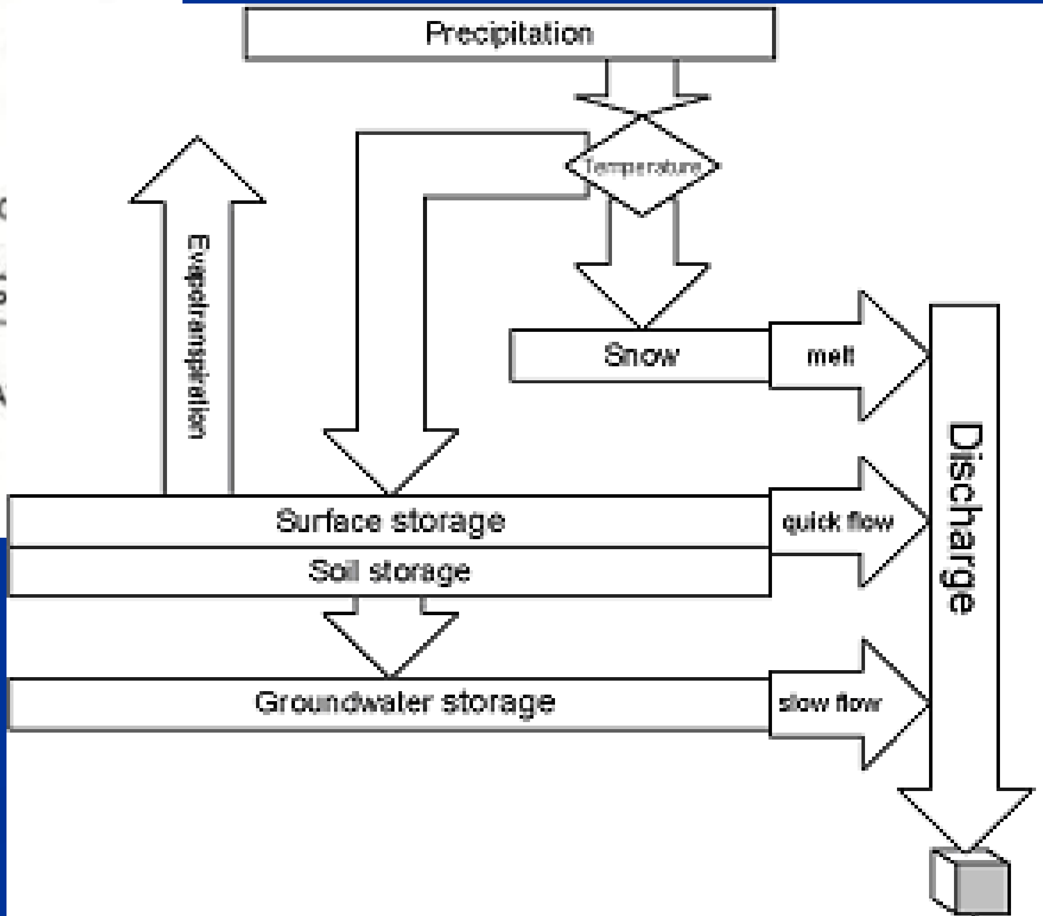
- Change in precipitation uncertain
  - ~ ½ of models project increase; ½ decrease
  - Drier to southwest; wetter to north
  - Climate models tend to show
    - Wetter winters
    - Drier summers

