The Southwestern Water Conservation District
The West Building, 841 E Second Avenue
Durango, CO 81301

NOTICE IS HEREBY GIVEN
A Regular Board Meeting of the
Southwestern Water Conservation District
will be held via teleconference on

Tuesday, August 4, 2020
8:30 a.m. – 11:30 a.m.

Wednesday, August 5, 2020
8:30 a.m. – 11:30 a.m.

Video: Click here to join Zoom
or
Phone Number: 346 248 7799
Meeting ID: 852 4669 2513
Participant ID: 931249

Posted and Noticed July 31, 2020

Tentative Agenda

Please text 970-901-1388 if you have difficulty joining the meeting.

*Please raise your hand to be recognized by the chair. To raise your hand by phone, dial*9. To raise your hand by computer, please use Alt+Y (Windows) or Option+Y (Mac). To mute and unmute by phone, dial *6.*

Tuesday, August 4, 2020

1.0 Call to Order – Roll Call, Verification of Quorum (8:30 a.m.)
2.0 Review and Approve Agenda (8:33 a.m.)
3.0 Executive Session (8:35 a.m.)
- 3.1 Process and Criteria for Hiring General Manager
- 3.2 Potential Consulting Services Agreement(s) for Engineering and/or other Services

4.0 Report from Executive Session (9:35 a.m.)
5.0 Introductions & Zoom Instructions (9:40 a.m.)
6.0 Old Business (9:45 a.m.)
- 6.1 SWCD Human Resources
  - 6.1.1 Short-Term and Long-Term SWCD Objectives, Organizational Structure, Staffing and Consultant Needs
    - 6.1.1.1 Discussion of draft SWCD Diagram and associated documents
    - 6.1.1.2 Review of recent allocation of staff time

6.1.1.3 General Manager job search goals, including job description, deadline for application and hiring process

Break (10:30 – 10:45 a.m.)

7.0 Approve and/or Remove Consent Agenda Items (10:45 a.m.)

8.0 Consent Agenda (10:47 a.m.)
- 8.1 Approval of Minutes (June 30)
- 8.2 Approval of Treasurer's Report (June 2020)

9.0 Reports (10:50 a.m.)
- 9.1 Director Reports
- 9.2 Board Committee Reports & Future Meetings
  - 9.2.1 Finance Committee (Notes July 9)
  - 9.2.2 Strategic Planning Committee (Notes July 15)
  - 9.2.3 Personnel Committee (Notes July 9, July 16)
- 9.3 Hydrologic Conditions Update
- 9.4 Office Update
  - 9.4.1 Possible scheduling of Special Meeting in September

Recess at 11:30 a.m. until Wednesday, August 5 at 8:30 a.m.

Wednesday, August 5, 2020

10.0 Call to Order – Roll Call, Verification of Quorum and Pledge of Allegiance (8:30 a.m.)
11.0 Introductions & Zoom Instructions (8:32 a.m.)
12.0 Review and Approve Agenda (8:33 a.m.)
13.0 Executive Session (8:35 a.m.)
- 13.1 Colorado River Interstate and Intra-state matters, including re-negotiation of the interim guidelines, Lake Powell Pipeline and exploration of demand management
- 13.2 La Plata River Exchange, Case No. 09CW51, Division 7
- 13.3 San Juan County Conditional Water Rights, Case No. 05CW88, Division 7

14.0 Report from Executive Session (9:20 a.m.)

15.0 Questions and Comments from Audience (9:25 a.m.)

16.0 Old Business (continued) (9:30 a.m.)
- 16.1 Colorado River matters
  - 16.1.1 Interstate and intra-state matters, including re-negotiation of the interim guidelines, Lake Powell Pipeline and exploration of demand management
  - 16.1.2 Colorado River Water Bank Working Group Update
- 16.2 Proposed Virtual Event to Replace SWCD Annual Water Seminar, Two-Day Morning October Board Meeting

Break (10:20-10:35 a.m.)

17.0 New Business (10:35 a.m.)
- 17.1 Update: CSU Southwestern Colorado Research Center – Katie Russell
- 17.2 Update and Request from Environmental Impact Fund – Ellen Roberts
- 17.3 Proposed Revisions to SWCD Grant Program Guidelines

17.4 Colorado Water Congress Request for Financial Support to File Amicus Brief in Colorado v. EPA regarding the 2020 Waters of the United States Rule

18.0 Engineering Report (11:10 a.m.)

18.1 Upper Colorado & San Juan River Basin Recovery Implementation Programs
18.2 Paradox Valley Unit Draft Environmental Impact Statement
18.3 Animas Watershed Partnership

19.0 General Counsel Legal Report (11:20 a.m.)

19.1 Proposed Revisions to CWCB Instream Flow Program Rules
19.2 June Water Court Resume Review (Divisions 3, 4, 7)

20.0 Executive Session (if needed)

21.0 Adjournment (11:30a.m.)

Upcoming Meetings

September 9, 2020	9:00 a.m.	Budget Workshop
October 13-14, 2020	TBD	Regular Board Meeting
December 8-9, 2020	TBD	Regular Board Meeting

Except the time indicated for when the meeting is scheduled to begin, the times noted for each agenda item are estimates and subject to change. The Board may address and act on agenda items in any order to accommodate the needs of the Board and the audience. Agenda items can also be added during the meeting at the consensus of the Board.

Agenda items may be placed on the Consent Agenda when the recommended action is non-controversial. The Consent Agenda may be voted on without reading or discussing individual items. Any Board member may request clarification about items on the Consent Agenda. The Board may remove items from the Consent Agenda at their discretion for further discussion.

Southwestern Water Conservation District
Budget Comparison Summary
January through June 2020

	Jan - Jun 20	Budget	$ Over Budget	% of Budget
Income				
4 · SWCD INCOME				
4.1 · Property Tax	1,314,956	1,620,102	(305,147)	81%
4.2 · Specific Ownership Tax	55,052	100,000	(44,948)	55%
4.3 · Interest, PILT & Other Taxes	36,128	35,500	628	102%
4.4 · Other Income				
4.4.1 · Interest Earned	30,901	40,000	(9,099)	77%
4.4.2 · Loan Interest	0	275	(275)	0%
4.4.3 · Miscellaneous Income	2,845	5,000	(2,155)	57%
4.4.4 · Water Seminar Registration	0	6,000	(6,000)	0%
4.4.5 · ALP/WIP Cost Sharing	0	200	(200)	0%
4.4.7 · SJRBRIP Water User Committee	50,873	50,873	0	100%
4.4.8 · Stream Gaging Reimbursement	17,913	32,481	(14,568)	55%
4.4.9 · Water Info Program	34,954	37,850	(2,896)	92%
Total 4.4 · Other Income	137,487	172,679	(35,192)	80%
Total 4 · SWCD INCOME	1,543,622	1,928,281	(384,659)	80%
Total Income	1,543,622	1,928,281	(384,659)	80%
Gross Profit	1,543,622	1,928,281	(384,659)	80%
Expense				
5 · SWCD EXPENSES				
5.01 · Water Management & Development				
5.1.1 · SWCD Grant Program	80,080	400,000	(319,920)	20%
5.1.2 · Previously Committed Grants	0	85,694	(85,694)	0%
5.1.3 · Project Reserve Fund	0	350,000	(350,000)	0%
5.1.4 · SJRBRIP Water User Committee	33,969	101,746	(67,777)	33%
5.1.5 · SWCD Project Water Rights	0	10,000	(10,000)	0%
5.1.6 · Weather Modification	17,320	117,000	(99,680)	15%
5.1.7 · Emergency Reserve Fund	0	500,000	(500,000)	0%
Total 5.01 · Water Management & Development	131,369	1,564,440	(1,433,071)	8%
5.02 · Data Collection				
5.2.1 · Center for Snow & Avalanche	7,000	7,000	0	100%
5.2.2 · Stream Gaging - Federal	24,253	108,500	(84,247)	22%
5.2.3 · Stream Gaging - Colorado	0	2,640	(2,640)	0%
5.2.4 · Water Quality Studies	7,000	13,000	(6,000)	54%
5.2.5 · SW Colorado Permanent Radar	0	10,000	(10,000)	0%
Total 5.02 · Data Collection	38,253	141,140	(102,887)	27%
5.03 · Ongoing Organizational Support				
5.3.1 · Event Sponsorships	700	6,000	(5,300)	12%
5.3.2 · Dues & Memberships	20,879	22,350	(1,471)	93%
5.3.3 · Bonita Peak CAG	5,000	5,000	0	100%
5.3.4 · Water Bank Working Group	11,000	17,500	(6,500)	63%
5.3.5 · Demo CSU Farm/Water Efficiency	0	10,000	(10,000)	0%
Total 5.03 · Ongoing Organizational Support	37,579	60,850	(23,271)	62%
5.04 · Water Education				
5.4.1 · Water Info Program	26,312	72,095	(45,783)	36%

Southwestern Water Conservation District
Budget Comparison Summary
January through June 2020