Estimating Effect of Climate Change on Runoff

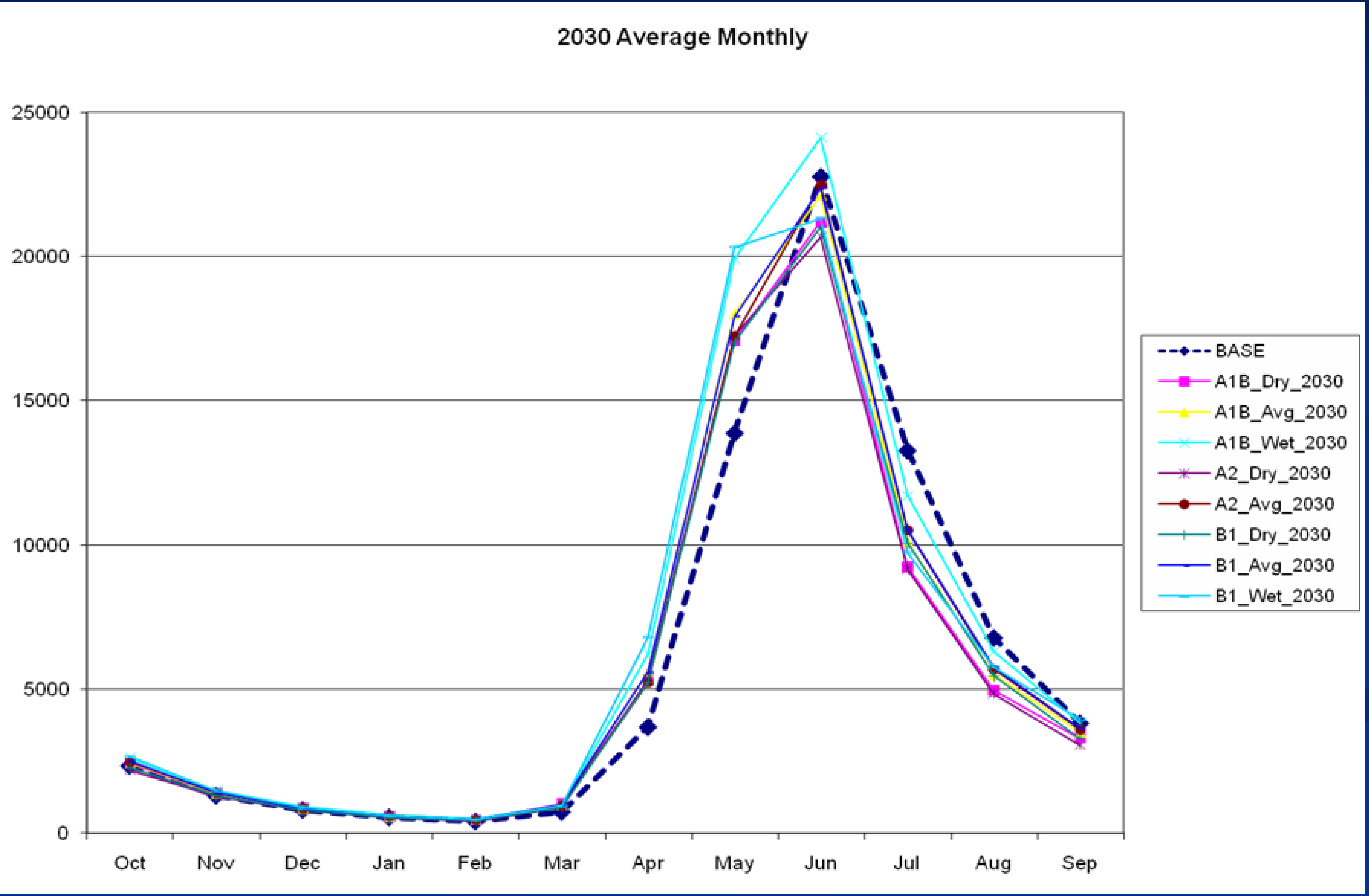


CLIRUN-2 HYDROLOGIC MODEL

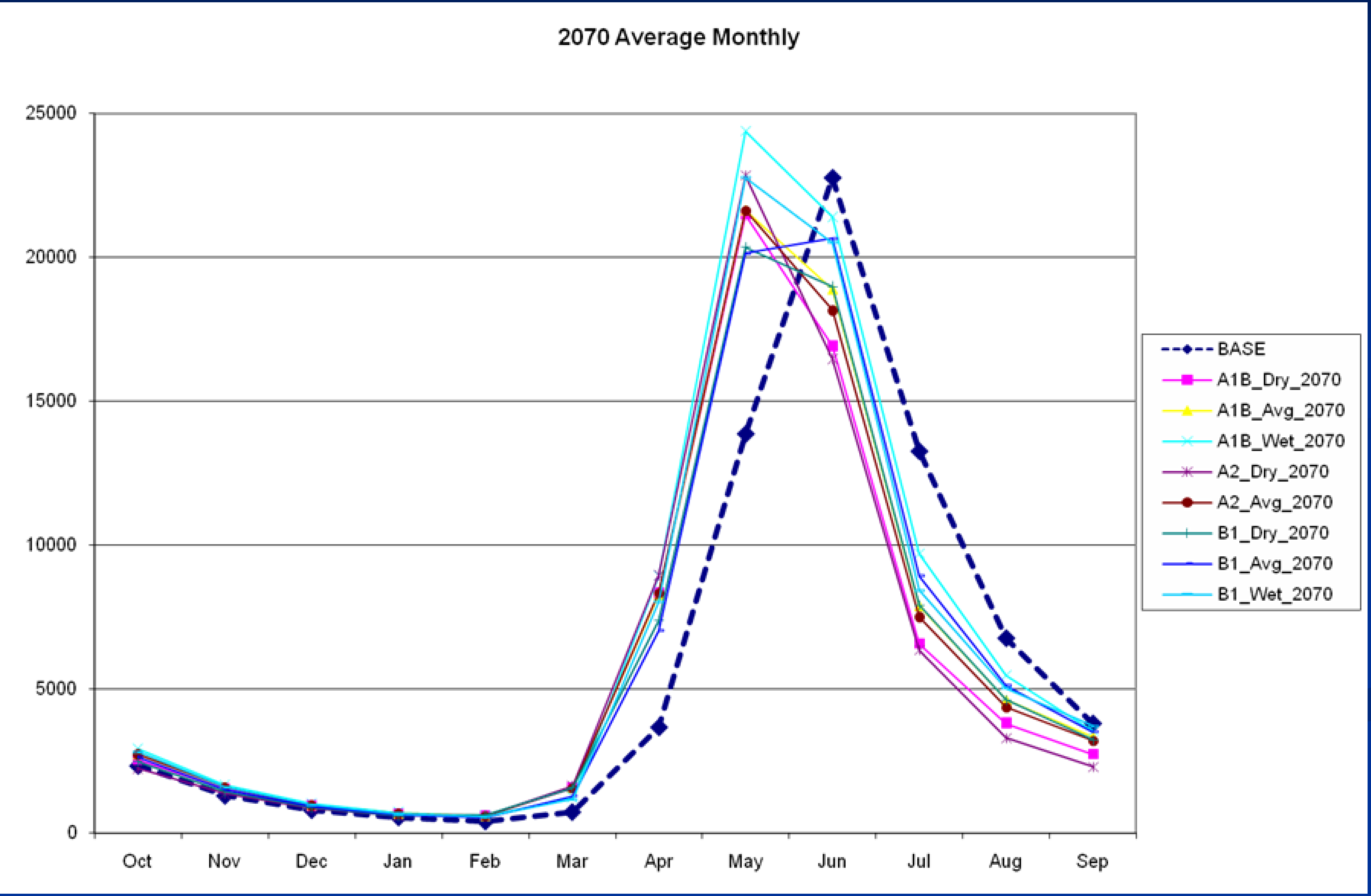




Boulder Creek Near Orodell - 2030



Boulder Creek Near Orodell - 2070



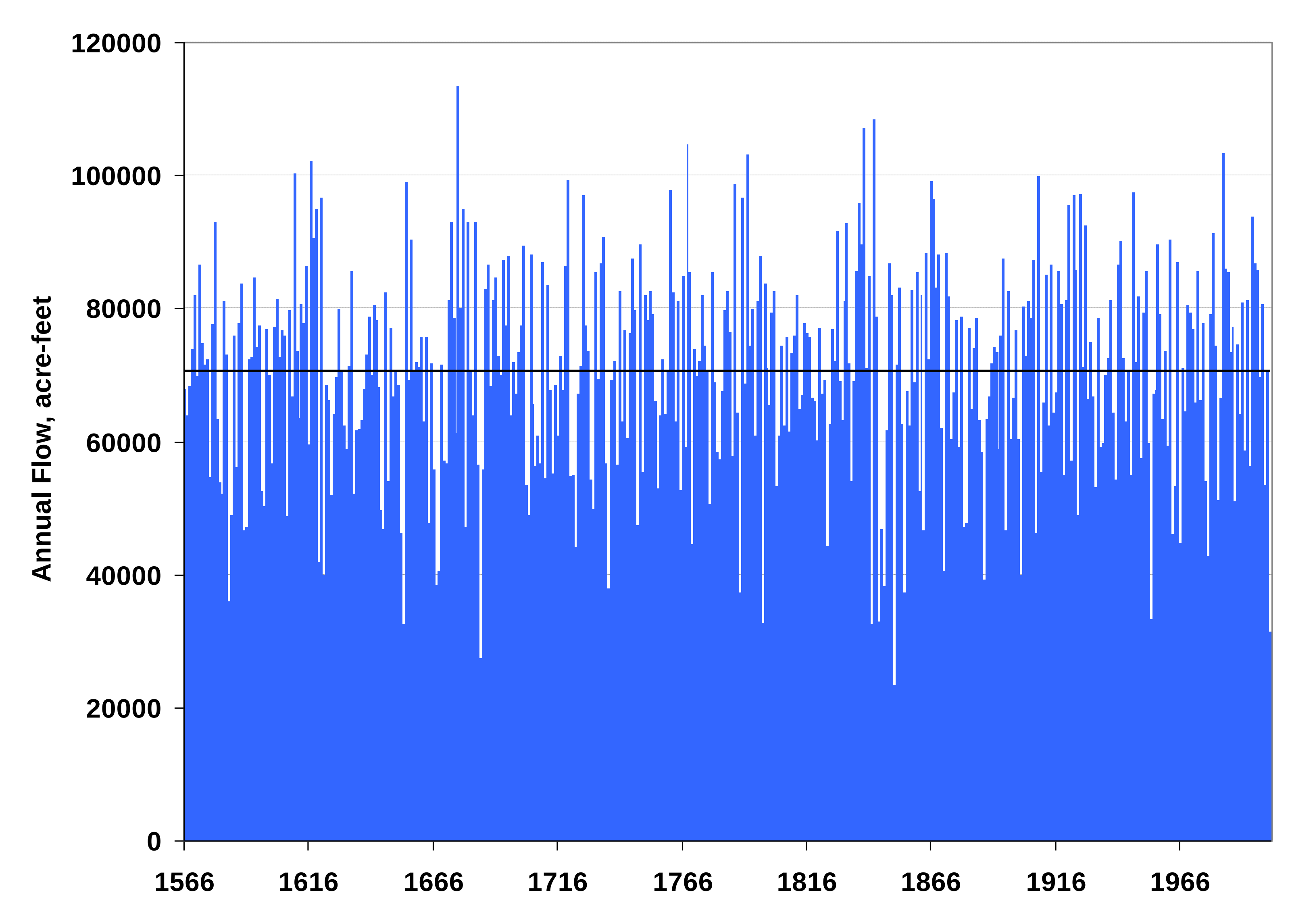
Seasonal Change in Flow

Scenario	Annual	Winter	Spring	Summer	Fall
Base Case	0%	0%	0%	0%	0%
B1 Wet 2030	7%	19%	19%	-18%	15%
B1 Mid 2030	-2%	4%	13%	-28%	-7%
B1 Dry 2030	-3%	9%	7%	-21%	-1%
A1B Wet 2030	12%	21%	24%	-8%	14%
A1B Mid 2030	-2%	5%	13%	-25%	-12%
A1B Dry 2030	-4%	19%	8%	-26%	6%
A1B Dry3 2030	-6%	-3%	2%	-23%	0%
A2 Mid 2030	-1%	8%	10%	-22%	4%
A2 Dry 2030	-5%	8%	7%	-28%	-2%
B1 Wet 2070	9%	38%	27%	-28%	23%
B1 Mid 2070	0%	23%	16%	-27%	2%
B1 Dry 2070	0%	62%	15%	-34%	9%
A1B Wet 2070	16%	45%	35%	-21%	27%
A1B Mid 2070	5%	46%	25%	-35%	16%
A1B Dry 2070	-4%	65%	15%	-44%	12%
A1B Dry3 2070	-3%	32%	13%	-35%	7%
A2 Mid 2070	0%	47%	20%	-41%	11%
A2 Dry 2070	-4%	62%	19%	-49%	0%

Using the Paleo-Climate Record

Has not been done in climate change studies

New Tree Ring Reconstruction



Nearest Neighbor Approach

(1) Tree-ring reconstruction of annual streamflow: Boulder Creek at Orodell (Connie Woodhouse)

1566 — 2002

(2) Corrected annual virgin :
Boulder Creek near Orodell (Lee Rozaklis)

1907 — 2004

(3) Monthly mean and ,
Niwot Ridge – C1 (Mark Losleben, INSTAAR) &
Boulder (NOAA)

1953 — 2004

(4) There is a 50 year period over which the available data overlap (1953 – 2002)

Summary

- No significant change in annual flow
- Earlier runoff
- Larger peak