	Jan - Jun 20	Budget	$ Over Budget	% of Budget
5.4.2 · Water Seminar	66	18,000	(17,934)	0%
5.4.3 · Water Education Colorado	10,500	10,500	0	100%
5.4.4 · Water Leaders Scholarship	3,500	5,000	(1,500)	70%
5.4.5 · Children's Water Festival	729	9,500	(8,771)	8%
5.4.6 · Watershed Education Program	6,000	6,000	0	100%
Total 5.04 · Water Education	47,107	121,095	(73,988)	39%
5.05 · Technical Support				
5.5.01 · Attorney Fees - General Counsel	74,115	140,000	(65,885)	53%
5.5.02 · Travel Exps - General Counsel	1,152	15,000	(13,848)	8%
5.5.03 · Litigation - General Counsel	13,618	30,000	(16,382)	45%
5.5.04 · Co River Litigation- General Co	0	40,000	(40,000)	0%
5.5.05 · Attorney Fees - Special Counsel	14,237	10,000	4,237	142%
5.5.06 · Attorney Exps - Special Counsel	0	5,000	(5,000)	0%
5.5.07 · Lobbying Fees	37,250	50,000	(12,750)	75%
5.5.08 · Lobbying Expenses	708	5,500	(4,792)	13%
5.5.09 · Engineering - General	16,253	45,000	(28,747)	36%
5.5.10 · Engineering - Special Projects	0	25,000	(25,000)	0%
5.5.11 · Technical Other Expenses	0	50,000	(50,000)	0%
Total 5.05 · Technical Support	157,334	415,500	(258,166)	38%
5.06 · District Staff				
5.6.1 · Wages - Executive Director	71,794	146,450	(74,656)	49%
5.6.2 · Wages - Programs Coordinator	25,891	50,393	(24,502)	51%
5.6.4 · Wages - Payroll Taxes	7,766	17,716	(9,950)	44%
5.6.5 · Wages - Retirement Benefit	4,954	11,811	(6,857)	42%
5.6.6 · Wages - Health & Life Insurance	14,054	46,260	(32,206)	30%
5.6.7 · Wages - ED Bonus	0	0	0	0%
5.6.8 · Wages - Coordinator Bonus	0	0	0	0%
Total 5.06 · District Staff	124,459	272,629	(148,170)	46%
5.07 · Meetings & Travel				
5.7.1 · Director Fees	7,250	21,000	(13,750)	35%
5.7.2 · Director Travel	4,630	31,000	(26,370)	15%
5.7.3 · Registration Fees	5,388	8,500	(3,112)	63%
5.7.4 · Meeting Expenses	1,240	10,000	(8,761)	12%
5.7.5 · Staff Travel	8,063	35,000	(26,937)	23%
Total 5.07 · Meetings & Travel	26,571	105,500	(78,929)	25%
5.08 · Administration				
5.8.01 · Audit	0	8,400	(8,400)	0%
5.8.02 · Accounting	1,249	500	749	250%
5.8.03 · Capital Outlay	14,960	15,000	(40)	100%
5.8.04 · Casual Labor	0	200	(200)	0%
5.8.05 · ED Discretionary Budget	759	2,000	(1,241)	38%
5.8.06 · Equipment Leasing	900	1,800	(900)	50%
5.8.07 · Insurance - General Liability	6,734	6,000	734	112%
5.8.08 · Legal Notices	0	600	(600)	0%
5.8.09 · Miscellaneous	0	500	(500)	0%
5.8.10 · Office Expenses	2,523	7,500	(4,977)	34%
5.8.11 · Postage	681	1,000	(319)	68%
5.8.12 · Rent	17,134	30,796	(13,662)	56%
5.8.13 · Staff Training/Development	0	2,500	(2,500)	0%
5.8.14 · Telephone	1,489	3,500	(2,011)	43%
Total 5.08 · Administration	46,429	80,296	(33,867)	58%

Southwestern Water Conservation District
Budget Comparison Summary
January through June 2020

	Jan - Jun 20	Budget	$ Over Budget	% of Budget
5.09 · County Treasurer Fees	38,497	52,668	(14,171)	73%
5.10 · TABOR Reserve	0	84,424	(84,424)	0%
5.11 · Contingency Reserve	0	96,414	(96,414)	0%
Total 5 · SWCD EXPENSES	647,598	2,994,956	(2,347,358)	22%
Total Expense	647,598	2,994,956	(2,347,358)	22%
Net Income	**896,024**	**(1,066,675)**	**1,962,699**	**(84)%**

Southwestern Water Conservation District
Bank Account Summary
As of June 30, 2020

	Jun 30, 20
ASSETS	
Current Assets	
Checking/Savings	
100 · SWCD Checking	357,996.23
101 · SWCD Credit Card	(1,442.01)
102 · SJRBRIP Checking	88,103.63
103 · WIP Checking	109,760.99
105 · COLOTrust Project Reserve	485,066.86
106 · COLOTrust Emergency Reserve	264,852.10
107 · COLOTrust General	752,749.73
123 · CD1 - 24 Month	1,540,665.39
159 · CD2 - 12 Month	412,298.38
160 · CD3 - 12 Month	101,177.52
Total Checking/Savings	4,111,228.82
Other Current Assets	
131 · Bauer Lake Loan	11,011.25
Total Other Current Assets	11,011.25
Total Current Assets	4,122,240.07
TOTAL ASSETS	**4,122,240.07**
LIABILITIES & EQUITY	0.00

Southwestern Water Conservation District

Check Detail

June 2020

Num	Date	Name	Memo	Account	Original Amount
ACH	**06/01/2020**	**Laura E Spann**	**05/18-31/20**	**100 · SWCD Checking**	**-1,355.91**
			05/18-31/20	5.6.2 · Wages - Programs Coordinator	1,938.40
			05/18-31/20	5.6.6 · Wages - Health & Life Insurance	-143.74
			05/18-31/20	221 · 457 Withholding	-48.46
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-162.00
			05/18-31/20	5.6.4 · Wages - Payroll Taxes	120.18
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-120.18
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-120.18
			05/18-31/20	5.6.4 · Wages - Payroll Taxes	28.11
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-28.11
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-28.11
			05/18-31/20	216 · State W/H Tax Payable	-80.00
TOTAL					1,355.91
ACH	**06/01/2020**	**Frank J Kugel**	**05/18-31/20**	**100 · SWCD Checking**	**-3,301.75**
			05/18-31/20	5.6.1 · Wages - Executive Director	5,576.92
			05/18-31/20	5.6.6 · Wages - Health & Life Insurance	-87.14
			05/18-31/20	221 · 457 Withholding	-665.39
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-876.00
			05/18-31/20	5.6.4 · Wages - Payroll Taxes	345.77
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-345.77
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-345.77
			05/18-31/20	5.6.4 · Wages - Payroll Taxes	80.87
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-80.87
			05/18-31/20	215 · FICA/Medicare/Fed W/H	-80.87
			05/18-31/20	216 · State W/H Tax Payable	-220.00
TOTAL					3,301.75
ACH	**06/01/2020**	**Lincoln Financial Group**	**5/18-31/20**	**100 · SWCD Checking**	**-1,096.93**
			5/18-31/20	221 · 457 Withholding	713.85
			5/18-31/20	5.6.5 · Wages - Retirement Benefit	383.08
TOTAL					1,096.93
Bill.com	**06/02/2020**	**Kogovsek & Associates, Inc.**	**3Q2020**	**100 · SWCD Checking**	**-12,500.00**
			3Q2020	5.5.07 · Lobbying Fees	12,500.00
TOTAL					12,500.00
Bill.com	**06/02/2020**	**HabiTech, Inc**	**March 25-May 29, 2020**	**102 · SJRBRIP Checking**	**-8,855.00**
			March 25-May 29, 2020	5.1.4 · SJRBRIP Water User Committee	8,855.00
TOTAL					8,855.00
Bill.com	**06/04/2020**	**Elaine Chick Consulting**	**Mileage, Meal PEPO Video Shoot 5/11-12/20**	**103 · WIP Checking**	**-121.27**
			Mileage, Meal PEPO Video Shoot 5/11-12/20	54115 · WIP Mileage & Travel	121.27
TOTAL					121.27
Bill.com	**06/04/2020**	**Elaine Chick Consulting**	**May 2020**	**103 · WIP Checking**	**-4,120.47**
			May 2020	54111 · WIP Contract Coordination	4,120.47
TOTAL					4,120.47
VISA	**06/05/2020**	**Blue Channel**	**GSuite Assist, Set Up**	**101 · SWCD Credit Card**	**-45.00**
			GSuite Assist, Set Up	5.8.10 · Office Expenses	45.00
TOTAL					45.00
VISA	**06/05/2020**	**Best Buy**	**Director Computer (Remote Mtg, Packet Access)**	**101 · SWCD Credit Card**	**-758.79**
			Director Computer (Remote Mtg, Packet Access)	5.8.05 · ED Discretionary Budget	758.79
TOTAL					758.79
VISA	**06/05/2020**	**Charter Spectrum**	**June 2020**	**101 · SWCD Credit Card**	**-69.99**
			June 2020	5.8.14 · Telephone	69.99
TOTAL					69.99

Southwestern Water Conservation District

Check Detail

June 2020

Num	Date	Name	Memo	Account	Original Amount
ACH	**06/08/2020**	**Bank of Colorado**	**Wire Fee (Montrose Cty Pymt)**	**100 · SWCD Checking**	**-5.00**
			Wire Fee (Montrose Cty Pymt)	5.8.02 · Accounting	5.00
TOTAL					5.00
VISA	**06/08/2020**	**ImageNet**	**June 2020**	**101 · SWCD Credit Card**	**-150.00**
			June 2020	5.8.06 · Equipment Leasing	150.00
TOTAL					150.00
VISA	**06/08/2020**	**Zoom**	**June 2020-June 2021**	**101 · SWCD Credit Card**	**-107.99**
			June 2020-June 2021	5.8.14 · Telephone	107.99
TOTAL					107.99
VISA	**06/08/2020**	**Charter Spectrum**	**July 2020**	**101 · SWCD Credit Card**	**-69.99**
			July 2020	5.8.14 · Telephone	69.99
TOTAL					69.99
ACH	**06/09/2020**	**Bill.com**	**May 2020**	**100 · SWCD Checking**	**-127.46**
			May 2020	5.8.02 · Accounting	127.46
TOTAL					127.46
Bill.com	**06/09/2020**	**Luna Display**	**Display Dongle Conf Room AV Upgrade**	**101 · SWCD Credit Card**	**-49.99**
			Display Dongle Conf Room AV Upgrade	5.8.03 · Capital Outlay	49.99
TOTAL					49.99
Bill.com	**06/09/2020**	**Van Vurst Law**	**May 2020**	**100 · SWCD Checking**	**-18,984.00**
			May 2020	5.5.01 · Attorney Fees - General Counsel	17,972.00
			May 2020	5.5.03 · Litigation - General Counsel	1,012.00
TOTAL					18,984.00
Bill.com	**06/10/2020**	**Moxiecran Media LLC**	**May 2020 PEPO Video**	**103 · WIP Checking**	**-1,500.00**
			May 2020 PEPO Video	54119 · WIP Educational Products	1,500.00
TOTAL					1,500.00
ACH	**06/11/2020**	**Frank J Kugel**	**6/1-6/11/2020**	**100 · SWCD Checking**	**-2,946.73**
			6/1-6/11/2020	5.6.1 · Wages - Executive Director	5,019.23
			6/1-6/11/2020	5.6.6 · Wages - Health & Life Insurance	-87.14
			6/1-6/11/2020	221 · 457 Withholding	-665.39
			6/1-6/11/2020	215 · FICA/Medicare/Fed W/H	-742.00
			6/1-6/11/2020	5.6.4 · Wages - Payroll Taxes	311.19
			6/1-6/11/2020	215 · FICA/Medicare/Fed W/H	-311.19
			6/1-6/11/2020	215 · FICA/Medicare/Fed W/H	-311.19
			6/1-6/11/2020	5.6.4 · Wages - Payroll Taxes	72.78
			6/1-6/11/2020	215 · FICA/Medicare/Fed W/H	-72.78
			6/1-6/11/2020	215 · FICA/Medicare/Fed W/H	-72.78
			6/1-6/11/2020	216 · State W/H Tax Payable	-194.00
TOTAL					2,946.73
ACH	**06/11/2020**	**Lincoln Financial Group**	**06/11/2020 Frank PTO Payout**	**100 · SWCD Checking**	**-991.13**
			06/11/2020 Frank PTO Payout	221 · 457 Withholding	665.39
			06/11/2020 Frank PTO Payout	5.6.5 · Wages - Retirement Benefit	325.74
TOTAL					991.13
ACH	**06/12/2020**	**United States Treasury**	**May 2020**	**100 · SWCD Checking**	**-6,116.98**
			May 2020	215 · FICA/Medicare/Fed W/H	2,964.00
			May 2020	215 · FICA/Medicare/Fed W/H	1,277.68
			May 2020	215 · FICA/Medicare/Fed W/H	1,277.68
			May 2020	215 · FICA/Medicare/Fed W/H	298.81
			May 2020	215 · FICA/Medicare/Fed W/H	298.81
TOTAL					6,116.98

Southwestern Water Conservation District

Check Detail

June 2020

Num	Date	Name	Memo	Account	Original Amount
Bill.com	**06/12/2020**	**San Juan RC & D**	**2020 Support for Bonita Peak CAG Operations**	**100 · SWCD Checking**	**-5,000.00**
			2020 Support for Bonita Peak CAG Operations	5.3.3 · Bonita Peak CAG	5,000.00
TOTAL					5,000.00
ACH	**06/13/2020**	**Frank J Kugel**	**PTO Payout 77.88 hours**	**100 · SWCD Checking**	**-3,294.30**
			PTO Payout 77.88 hours	5.6.1 · Wages - Executive Director	5,429.01
			PTO Payout 77.88 hours	221 · 457 Withholding	-665.39
			PTO Payout 77.88 hours	215 · FICA/Medicare/Fed W/H	-841.00
			PTO Payout 77.88 hours	5.6.4 · Wages - Payroll Taxes	336.60
			PTO Payout 77.88 hours	215 · FICA/Medicare/Fed W/H	-336.60
			PTO Payout 77.88 hours	215 · FICA/Medicare/Fed W/H	-336.60
			PTO Payout 77.88 hours	5.6.4 · Wages - Payroll Taxes	78.72
			PTO Payout 77.88 hours	215 · FICA/Medicare/Fed W/H	-78.72
			PTO Payout 77.88 hours	215 · FICA/Medicare/Fed W/H	-78.72
			PTO Payout 77.88 hours	216 · State W/H Tax Payable	-213.00
TOTAL					3,294.30
ACH	**06/15/2020**	**Laura E Spann**	**06/1-14/20**	**100 · SWCD Checking**	**-1,355.91**
			06/1-14/20	5.6.2 · Wages - Programs Coordinator	1,938.40
			06/1-14/20	5.6.6 · Wages - Health & Life Insurance	-143.74
			06/1-14/20	221 · 457 Withholding	-48.46
			06/1-14/20	215 · FICA/Medicare/Fed W/H	-162.00
			06/1-14/20	5.6.4 · Wages - Payroll Taxes	120.18
			06/1-14/20	215 · FICA/Medicare/Fed W/H	-120.18
			06/1-14/20	215 · FICA/Medicare/Fed W/H	-120.18
			06/1-14/20	5.6.4 · Wages - Payroll Taxes	28.11
			06/1-14/20	215 · FICA/Medicare/Fed W/H	-28.11
			06/1-14/20	215 · FICA/Medicare/Fed W/H	-28.11
			06/1-14/20	216 · State W/H Tax Payable	-80.00
TOTAL					1,355.91
ACH	**06/15/2020**	**Lincoln Financial Group**	**06/1-14/2020**	**100 · SWCD Checking**	**-1,063.46**
			06/1-14/2020	221 · 457 Withholding	713.85
			06/1-14/2020	5.6.5 · Wages - Retirement Benefit	349.61
TOTAL					1,063.46
ACH	**06/16/2020**	**United States Treasury**	**Stop Pymt Penalty on QB Online Dbl Payment (Laura Protesting)**	**100 · SWCD Checking**	**-85.98**
			Stop Pymt Penalty on QB Online Dbl Payment (Laura Protesting)	5.8.02 · Accounting	85.98
TOTAL					85.98
Bill.com	**06/23/2020**	**Don Schwindt**	**4/12-6/4/20**	**100 · SWCD Checking**	**-525.00**
			4/12-6/4/20	5.7.1 · Director Fees	525.00
TOTAL					525.00
Bill.com	**06/23/2020**	**Colorado Employer Benefit Trust**	**July 2020**	**100 · SWCD Checking**	**-1,560.17**
			July 2020	5.6.6 · Wages - Health & Life Insurance	1,560.17
TOTAL					1,560.17
ACH	**06/23/2020**	**United States Treasury**	**Interest Penalty on March 2020 stop payment (Laura protesting)**	**100 · SWCD Checking**	**-0.25**
			Interest Penalty on March 2020 stop payment (Laura protesting)	5.6.4 · Wages - Payroll Taxes	0.25
TOTAL					0.25
Bill.com	**06/24/2020**	**Trout Raley**	**May 2020**	**100 · SWCD Checking**	**-1,349.60**
			May 2020	5.5.05 · Attorney Fees - Special Counsel	1,349.60
TOTAL					1,349.60
Bill.com	**06/24/2020**	**Jenny Russell**	**Mtgs 4/8-6/16/20**	**100 · SWCD Checking**	**-1,000.00**
			Mtgs 4/8-6/16/20	5.7.1 · Director Fees	1,000.00
TOTAL					1,000.00