- Lower summer runoff
- Increased irrigation demand

Consequences for Boulder's Water Supply

The Boulder Creek Model

- All major aspects of Boulder Creek basin: hydrology, water rights, imports, exports, diversion/storage facilities, operating policies, water uses, return flows
- Operation of CBT and Windy Gap projects and deliveries to Boulder Creek users
- Calls by water rights downstream of Boulder Creek

Use of Boulder Creek Model in Climate Change Study

- Accounted for changes in runoff
- Accounted for changes in Boulder Creek and South Platte basin irrigation demands
  - Assumed no change in crop mix
- Assumed relatively high demand for Boulder (build-out plus 10% safety factor)
- Assumed no Colorado compact calls or inadequacies in CBT replacement supplies

Results

Summary of Results – Boulder's Water Supply

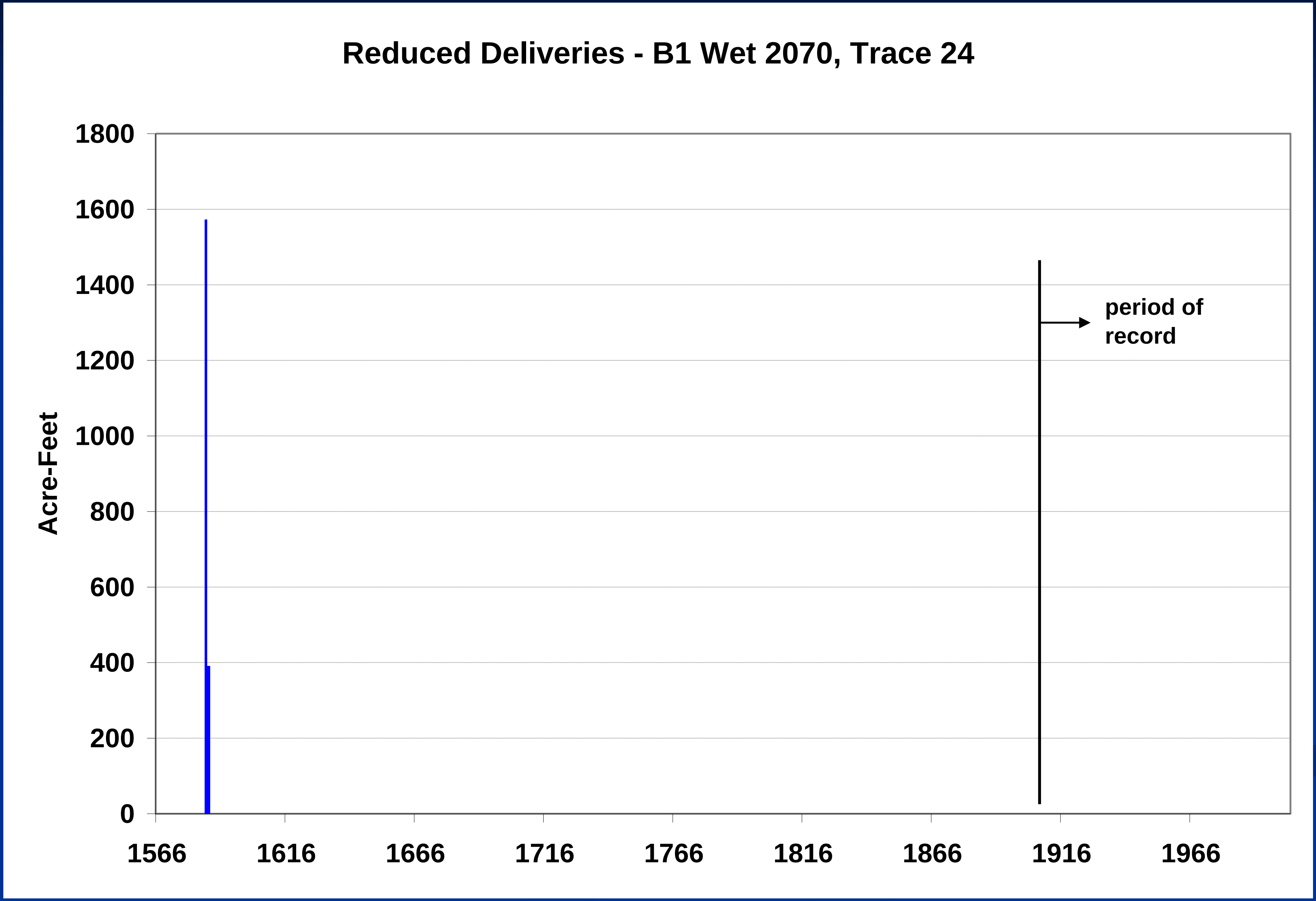
Emission Scenario	Model Type	Year	1-in-20 year criterion met?	1-in-100 year criterion met?	1-in-1000 year criterion met?
Drought Plan (300 years)			yes	yes	yes
BASE CASE			yes	yes	yes
B1	Wet	2030	yes	yes	yes
B1	Mid	2030	yes	yes	yes
B1	Dry	2030	**no**	yes	yes
A1B	Wet	2030	yes	yes	yes
A1B	Mid	2030	yes	yes	yes
A1B	Dry	2030	**no**	yes	yes
A1B	Dry3	2030	**no**	**no**	**no**
A2	Mid	2030	yes	yes	yes
A2	Dry	2030	**no**	yes	yes
B1	Wet	2070	yes	yes	yes
B1	Mid	2070	yes	yes	yes
B1	Dry	2070	yes	yes	yes
A1B	Wet	2070	yes	yes	yes
A1B	Mid	2070	yes	yes	yes
A1B	Dry	2070	**no**	yes	**no**
A1B	Dry3	2070	**no**	yes	yes
A2	Mid	2070	**no**	yes	yes
A2	Dry	2070	**no**	**no**	**no**