Southwestern Water Conservation District

Check Detail

June 2020

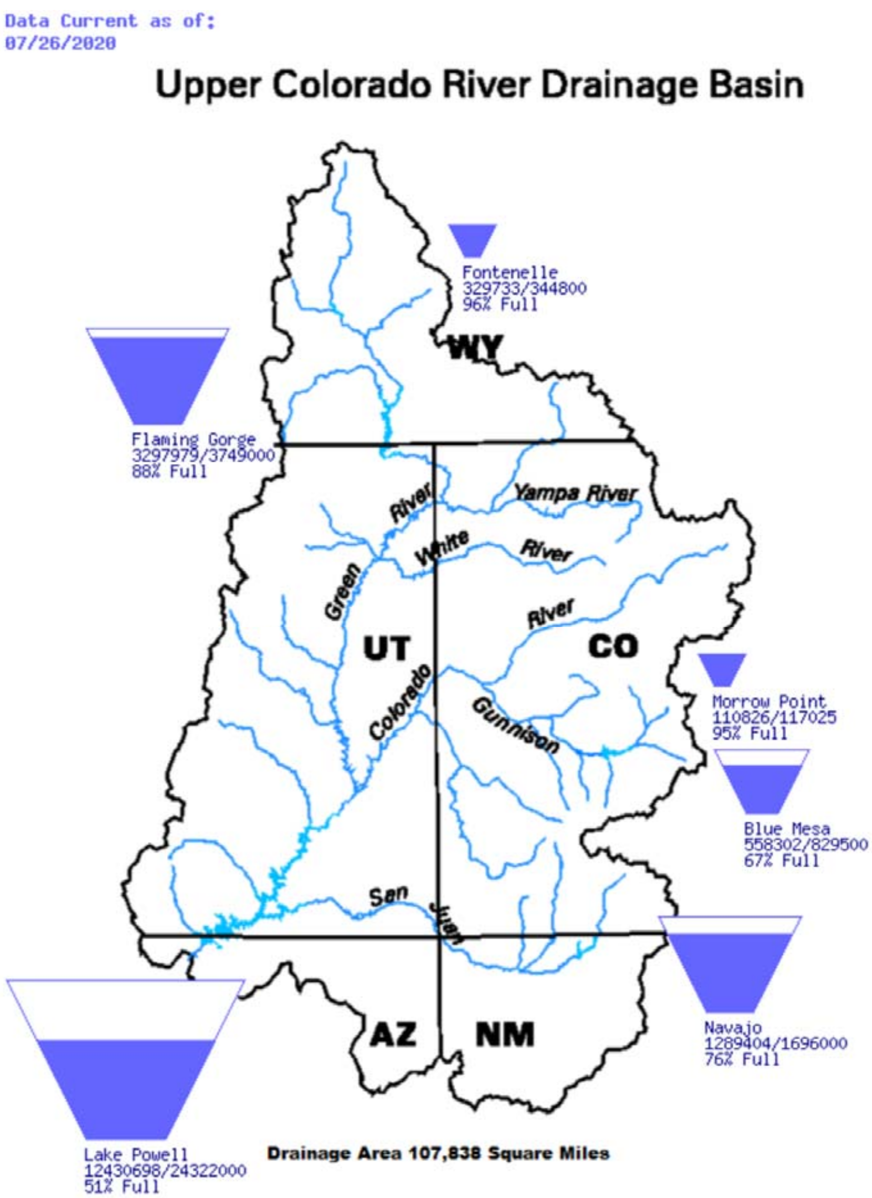
Num	Date	Name	Memo	Account	Original Amount
Bill.com	**06/25/2020**	**Robert Wolff**	**Mtgs 5/27-6/22/20**	**100 · SWCD Checking**	**-713.68**
			Mtgs 5/27-6/22/20	5.7.1 · Director Fees	700.00
			Mtgs 5/27-6/22/20	5.7.2 · Director Travel	13.68
TOTAL					713.68
Bill.com	**06/25/2020**	**ImageNet**	**3Q2020 Base**	**100 · SWCD Checking**	**-303.53**
			3Q2020 Base	5.8.10 · Office Expenses	303.53
TOTAL					303.53
VISA	**06/25/2020**	**US Postal Service**	**Board Packet Supplemental Mailing 6-30-20**	**101 · SWCD Credit Card**	**-158.10**
			Board Packet Supplemental Mailing 6-30-20	5.8.11 · Postage	158.10
TOTAL					158.10
VISA	**06/25/2020**	**iMeet**	**April 2020**	**101 · SWCD Credit Card**	**-32.16**
			April 2020	5.8.14 · Telephone	32.16
TOTAL					32.16
Bill.com	**06/26/2020**	**Laura Spann-V**	**Board packet mailing 6-30-20**	**100 · SWCD Checking**	**-158.10**
			Board packet mailing 6-30-20	5.8.11 · Postage	158.10
TOTAL					158.10
ACH	**06/28/2020**	**Laura E Spann**	**6/15-28/20**	**100 · SWCD Checking**	**-1,395.38**
			6/15-28/20	5.6.2 · Wages - Programs Coordinator	1,938.40
			6/15-28/20	5.6.6 · Wages - Health & Life Insurance	-143.74
			6/15-28/20	215 · FICA/Medicare/Fed W/H	-168.00
			6/15-28/20	5.6.4 · Wages - Payroll Taxes	120.18
			6/15-28/20	215 · FICA/Medicare/Fed W/H	-120.18
			6/15-28/20	215 · FICA/Medicare/Fed W/H	-120.18
			6/15-28/20	5.6.4 · Wages - Payroll Taxes	28.10
			6/15-28/20	215 · FICA/Medicare/Fed W/H	-28.10
			6/15-28/20	215 · FICA/Medicare/Fed W/H	-28.10
			6/15-28/20	216 · State W/H Tax Payable	-83.00
TOTAL					1,395.38
Bill.com	**06/29/2020**	**The West Building**	**July 2020**	**100 · SWCD Checking**	**-2,512.85**
			July 2020	5.8.12 · Rent	2,512.85
TOTAL					2,512.85

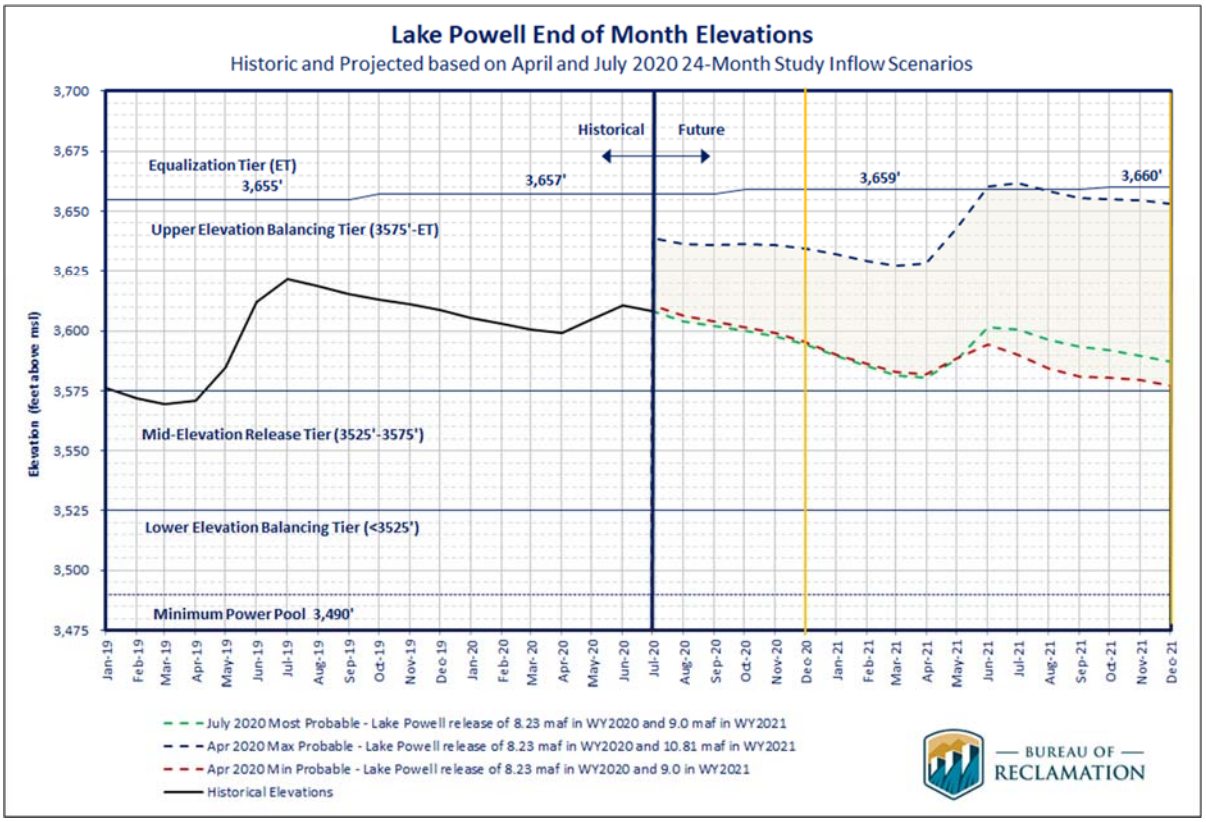
Hydrologic Conditions July 2020

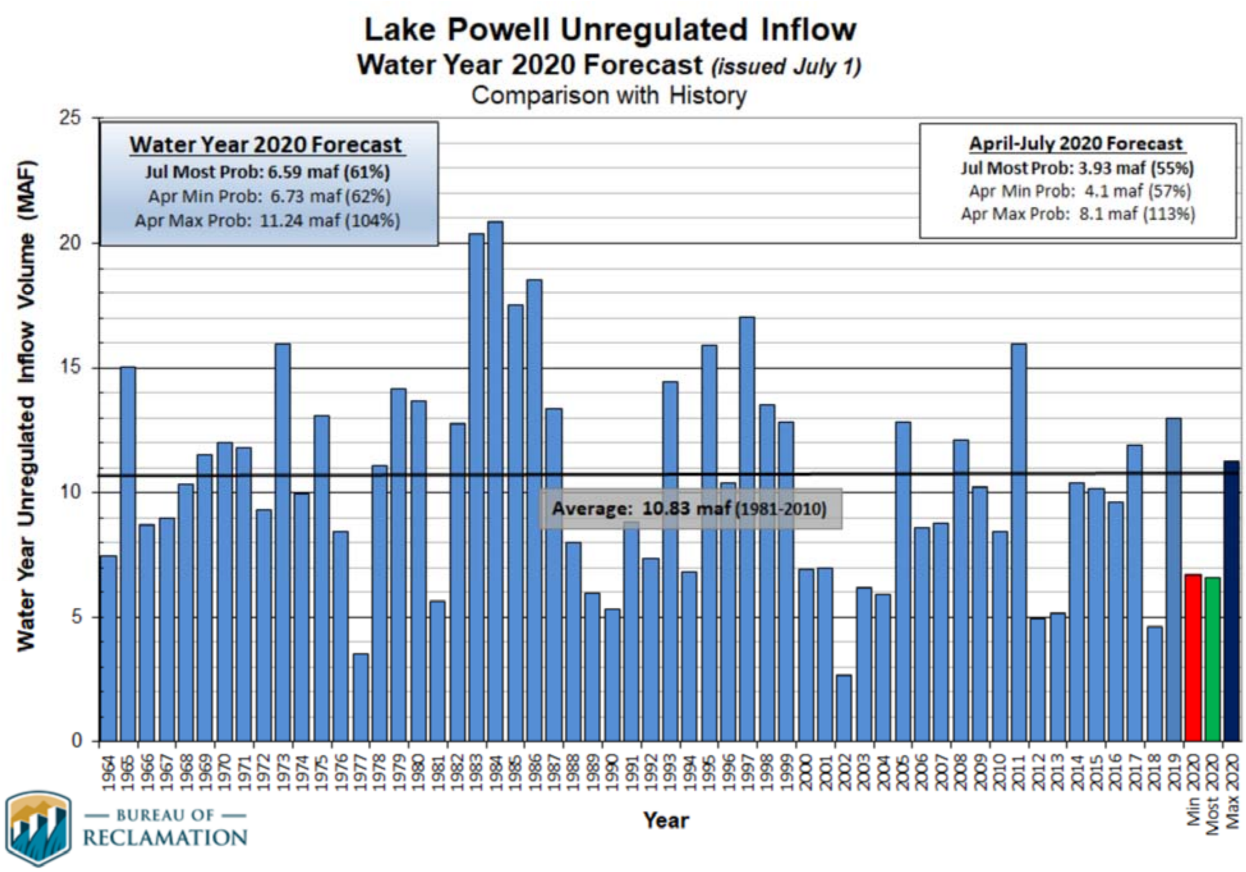
Southwestern Water Conservation District

THE COLORADO RIVER

COLORADO RIVER HYDROLOGY & STORAGE CONDITIONS The period 2000-2019 was the lowest 20-year period since the gates were closed at Glen Canyon Dam in 1963, with only 5 of the 19 years yielding above average hydrology. **Lake Powell** levels were at 51% of capacity with 12.4 maf in storage on July 26th and the content at **Lake Mead** was 40% of capacity with 10.4 maf in storage. **For Water Year 2020**, coordinated reservoir operations are in the Upper Elevation Balancing Tier. Under this Tier the initial annual water year release volume is 8.23 maf.




Lake Powell End of Month Elevations
Historic and Projected based on April and July 2020 24-Month Study Inflow Scenarios
Elevation (feet above msl)
Historical
Future
Equalization Tier (ET)
3,655'
3,657'
3,659'
3,660'
Upper Elevation Balancing Tier (3575'-ET)
Mid-Elevation Release Tier (3525'-3575')
Lower Elevation Balancing Tier (<3525')
Minimum Power Pool 3,490'
July 2020 Most Probable - Lake Powell release of 8.23 maf in WY2020 and 9.0 maf in WY2021
Apr 2020 Max Probable - Lake Powell release of 8.23 maf in WY2020 and 10.81 maf in WY2021
Apr 2020 Min Probable - Lake Powell release of 8.23 maf in WY2020 and 9.0 in WY2021
Historical Elevations
BUREAU OF RECLAMATION


Lake Powell Unregulated Inflow
Water Year 2020 Forecast (issued July 1)
Comparison with History
Water Year 2020 Forecast
Jul Most Prob: 6.59 maf (61%)
Apr Min Prob: 6.73 maf (62%)
Apr Max Prob: 11.24 maf (104%)
April-July 2020 Forecast
Jul Most Prob: 3.93 maf (55%)
Apr Min Prob: 4.1 maf (57%)
Apr Max Prob: 8.1 maf (113%)
Average: 10.83 maf (1981-2010)
Water Year Unregulated Inflow Volume (MAF)
Year
BUREAU OF RECLAMATION

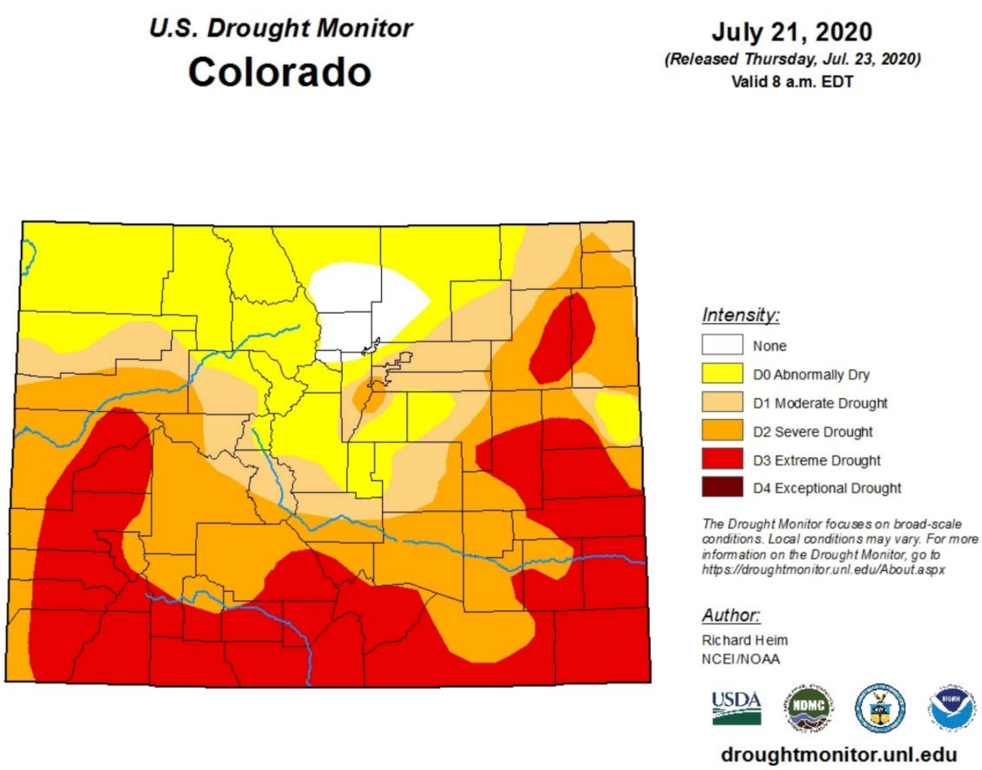
HYDROLOGY SNAPSHOT

STREAMFLOWS/DROUGHT REPORT

Here are stream flows from across our region. Flows on the San Miguel, Dolores, McElmo and La Plata increased slightly since the June report.

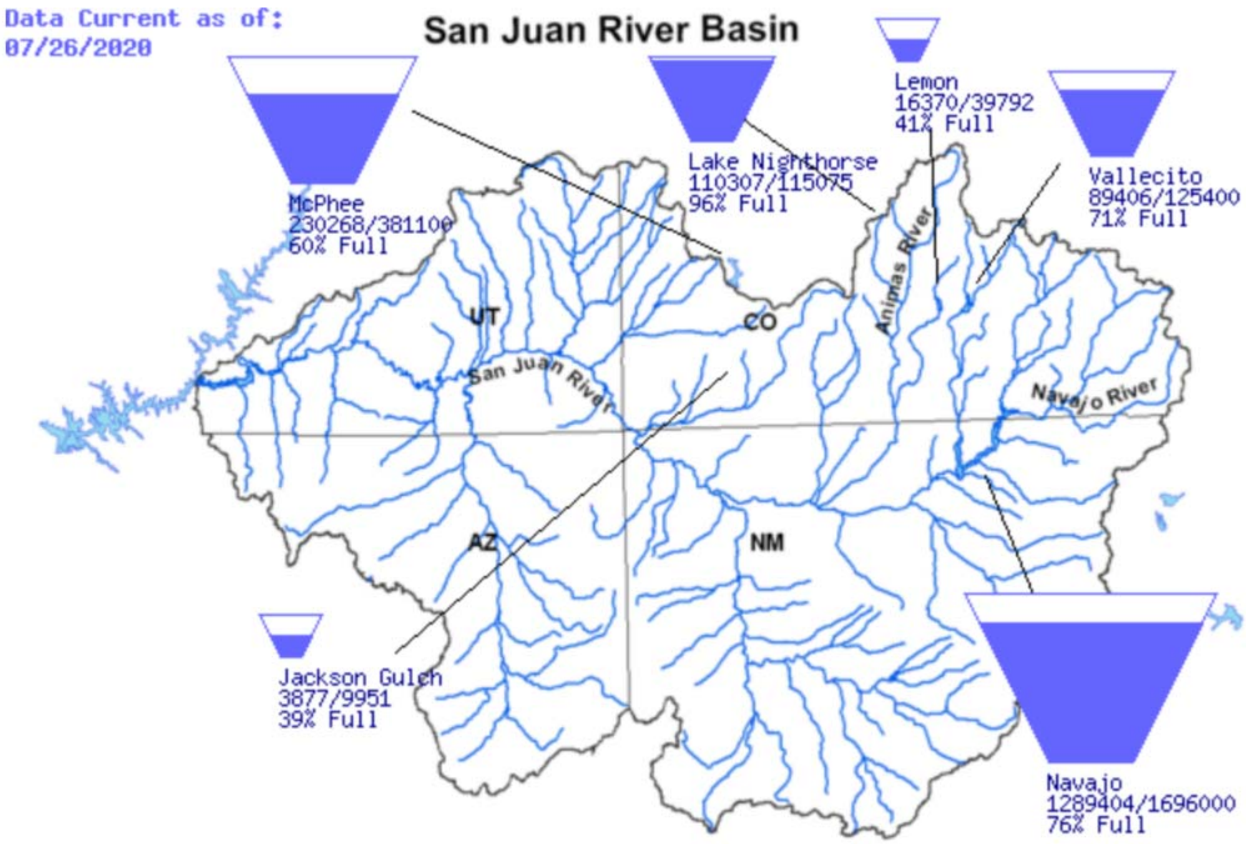
STREAM FLOWS ON 7/27/20

San Juan at Pagosa Springs – 135 cfs
Piedra at Arboles – 68.2 cfs
Pine near Ignacio – 2.95 cfs
Animas at Durango – 770 cfs
La Plata at Hesperus – 30.7 cfs
Mancos near Towaoc – 0 cfs
McElmo Creek near Cortez – 48.2 cfs
Dolores at Dolores – 331 cfs
San Miguel at Placerville – 275 cfs



The latest U.S. Drought Monitor shows extreme and severe drought conditions across the District.