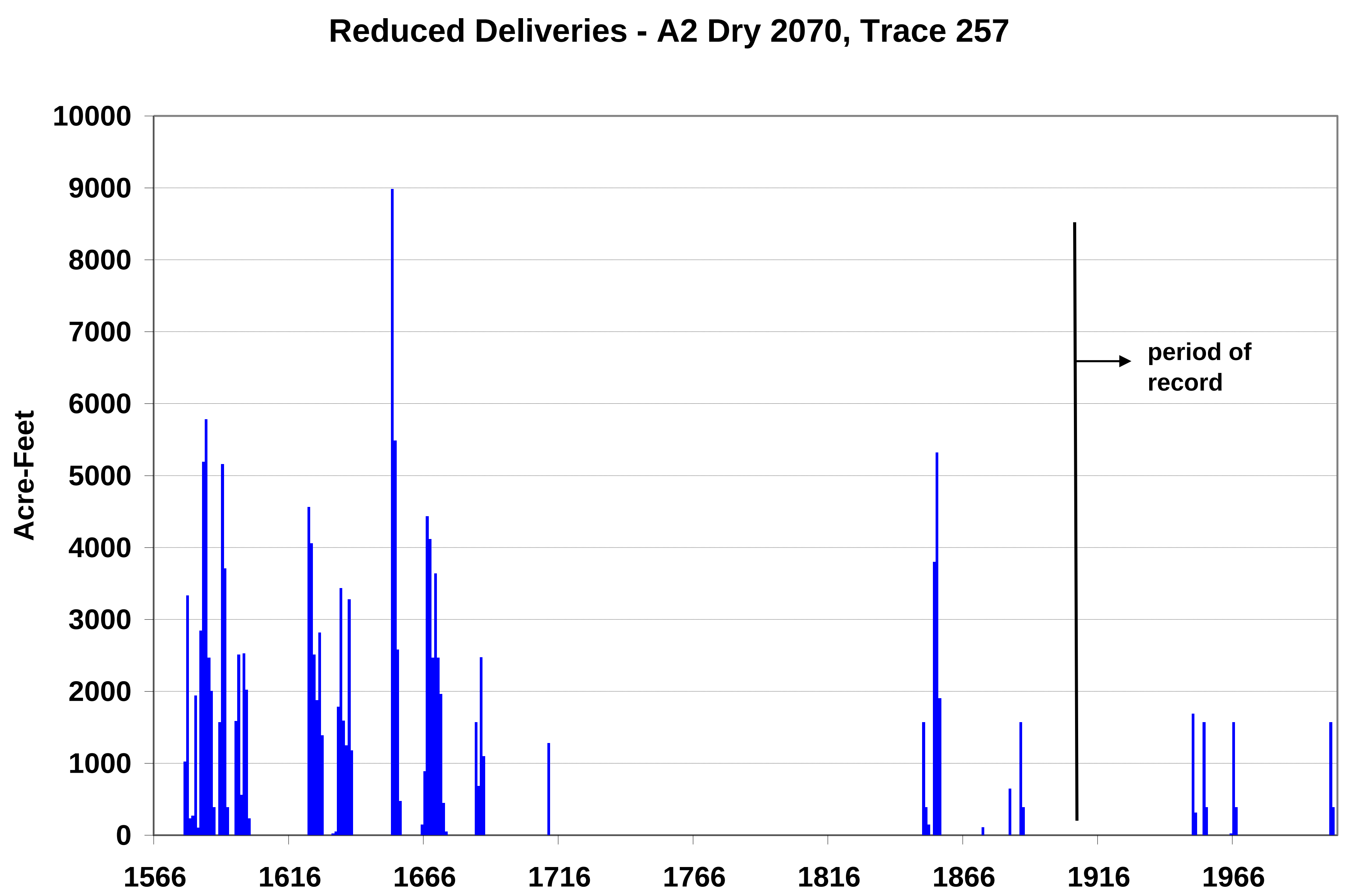
Note: "yes" = criteria met in each of the 11 traces

Summary of Model Results

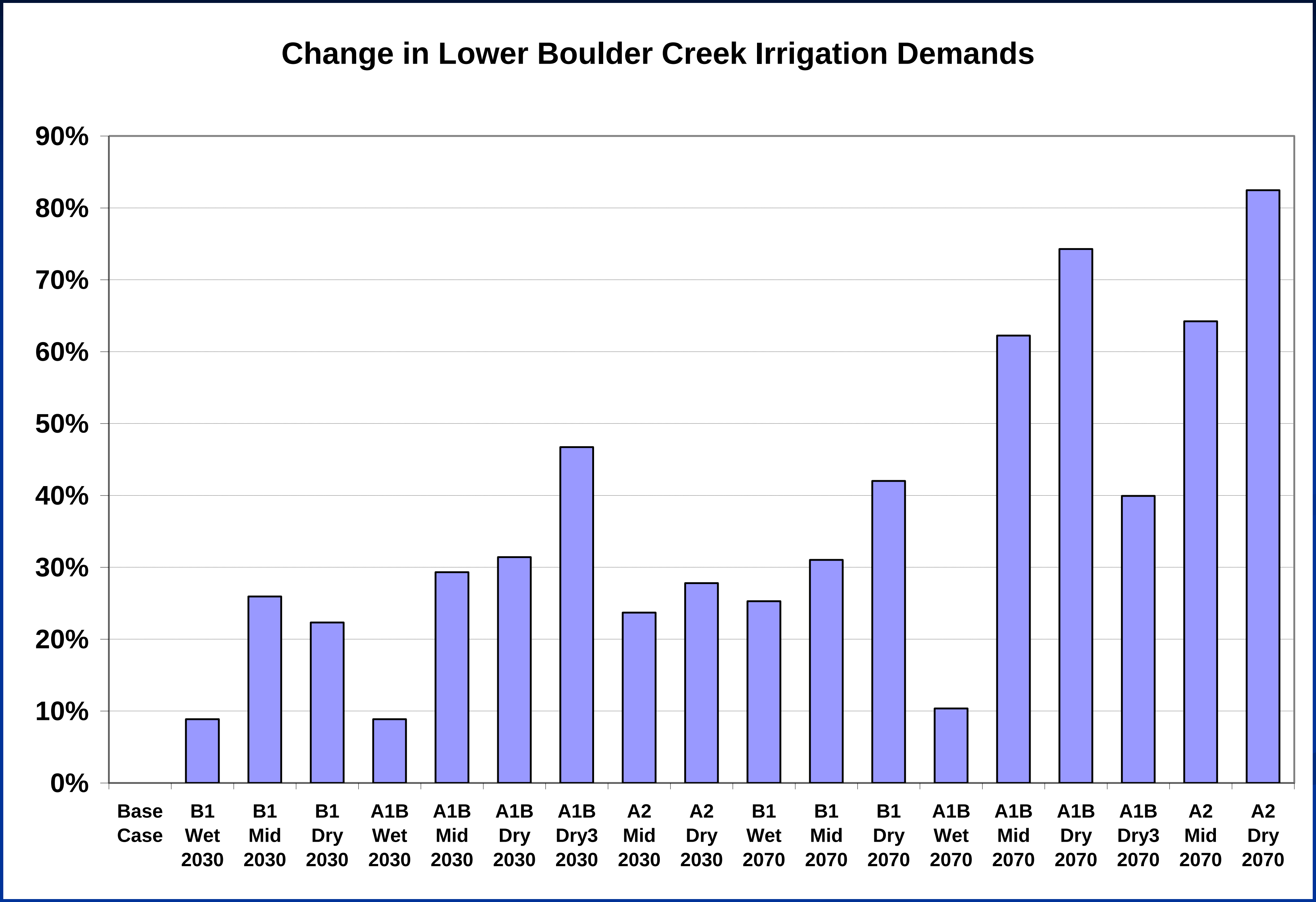
Emission Scenario	Model Type	Year	1-in-20 year criterion met?	1-in-100 year criterion met?	1-in-1000 year criterion met?	% of years with reduced deliveries Avg	% of years with reduced deliveries Max	# of "events" (1 or more consecutive years with reduced deliveries) Avg	# of "events" Max	maximum event length, years Avg	maximum event length, years Max	maximum delivery reduction (AF) Avg	maximum delivery reduction (AF) Max	average of delivery reductions, (AF) Avg	average of delivery reductions, (AF) Max
Drought Plan (300 years)			yes	yes	yes	3%		6		4		6552		3313	
BASE CASE			yes	yes	yes	2%	3%	3	5	4.8	7	2526	5334	1247	1604
B1	Wet	2030	yes	yes	yes	0%	0%	0	2	0.5	2	524	1573	1159	1573
B1	Mid	2030	yes	yes	yes	4%	5%	5	8	6.6	11	2848	5334	1369	1899
B1	Dry	2030	no	yes	yes	5%	7%	7	11	6.3	10	4138	9377	1419	1800
A1B	Wet	2030	yes	yes	yes	0%	0%	0	2	0.3	1	295	1573	719	982
A1B	Mid	2030	yes	yes	yes	4%	5%	5	7	5.8	7	3120	5334	1371	1724
A1B	Dry	2030	no	yes	yes	7%	11%	10	16	7.1	10	3953	5838	1448	1864
A1B	Dry3	2030	no	no	no	23%	27%	27	36	11.3	14	10120	12130	1847	2232
A2	Mid	2030	yes	yes	yes	3%	5%	5	6	5.2	6	2736	5334	1286	1656
A2	Dry	2030	no	yes	yes	13%	18%	16	22	8.5	11	4426	5838	1484	1716
B1	Wet	2070	yes	yes	yes	0%	0%	0	2	0.5	2	426	1573	893	1234
B1	Mid	2070	yes	yes	yes	2%	3%	3	6	4.2	6	2533	5334	1217	1713
B1	Dry	2070	yes	yes	yes	3%	5%	4	6	4.8	6	3098	5838	1414	2044
A1B	Wet	2070	yes	yes	yes	0%	0%	0	2	0.3	1	295	1573	719	982
A1B	Mid	2070	yes	yes	yes	2%	3%	3	6	3.7	6	2531	5652	1106	1818
A1B	Dry	2070	no	yes	no	14%	16%	18	26	8.9	13	9657	11398	1857	2253
A1B	Dry3	2070	no	yes	yes	4%	6%	6	10	5.5	7	3829	5838	1481	1755
A2	Mid	2070	no	yes	yes	5%	6%	7	10	5.8	7	5933	9036	1431	2078
A2	Dry	2070	no	no	no	21%	26%	23	29	12.8	17	10475	12332	2153	2467

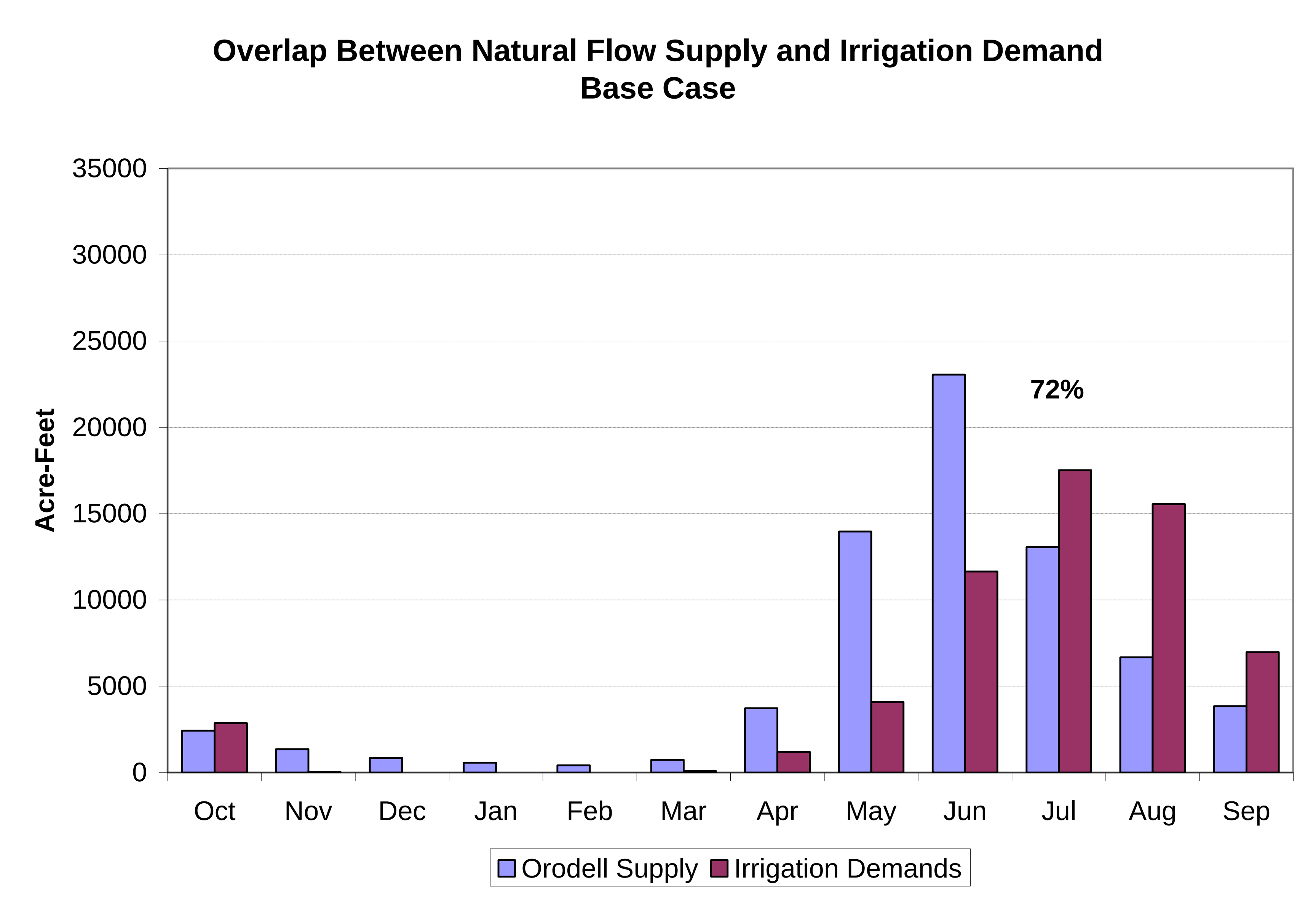
(Averages and maxima for the eleven 437-year traces in each scenario)


Reduced Deliveries - B1 Wet 2070, Trace 24
Acre-Feet
1800
1600
1400
1200
1000
800
600
400
200
0
1566
1616
1666
1716
1766
1816
1866
1916
1966
period of record