Reservoir storage remains just above average for most major basins in Colorado.



COLORADO
Colorado Water
Conservation Board
Department of Natural Resources

1313 Sherman Street, Room 718
Denver, CO 80203

P (303) 866-3441
F (303) 866-4474

Jared Polis, Governor

Dan Gibbs, DNR Executive Director

Rebecca Mitchell, CWCB Director

TO: Colorado Water Conservation Board Members

FROM: Lauren Ris, CWCB Deputy Director
Anna Mauss, CWCB Chief Operating Officer

DATE: July 15-16, 2020

AGENDA ITEM: 10. Budget Update

Introduction:

This informational agenda item will describe the CWCB budget impacts as a result of the economic consequences associated with COVID-19. These impacts will likely span three fiscal years: fiscal year 2019-20 (ended on June 30, 2020), the current fiscal year 2020-21, and the next fiscal year 2021-22.
Discussion:

Fiscal Year 2019-20

General Fund revenue declined dramatically in the last quarter of FY 2019-20 due to the economic impacts of COVID-19. In response, Governor Polis issued a sequestration plan through Executive Order D 2020 050, in addition to other statewide fiscal conservation guidance from the Governor's Office of State Planning and Budgeting. The order implemented a targeted state-wide spending reduction of $228.7 million General Fund to maintain minimum statutory reserve requirements. As part of this sequestration plan, approximately $866,000 of the $1.7 million General Fund appropriation for CWCB's demand management feasibility study (authorized by Senate Bill 19-212) was redirected to help address this general fund shortfall. Due to the COVID-19 related travel and meeting restrictions that impacted the demand management work groups, and being able to do more work in house than previously anticipated, CWCB does not expect any significant impacts to the effort.

In this fiscal year, the CWCB's Perpetual Base Fund and Construction Fund each contributed $33 million to the TABOR emergency reserve ($66 million total). While these funds were not ultimately drawn on for this purpose, this fact contributed to the overall uncertainty of the status of these funds and their availability for new expenditures.

Due to the significant revenue shortfalls projected, and the role that CWCB's cash funds would play in backfilling these shortfalls either through the TABOR emergency reserve or through any budget balancing actions by the General Assembly, CWCB staff postponed bringing Water Plan Grant recommendations scheduled for the May Board meeting to this July meeting (Agenda Item 21).

Fiscal Year 2020-21

As part of the budget balancing package to backfill the $3.3 billion General Fund revenue shortfall for FY 2020-21, the Long Bill package redirected $45.5 million from the Perpetual Base Fund to the General Fund. In taking this action, the Joint Budget Committee considered the needs of CWCB's Loan Program allowing staff to bring new loan recommendations for this year. Additionally, the Long Bill included only $33 million from the Construction Fund for the TABOR Emergency Reserve for this fiscal year (as compared to the previous year's inclusion of an additional $33 million from the Perpetual Base Fund).

The June 2020 Legislative Council Staff Revenue Forecast projects an 81% decline in statewide severance tax revenue compared to Fiscal Year 2019-20 resulting from the historic collapse in oil prices that occurred in mid-March 2020. Based on this forecast, both DNR severance tax cash funds--the Perpetual Base Fund and the Operational Fund--are projected to receive only $5 million each in FY 2020-21. In order to ensure that there is sufficient revenue in the Operational Fund to support the staff salaries and ongoing operations in DNR Core Programs, DNR is restricting spending of the August disbursement of funding to the DNR Grant Programs (including the Water Supply Reserve Fund, the Water Efficiency Grant Program, and IBCC) until the fund has stabilized. In addition, the CWCB receives up to 5% of the Core Program funding for Operational Fund Grants on an annual basis. These grants were approved by the Board in March, however in order to support the other Core Programs, these grants will not receive funding and the grant program will be suspended pending future revenue projections. DNR is monitoring the status of Operational Fund on a continuous basis and will revisit restrictions after every quarterly revenue forecast.

Additionally, the 2020 Projects Bill (HB 20-1403) passed which included appropriations from the Construction Fund to a variety of programs, including additional funding for the Water Plan Grant Program, the Watershed Restoration Program, and the Alternative Transfer Methods (ATM) Program. However, due to the continued economic uncertainty, CWCB staff anticipates needing to budget conservatively and stretch available grant program funding over the next three fiscal years. Additional information as it relates to this spending plan will be discussed during the September Finance Committee meeting. Table 1. Summarizes the various impacts to CWCB programs.

Table 1. Budget Impacts to CWCB Programs.

SEVERANCE TAX SUPPORTED PROGRAMS	IMPACT
Severance Tax Operational Fund Grants	Grants approved by the board in March 2020 that were expected to begin in July 2020 will not proceed with contracting. Funding for this grant program is suspended until further notice.
Water Supply Reserve Fund Grants	No new funding in FY21. Roundtables can still award grants from the current basin account fund balances. Grants that were approved by the CWCB in FY 19/20 are still moving forward. The current balance for the statewide account will be stretched over the next three fiscal years.
Water Efficiency Grant Program	The program will not receive additional funding in FY21. Limited grants can be awarded based on the fund balance. The current balance will be stretched over the next three fiscal years.
Species Conservation Trust Fund	The program will not receive additional severance tax funding in FY21. Limited projects will continue based on the fund balance. This does not affect funding that was authorized in this year's SCTF legislation (SB20-201).
Interbasin Compact Committee	This program will not receive additional funding in FY21. Funding can be spent from the existing balances. However, funds for meeting space, food, travel will be limited (and may not be permitted at all depending on public health orders in place at the time of the meeting).
Loan Program	No impacts expected this Fiscal Year. Loan applications are being accepted.
CONSTRUCTION FUND SUPPORTED PROGRAMS	IMPACT
Water Plan Grant Program	The Projects Bill passed including funding for new grants. The board will consider applications postponed in May at its July 2020 meeting (stemming from the February 1, 2020 application round). The Board will consider staff's recommendation for Future application deadlines in Agenda Item 20.
CO Watershed Restoration Grant Program	The Projects Bill passed including funding for grants. The current balance will be stretched over the next three fiscal years.
ATM Grant Program	The Projects Bill passed including funding for grants. The current balance will be stretched over the next three fiscal years.

Fiscal Year 2021-22

While state revenue is projected to rebound, revenue collections for FY 2021-22 are expected to remain below FY 2018-19 levels. The State and Legislative economists caution that the economic outlook is especially uncertain in light of the evolving COVID-19 crisis and depends on the trajectory of the pandemic, the pace of the recovery, and the availability of federal aid. Even with a strong rebound in economic activity, the state budget situation is still expected to be very challenging in FY 2021-22 with a significant General Fund revenue shortfall to account for.

In spite of this uncertainty, the budget planning cycle for Fiscal Year 2021-22 has already begun. Agencies are currently in the process of preparing budget scenarios for the Office of State Planning and Budgeting and DNR anticipates responding to future budget reduction targets.

After the passage of Proposition DD during the November 2019 election, sports betting launched on May 1; however, revenues face an uncertain near-term future with all professional sports indefinitely suspended in the U.S. A forecast of sports betting revenue will be available in future forecasts, once tax collections data for several months become available.

Background:

Severance Tax Perpetual Base Fund

Revenue into the Perpetual Base Fund comes from interest on loans, treasury interest, and 25% of statewide Severance Tax Revenue. The CWCB is authorized to use the fund to make low-interest loans. Interest generated from these loans goes back into the fund.

DNR Severance Tax Operational Fund

The DNR Operational Fund receives 25% of severance tax revenue to support two tiers of programs: Core Programs and Grants. Core Programs provide funding for staff salaries and operations in several DNR agencies including the Oil and Gas Conservation Commission, Division of Reclamation Mining and Safety, Avalanche Information Center, and Colorado Parks and Wildlife. CWCB also receives up to 5% of this Core Program funding, however, unlike the other DNR agencies, CWCB uses that funding for Severance Tax Operational Fund Grants (typically about $1.3 million). See Figure 1.

When the annual revenue into the Operational Fund exceeds $17 million satisfying the funding needs of the Core Programs plus the 100% Core Program reserve requirement is met, any additional revenue is distributed proportionally to DNR Grant Programs. See Figure 2. The CWCB Grant Programs include:

- Water Supply Reserve Fund (up to $10 million)
- Species Conservation Trust Fund (up to $5 million)
- Water Efficiency Grant Program (up to $550K)
- Interbasin Compact Committee Operations Fund (up to $745K)

Figure 1. Distribution of severance tax revenue.