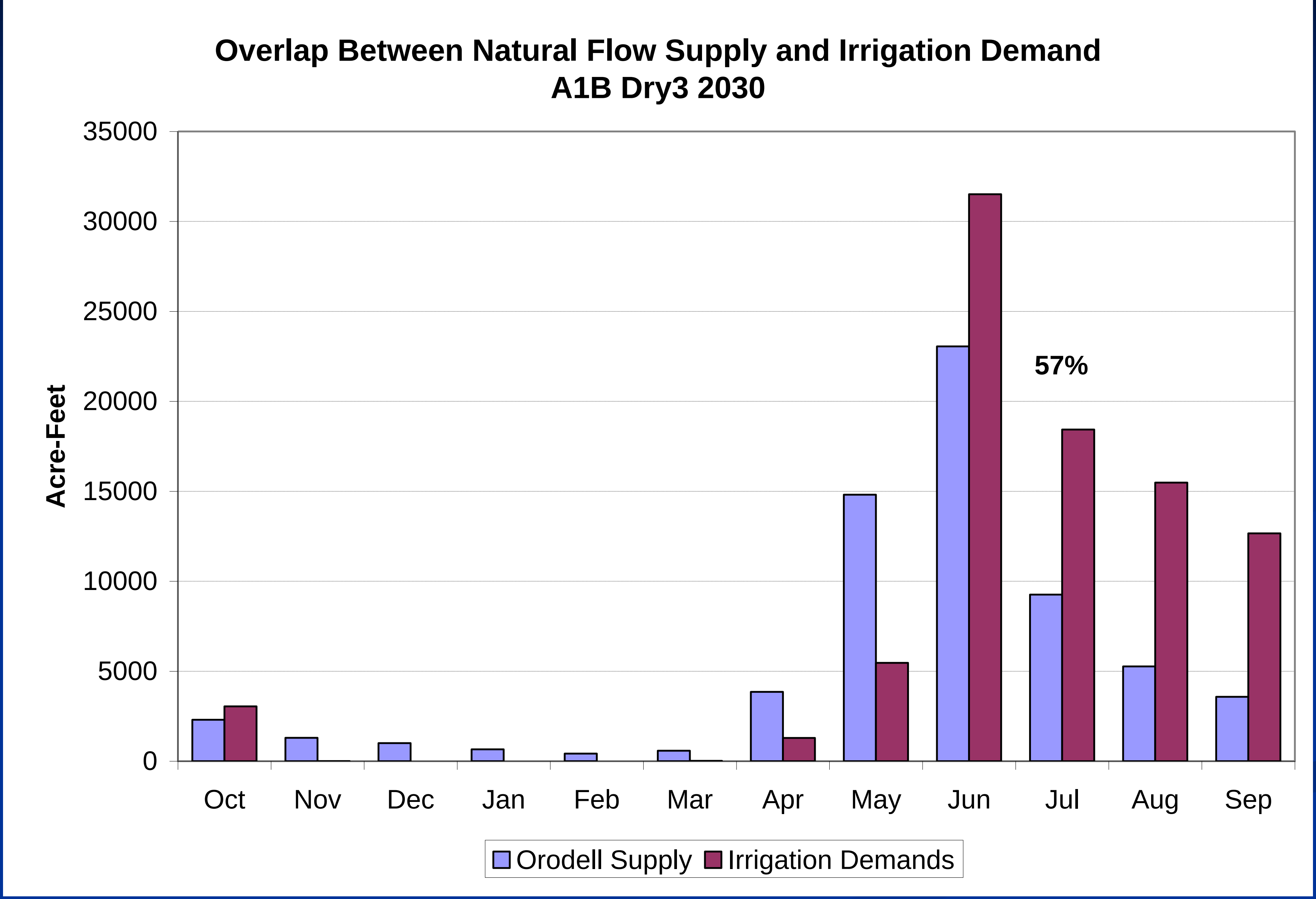


Reduced Deliveries - A2 Dry 2070, Trace 257
Acre-Feet
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
1566
1616
1666
1716
1766
1816
1866
1916
1966
period of
record

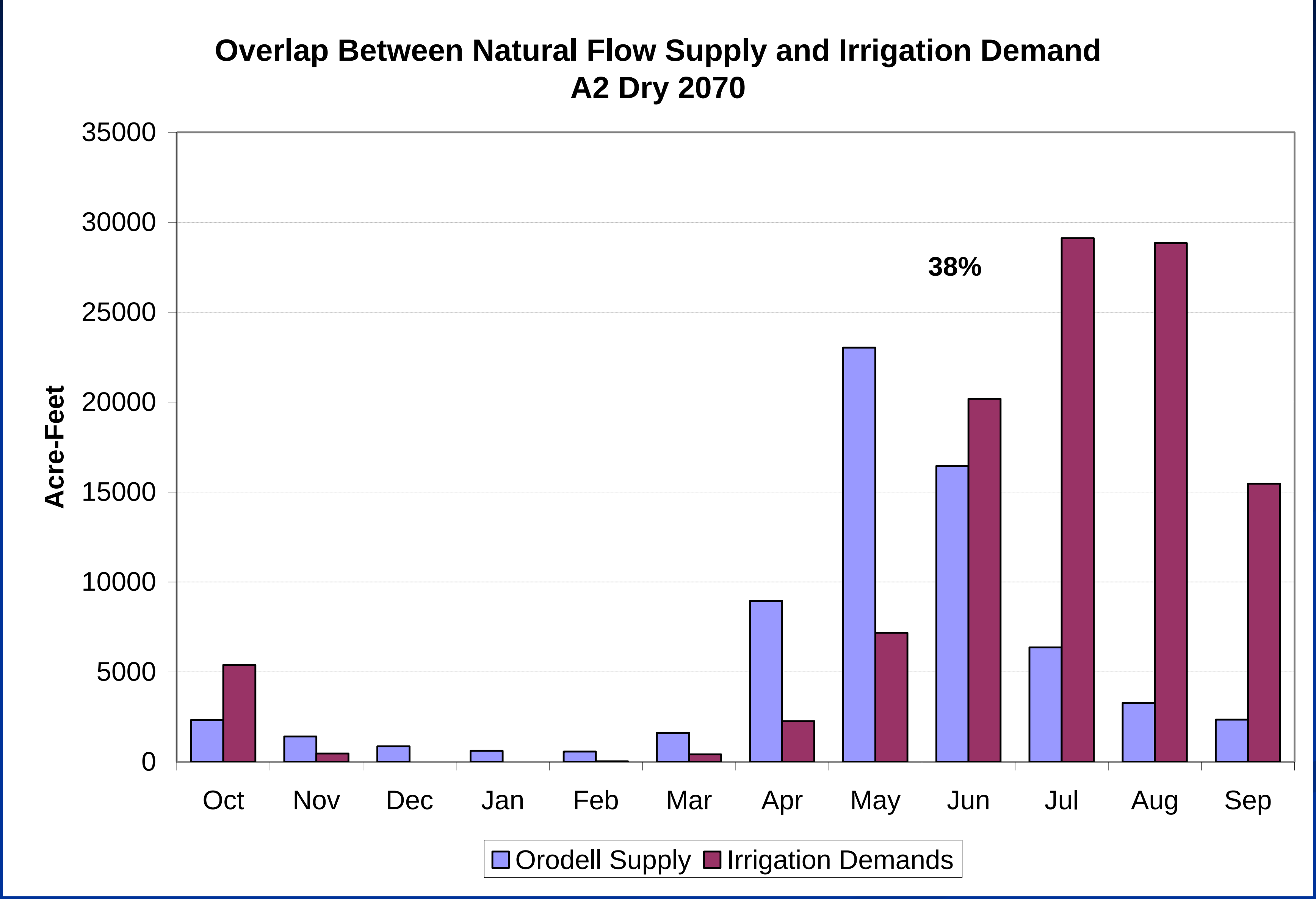

Change in Lower Boulder Creek Irrigation Demands
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Base Case
B1 Wet 2030
B1 Mid 2030
B1 Dry 2030
A1B Wet 2030
A1B Mid 2030
A1B Dry 2030
A1B Dry3 2030
A2 Mid 2030
A2 Dry 2030
B1 Wet 2070
B1 Mid 2070
B1 Dry 2070
A1B Wet 2070
A1B Mid 2070
A1B Dry 2070
A1B Dry3 2070
A2 Mid 2070
A2 Dry 2070