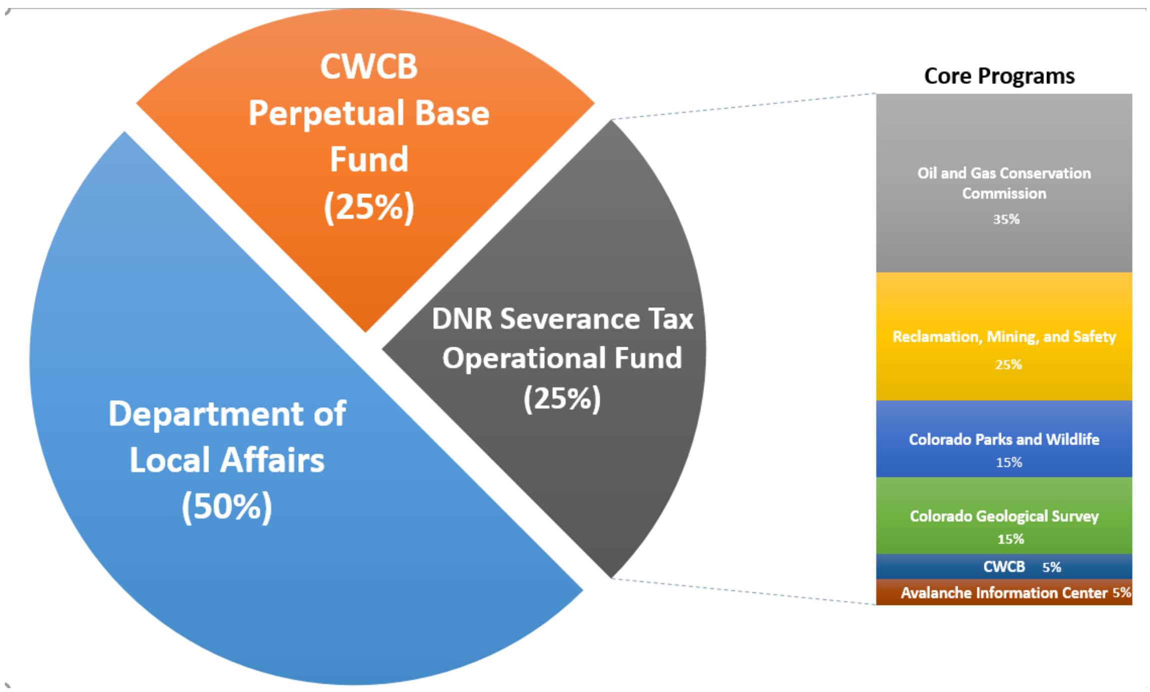
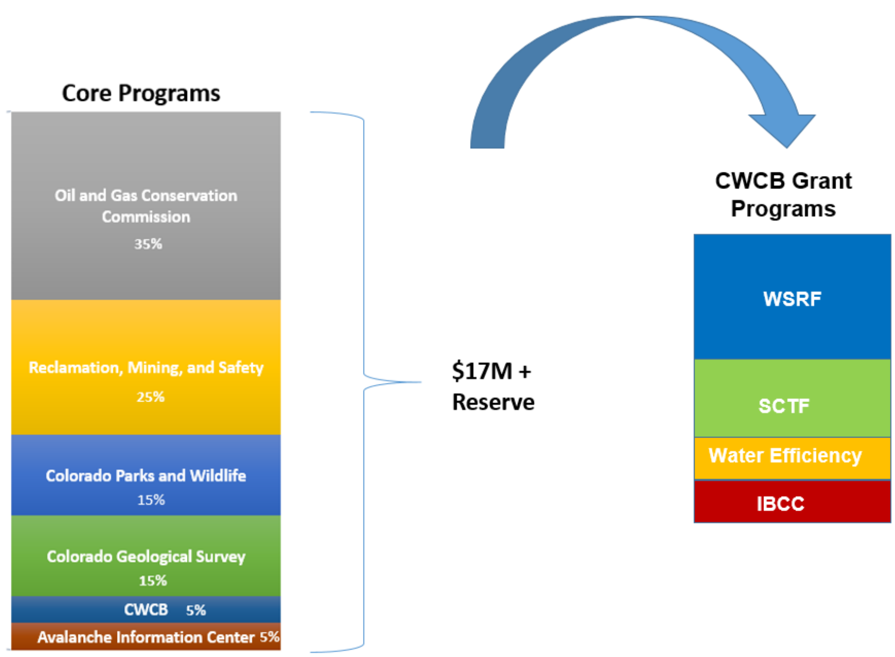


Figure 2. Distribution of of severance tax revenue once the Core Programs funding obligation has been met to Grant Programs.



MEMO

From: Gigi Richard and Laura Spann
To: SWCD Board
Date: July 24, 2020
Subject: Proposed SWCD-Four Corners Water Center Virtual Outreach Event

---

The SWCD Board requested options to consider at the August board meeting for hosting a virtual fall outreach event to replace SWCD's Annual Water Seminar. Fort Lewis College will also be cancelling their Fall Forum. In lieu of both events, we suggest our organizations collaborate to host a virtual event focused on southwest Colorado hydrology, news from the state, and local water-related efforts:

Virtual Event: Water Connections in Southwest Colorado (Final Title TBD)
Hosts: SWCD and Four Corners Water Center at Fort Lewis College
Target Audience: Southwest Colorado public and partner water organizations
Date: Wednesday, October 14, 2020
Time: 4:00-5:30pm
Cost: Free

We propose a short, free evening event on the date people are holding for SWCD's annual water seminar. By providing this evening time, we hope that may allow producers or other working people to attend.

Our proposal seeks to counter "Zoom fatigue" by offering an attractive, unique opportunity to connect people. This virtual event will provide southwest Colorado a chance to congregate online and share in an engaging way.

We are also discussing opportunities for student participation. For example, a student could be assigned a speaker to introduce and then solicit questions. If no question is asked, the student would come prepared with one question for the speakers.

Please continue to the next page to review a proposed agenda with speakers. No speakers will be invited until the SWCD board considers this proposal.

We look forward to hearing your reactions and input.

Tentative Virtual Event Agenda with Proposed Speakers to Invite:

Welcome (2-3 minutes)
Bob Wolff, Southwestern Water Conservation District
Gigi Richard, Four Corners Water Center at Fort Lewis College

Water Year 2020 Hydrologic Update (15 minutes with questions):
Rob Genualdi, Division 7 Engineer (2-3 minutes)
Bob Hurford, Division 4 Engineer (2-3 minutes)
Susan Behery, US Bureau of Reclamation (2-3 minutes)

Water User Anecdotes on 2020 Water Year (5-7 minutes with questions):
Ken Curtis, Dolores Water Conservancy District (1-2 minutes)
Gretchen Rank, Mancos Conservation District (1-2 minutes)

Tribal Update (5-7 minutes with questions):
Ute Farm & Ranch Enterprise or Ute Mountain Ute Tribe
Southern Ute Indian Tribe

State Fiscal Situation and Agricultural Update (15 minutes with questions):
Kate Greenberg, Colorado Department of Agriculture (5-7 minutes)
Celene Hawkins, Colorado Water Conservation Board (3-5 minutes)

Partner "Pop Ups": Share What You're Working On (30-45 minutes with questions)

This section intends to allow short (1-2 minutes) conversational updates from partners to bring together southwest Colorado as the seminar and FLC forum usually do. Organizations will be invited to sign up for a short update in advance.

Water Conservancy Districts, Irrigation Districts
Local Reps from State & Federal Agencies
Local Water Education & Science Organizations
Stream Management Planning Efforts
Municipal Water Suppliers
Local Environmental Advocates
Recreation Industry Representatives
Local Forest Health Collaboratives

Wrap-Up and Invite Feedback (2-3 minutes)
Bob Wolff, Southwestern Water Conservation District
Gigi Richard, Four Corners Water Center at Fort Lewis College

FROM: Aaron Kimple, Mountain Studies Institute

SUBJECT: SW CO Environmental Impact Fund (EIF) Status Update, August 2020

The EIF team is excited to announce that we have secured two sources of support for the next phase of the project: structuring the Fund. The team was just notified that we were successful in our proposal to the Innovative Finance for National Forests (IFNF) grant program, a joint initiative between the US Forest Service and the US Endowment for Forestry & Communities. The submission included eight letters of support from local, state, and national organizations.

The regional commitment from the Southwestern Water Conservation District with your grant regarding water quality monitoring was key to obtaining this national source of funding. The EIF team will use SWCD's contribution specifically to quantify impacts of wildfire risk and forest health on regional water resources. The team has developed a scope of work and we are aligning it with partner needs, including water delivery to the City of Durango. Letters of support from other local organizations were also key to the EIF's grant funding success.

The EIF team now includes Bob Cole, a Colorado attorney with expertise in local government and special district law, to design the intergovernmental EIF entity. **The EIF team requests from SWCD the ability to share the draft of that entity agreement with your leadership and legal counsel to seek your feedback on this foundational document for the EIF entity.**

The draft agreement is being shared with La Plata County and the City of Durango as well as it creates a coordination structure for the organizations that will participate in the management and operation of the EIF. Participating in this process doesn't commit you beyond having input early on in the operation of the EIF entity. However, we would like to see SWCD as a active participant and potential payor as the EIF is stood up so that your priorities for critical watershed protection and wildfire mitigation are included in the work of the EIF.

The EIF project team has also closely followed the developments of the Rocky Mountain Restoration Initiative (RMRI) and worked with RMRI local team members to conceptualize ways the RMRI and EIF could work together to support lasting forest health solutions in SW Colorado. The EIF offers an efficient and localized mechanism to deploy resources from a variety of sources to support the 65,000-acre treatment program. As a locally driven, self-sustaining fund, the EIF can carry RMRI objectives of regional forest health into the future.

We know COVID-19 presents a significant and urgent challenge for the region, and that many local governments are focused on proactive measures to avoid the worst impacts of this public health emergency. That said, we also know that proactive steps such as the EIF creation and operation, need to be taken to mitigate further harm to our people, forests and watersheds. We believe the effort We appreciate your time and input on this important project and hope you will review and participate in the development of the EIF agreement with our other local governmental partners.