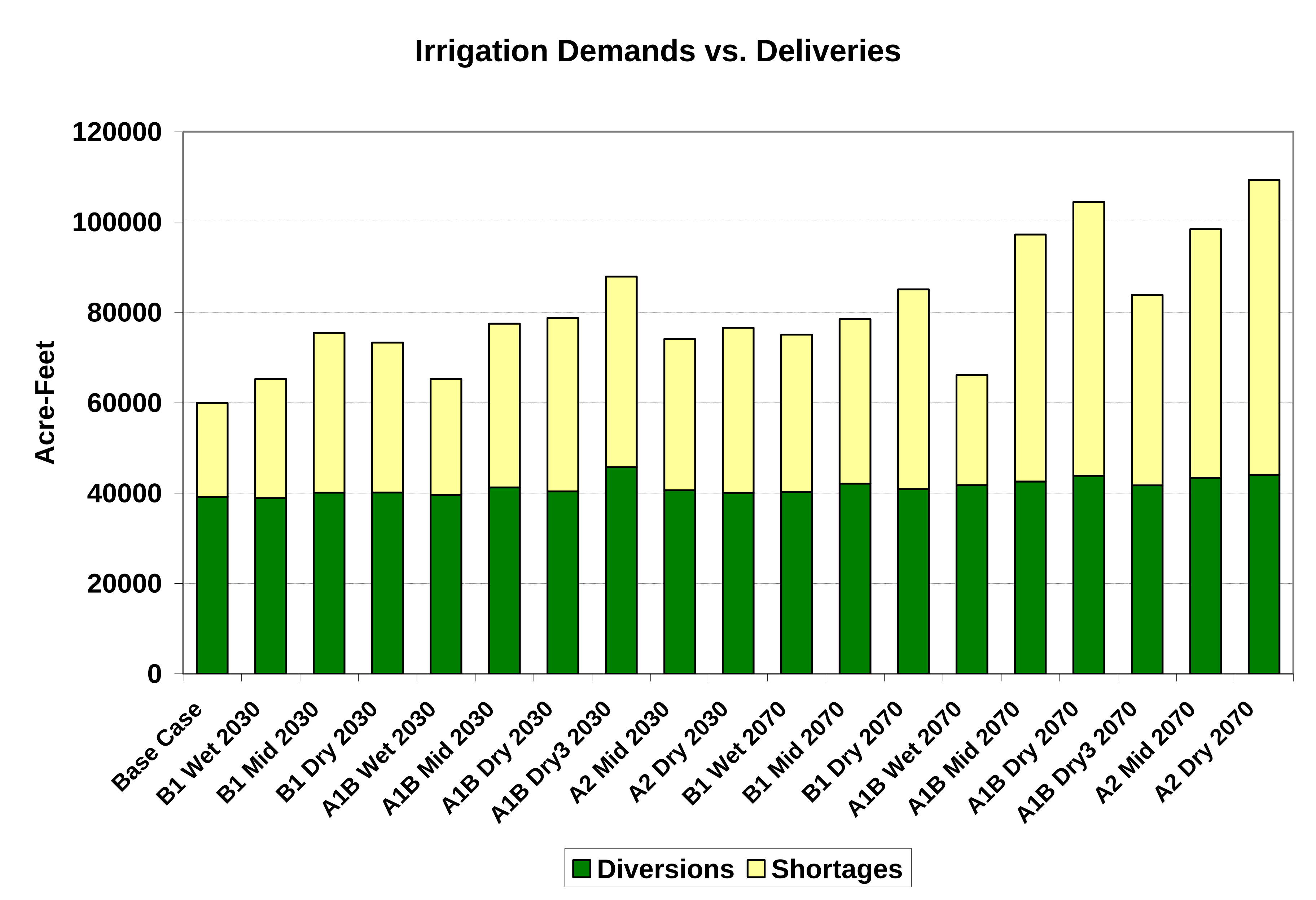
Overlap Between Natural Flow Supply and Irrigation Demand
Base Case
Acre-Feet
35000
30000
25000
20000
15000
10000
5000
0
72%
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Orodell Supply
Irrigation Demands



Overlap Between Natural Flow Supply and Irrigation Demand
A1B Dry3 2030
Acre-Feet
35000
30000
25000
20000
15000
10000
5000
0
57%
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Orodell Supply
Irrigation Demands



Overlap Between Natural Flow Supply and Irrigation Demand
A2 Dry 2070
Acre-Feet
35000
30000
25000
20000
15000
10000
5000
0
38%
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Orodell Supply
Irrigation Demands



Irrigation Demands vs. Deliveries
Acre-Feet
120000
100000
80000
60000
40000
20000
0
Base Case
B1 Wet 2030
B1 Mid 2030
B1 Dry 2030
A1B Wet 2030
A1B Mid 2030
A1B Dry 2030
A1B Dry3 2030
A2 Mid 2030
A2 Dry 2030
B1 Wet 2070
B1 Mid 2070
B1 Dry 2070
A1B Wet 2070
A1B Mid 2070
A1B Dry 2070
A1B Dry3 2070
A2 Mid 2070
A2 Dry 2070
Diversions
Shortages

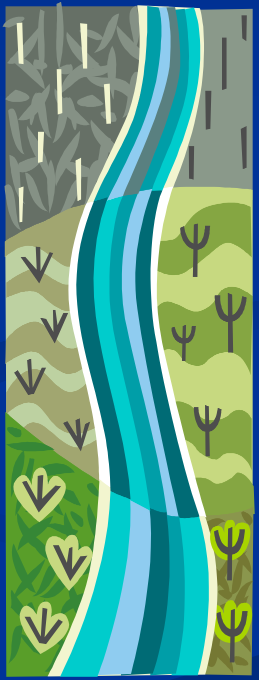
Policy Implications

Earlier Runoff

Water rights — Winners and losers

Even if total amount of water available doesn't change, there will be redistribution of existing water supplies

- High altitude reservoirs — winners
  - Earlier spring fill window could lessen competition from other water rights
- Junior direct flow rights — losers
  - Lower late summer streamflow = called out more
- Decrees with fixed start dates — losers?



Likely Water Policy Changes due to Temperature Change

- Urban landscaping requirements favoring native vegetation and drought-tolerant plantings
- Greater public acceptance of "golden" late summer lawns and "alternative" landscapes
- Planting agricultural crops with early season maturity and/or spring frost tolerance
- More reservoir storage space built and rehabilitated
- More underground water recharge projects

Boulder's Current Response to Study

- **Monitoring**
  - future improvements in climate science
  - actual climate changes
- **Modeling**
  - identify when climate changes move outside capabilities of existing water system
- **Plan** — adaptation as needed
    - More reservoir storage?
    - Long-term demand reduction?
    - Changes to reliability criteria?
    - Modify drought recognition criteria?
- **Actions** – those with "no regrets"
  - Water management changes to increase efficiency
  - Earlier initiation of river exchanges
  - Facilities construction that increases operational flexibility with or without negative climate changes
- **Education**
  - Continued public education efforts on water supply limits

Possible Differences Between Boulder's Water System and Others

- High elevation reservoirs and diversion points
- City is 90% built-out
- Participant in CBT Project with associated large reservoirs
- Mixture of east slope and west slope water sources
- Senior direct flow rights
- Two water treatment plants
- Two-thirds of use is indoor

Suggestions that may have general applicability

- Improve water system modeling
  - Emulate drought responses (triggers and demand reductions)
  - Extend historic hydrologic record
  - Model synthetic hydrologic traces to test system limits
  - Include climate change info and consider climate-driven changes in irrigation water rights
- Monitor climate science development
- Educate decision-makers on climate and water
- Establish criteria for expected reliability of water system
  - Water shortages are planned for as part of expected performance of water system
  - Changes attitudes—drought water shortages do not mean water provider failure to perform
  - Educates public that droughts will occur and full water supply every year should not be expected

In Summary: Key Findings

- Boulder is particularly sensitive to:
  - Reduced winter precipitation at higher elevation
  - Increased demand
  - Higher GHGs increase risk
- Wetter or little change in precipitation does not appear to impose significant risks
- Some climate change scenarios could benefit Boulder’s water supplies
- Farmers may get a lower % of water demanded
- Risks to other Front Range communities may be larger

On behalf of the Team- Thanks!

lee.rozaklis@amec.com

Governor's Conference on Managing Drought & Climate Risk
October 8 - 10, 2008

Abstract - Boulder's Experiences Planning for Drought and Climate Change

Lee Rozaklis, AMEC Earth & Environmental

The City of Boulder has been actively planning for drought and climate change for the past 20 years. Work began with development of a comprehensive water supply system planning model (the Boulder Creek Model) capable of simulating all major aspects of the Boulder Creek basin including hydrology, water rights, diversion and storage facilities, water supply system operating policies, water uses and return flows. The Boulder Creek Model also simulates the operation of the Colorado-Big Thompson and Windy Gap projects and Boulder's interests in those projects, and calls from South Platte water rights located outside the Boulder Creek basin. Since 1988, the Boulder Creek model has been a fundamental tool in planning for uncertainty and change.

In 1989, with extensive public input the Boulder City Council adopted policies regarding standards of water supply service that struck a balance between the costs of supply development, the uncertainty in supplies and the consequences of water supply shortages. Central to these policies were the water supply reliability criteria, which tied specific standards of water supply service to severities of drought.

- Unrestrained demands would be met in 95% of years; only in droughts with recurrence intervals of 1-in-20 years or greater would water supply restrictions be imposed.

- Restrictions would be small enough to ensure continued viability of landscaping during 99% of years; only in droughts with recurrence intervals of 1-in-100 years or greater would restrictions be large enough to cause significant loss of landscaping.

- Water supply sufficient to meet uses essential to basic public health, safety and welfare (indoor domestic, commercial, industrial and firefighting uses) would be assured during 99.9 percent of years, i.e. in droughts with recurrence intervals of up to 1-in-1,000 years.

Boulder's water supply reliability criteria helped the City to deal effectively with questions of water supply adequacy (how much is enough?), allowable non-municipal uses of municipal supplies (water rights dedicated to instream flows except during droughts) and water supply planning approaches (firm yield modeling vs. reliability assessment).

In 2001, with the assistance of NOAA scientists, Boulder incorporated tree ring-based reconstructions of natural stream flows and climate into the Boulder Creek model. This allowed for more robust examinations of the reliability of Boulder's water supply system and development of more sophisticated system operating rules.

In 2002, Boulder developed its Drought Plan, which provided specific guidance in recognizing and responding to varying severities of drought. The Drought Plan formulated four levels of drought responses (called Drought Alert Stages), which were designed to achieve specific amounts of demand reduction via a range of planned actions focused on water customers, city and other government agencies, the landscaping professional community and the news media. The Drought Alert Stages are tied to and invoked by Drought Response Triggers, which are specific, objective determinations made on May 1st of each year to assess the

likelihood and severity of impending drought. The Triggers were developed through the use of the Boulder Creek Model, which was modified to incorporate the Triggers and simulate the target demand reductions of the Drought Alert Stages. The Boulder Creek model was run iteratively, assuming Boulder's build-out demands, against 300 years of tree ring-based hydrology and irrigation demands. The parameters of the Drought Response Triggers and the relationships between the Drought Response Triggers and the Drought Alert Stages were adjusted to minimize the number and severity of demand reductions over the 300-year modeled period. A reliability assessment made at the conclusion of the Drought Plan development found that Boulder's water supply system is capable of meeting its projected build-out demands in a manner consistent with Boulder's adopted reliability criteria, over the 300-year modeled period.

Boulder's NOAA-funded climate change study combined the potential impacts of climate change with long-term climate variability to examine their effects on Boulder's water supply. The study examined outputs from general circulation models (GCMs) for grid boxes that include Boulder, Colorado, and selected the wettest model, two of the driest models, and a middle model. Estimates of climate change for 20-year periods centering on 2030 and 2070 were used. In addition, 437-year (1566-2002) reconstructions of streamflow in Boulder Creek, South Boulder Creek, and the Colorado River were used. A "nearest neighbor" approach was used to select years in the observed climate record that resemble the paleoclimate reconstructions. Average monthly GCM changes in temperature and precipitation for 2030 and 2070 were combined with multiple recreations of the paleoclimate record to simulate the combined effects of change in climate and paleoclimate variability.

Increase in temperature alone was estimated to have little effect on the total annual volume of runoff, but by 2070 would shift peak runoff approximately one month earlier. This results in higher late winter and spring runoff and lower summer runoff. Indeed, these seasonal changes (e.g., higher winter runoff, lower summer runoff) were estimated even with increased or decreased precipitation. Annual runoff is quite sensitive to change in precipitation, with runoff decreasing with reduced precipitation and increasing with higher precipitation.

Using the Boulder Creek Model and accounting for Boulder's population growth and changes in agricultural demands, the study found that wet and "middle" scenarios had little effect on the reliability of Boulder's water supply. But reduced precipitation scenarios resulted in violations of some of Boulder's water supply reliability criteria. By 2070, higher greenhouse gas emissions scenarios increase the risk of supply disruptions more than the lowest emissions scenario. Although Boulder's Drought Plan found that Boulder's water supplies would be reliable with a repeat of climate conditions from hundreds of years ago, this study found that the *combination* of climate change imposed on a reconstruction of events from the 16th and 17th centuries would cause more frequent violations of the city's water supply criteria. Demand for irrigation was projected to increase substantially, but very little of the increased demand would be met under the middle or dry scenarios.

In general, Boulder is in a relatively good position to adapt to climate change because it has relatively senior water rights and can fill its reservoirs during later winter and early spring months when runoff is projected to increase. Other municipalities without reservoirs or with junior water rights that will more frequently not be allowed to divert in late summer months would likely be at greater risk due to climate change. Boulder will work to increase the flexibility of operations for its water system and examine means to reduce demands and enhance supplies.

Lee Rozaklis, AMEC/Hydrosphere

Lee Rozaklis is a Principal with AMEC Earth & Environmental (formerly with Hydrosphere) with over 30 years of experience in water resources management including water resources systems analysis, water rights engineering and water quality analysis.

He has provided a wide range of services to the City of Boulder including development of Boulder's raw water master plan, instream flow program, water conservation plan and drought plan. He was a co-investigator in a study of the potential consequences of climate change for Boulder Colorado's water supply.

He has served as project manager and key technical analyst in several major water management and municipal water supply studies in Colorado, including the South Metro Water Supply Study, the Upper Colorado River Basin Study, the Metropolitan Water Supply Investigation, and the Denver Basin and South Platte River Basin Technical Study. He developed the analytical basis for Colorado's Plan for Future Depletions related to Central Platte River endangered species. He has provided expert services to the U.S. Bureau of Reclamation on South Platte River Basin water management issues in support of Reclamation's development of the Platte River Endangered Species Programmatic EIS.