Best,
The EIF Team

Aaron Kimple, MSI
Ellen Roberts, Ellen Roberts Consulting
Todd Appel, Quantified Ventures
Ben Cohen, Quantified Ventures

Bob Cole, Collins Cockrel & Cole
Jason Lawhon, San Juan National Forest
Laura Drescher, Quantified Ventures

Gmail

Laura Spann <lauras@swwcd.org>

Colorado v. EPA 2020 WOTUS Rule Lawsuit - Funding

Doug Kemper <dkemper@cowatercongress.org> Thu, Jul 2, 2020 at 6:55 PM
To: Andrew Colosimo <acolosimo@csu.org>, Laura Spann <lauras@swwcd.org>, "bob@durangodevelopment.net" <bob@durangodevelopment.net>, "chris.piper@denverwater.org" <chris.piper@denverwater.org>, "Kitzmann, Kathleen" <KKitzman@auroragov.org>, "ewwilk13@gmail.com" <ewwilk13@gmail.com>, Andy Mueller <amueller@crwcd.org>, "jcurrier@crwcd.org" <jcurrier@crwcd.org>, "jmcclow@ugrwcd.org" <jmcclow@ugrwcd.org>, "jwb@secwcd.com" <jwb@secwcd.com>, "award@pueblowater.org" <award@pueblowater.org>, Brad Wind <bwind@northernwater.org>, Donna Brosemer <Donna.Brosemer@greeleygov.com>, Emily Hunt <Emily.Hunt@cityofthornton.net>, "lbrooks@erwsd.org" <lbrooks@erwsd.org>, "jim.lochhead@denverwater.org" <jim.lochhead@denverwater.org>, "lclever@utewater.org" <lclever@utewater.org>, Cleave Simpson <cleave@rgwcd.org>, Sean Cronin <sean.cronin@svlhwcd.org>, "emily@coloradofb.org" <emily@coloradofb.org>
Cc: Peter Levish <peter@cowatercongress.org>, Chane Polo <Chane@cowatercongress.org>

All,

I am writing to gauge your interest in helping fund possible Colorado Water Congress involvement in the Colorado v. EPA 2020 WOTUS Rule litigation. The district court granted a preliminary injunction that blocked implementation of the 2020 WOTUS Rule in Colorado. The ruling has been appealed to the 10th Circuit. An expedited briefing schedule has been set by the 10th Circuit. Briefs are due July 16.

The CWC Board will soon consider whether the Water Congress should get involved in the case. We are likely to focus on concerns about CDPHE having duplicative or conflicting permitting processes on what the State calls "gap" waters – those waters that are considered waters of the State, but not waters of the U.S.

The tone of the current discussion is that CWC would file an amicus brief rather than seeking to intervene in the case. A motion to intervene would ultimately be very expensive with an uncertain outcome in this dynamic political environment.

If approved, we would need financial support. The Water Congress does not maintain a litigation fund.

The estimated budget for CWC legal involvement is $10,000 to $15,000. Contributions from many entities would make for a relatively light lift. I am writing to see if your organization or partnerships in which you participate might be interested in helping fund this work.

We simply will not be able to get involved in the case without financial support.

Time is obviously short here, but please let me know if you have any questions or might have funds available. Thank you.

Best regards,

Doug

Douglas Kemper | Executive Director

The Sentinel

Rare cutthroat trout saved from Colorado fire released

DURANGO, Colo. (AP) — While firefighting crews were in the throes of battling the 416 Fire as it rapidly spread through the San Juan National Forest north of Durango in June 2018, an unlikely rescue mission was being hatched.

Jim White, an aquatic biologist for Colorado Parks and Wildlife, said plans had to move fast as the blaze started inching toward prime habitat for a rare lineage of cutthroat trout that lives in the remote side streams of Hermosa Creek.

Colorado Parks and Wildlife knew what was at risk: the potential loss of a native fish that had survived in isolation, against the odds, through all the disturbances of the West's settlement.

With a massive wildfire as the latest threat, the survival of these trout depended on a small crew from CPW and the U.S. Forest Service who were granted special permission to enter the fire zone, with only hours to work.

"We couldn't have anything go wrong," White said. *"But if a fire burned through that drainage, you could lose an entire population and those genetics."*

Now, two years later, the fish saved during the rescue will be released back into the wild.

SURVIVING THE DECADES

By the late 1880s, Western settlers fished the Colorado River cutthroat trout to the point of extinction, and then dumped more competitive species of trout into rivers and streams to keep the food source available.

The magnitude of the cutthroat's loss has never been truly quantified, but best estimates show its range — which once spanned Colorado, New Mexico, Utah and Wyoming — has been cut by about 85%.

For the past 50 years, CPW biologists have scoured the backcountry looking for surviving populations of cutthroats. In the 1980s and 1990s, fish suspected of fitting the bill were discovered in eight small streams in Southwest Colorado.

But at the time, technology didn't exist to say for sure.

In 2018, however, DNA testing confirmed those suspicions, linking a cutthroat found in the San Juan River basin to fish samples collected and preserved in 1874 by naturalist Charles E. Aiken, who donated two trout to the Smithsonian National Museum of Natural History.

"It was super-exciting," Mike Japhet, a retired CPW biologist who helped discover the San Juan lineage of Colorado River cutthroat trout in the early 1990s, told The Durango Herald at the time. *"It's like going on a treasure hunt and finding you really discovered a hidden treasure."*

RESCUE MISSION

Everyone knew summer 2018, with its historic drought conditions, was going to be a bad year for wildfire, White said. In preparation, the groundwork for trapping some of the cutthroats in the Hermosa Creek watershed was laid the winter before.

"We knew a fire was a distinct possibly where one of these rare streams are and it could be terrible," he said.

So when a small spark north of Durango ballooned into the 85-square-mile (220-square-kilometer) fire that swept through the drainage, crews were ready to go. A small team of about seven people started early, taking ATVs as far into the backcountry as possible.

After the road ended, crews hiked 2 miles (3.2 kilometers) to reach the remote stream. Once there, they had three hours to catch as many fish as possible before having to escape the area before nightfall.

"It was spooky," White said, recalling the fire burning off in the distance. *"It had to be carefully orchestrated."*

Despite the odds, 54 cutthroats were recovered.

"The next day, the fire mushroomed, and we would never have been allowed back there," White said.

STRUGGLES IN

CAPTIVITY

The fish were brought back to the hatchery in Durango where they have been kept in isolation. At first, biologists were concerned because the fish did not spawn last year and some died of a parasite.

This year, however, CPW hit a stroke of luck.

"We're not getting a lot of eggs, but enough to provide some for a limited amount of stocking and some to start a captive population that will be sustainable," Durango Hatchery Manager Toby Mourning said in a statement.

This summer, CPW intends to trek the fish back to their native habitat and release them into the wild. And with the captive population at the hatchery, the agency can start to restock other streams throughout the Southwest.

"If we hadn't saved them, we would have seen substantial loss," White said. *"But now we can expand their range."*

RECOVERING SLOWLTY

By all accounts, aquatic biologists are hopeful reintroduction will be successful.

The 416 Fire has had substantial impact on water quality in the Hermosa Creek watershed, causing several debris flows and fish kills, especially in July and September 2018 when heavy monsoons hit the burn scar.

But slowly, the watershed is showing signs of recovering, said Scott Roberts, an aquatic biologist for Mountain Studies Institute, which is leading a robust study tracking water quality after the 416 Fire.

Watersheds usually take about three to five years to recover after a wildfire compromises the drainage. Roberts said all indicators point to Hermosa Creek being on track for that time frame.

“The impacts are highly localized, some areas were hard hit and the habitat transformed, while other places are trending toward pre-fire conditions quickly,” he said. *“But I feel confident there are areas fish can be successful up there.”*

The upper reaches of Hermosa Creek boast the largest continuous stretch of native Colorado River cutthroat trout in the state thanks to a dedicated conservation effort that dates back to the early 1990s

“The watershed is not perfect, but it’s stabilized, and we feel we can responsibly move fish up there,” White said. *“This is definitely a one small step at a time process, but we’re excited to have some fish to work with.”*

COLORADO RIVER DISTRICT
PROTECTING WESTERN COLORADO WATER SINCE 1937

FOR IMMEDIATE RELEASE
Tuesday, July 21, 2020

CONTACT: Jim Pokrandt – 970.319.1807

Colorado River District to ask voters for money to bolster protection of West Slope water

Board authorizes Nov. 3 ballot question to increase mill levy by $1.90 per year per assessed $100,000 of residential value

GLENWOOD SPRINGS, Colo. – The Colorado River District's board of directors adopted a resolution Tuesday, July 21, 2020, to ask voters in November to support a property tax increase to protect water security in Western Colorado while funding projects to improve water use and healthy streams.

River District General Manager Andy Mueller said the board's resolution asks for taxpayer support for the River District work directed at:

- Fighting to keep water on the West Slope;
- Protecting adequate water supplies for West Slope farmers and ranchers;
- Protecting sustainable drinking water supplies for West Slope communities; and
- Protecting fish, wildlife, and recreation by maintaining river levels and water quality.

The resolution also approves a Fiscal Implementation Plan that spells out how the added money would be invested across the district. Included in the plan is an explicit direction that the "district is committed to coordinating and consulting local elected officials in any and all relevant counties prior to committing funds to any specific project or activity pursued by the district."

If voters agree, the median residential property tax increase in the district's 15-county region would be $7.03 per year. The question will go on the Nov. 3, 2020, ballot in Grand, Summit, Eagle, Pitkin, Garfield, Routt, Moffat, Rio Blanco, Mesa, Delta, Ouray, Gunnison, and parts of Montrose, Saguache and Hinsdale counties.

The resolution references the mission of the Colorado River Water Conservation District to lead in the protection, conservation, use and development of the water resources of the Colorado River Basin for the welfare of the District and to safeguard for Colorado all waters of the Colorado River to which the state is entitled.

According to the resolution, in these increasingly contentious times of long-term drought and external pressure on water, Western Colorado needs "a strong and effective advocate." Meanwhile the district budget is "projected to continue to be negatively impacted due to declining revenues from the energy sector, the impacts of the Gallagher Amendment and the revenue limitations of the Taxpayer Bill of Rights (known commonly as TABOR)."

According to the Fiscal Implementation Plan, the new mill levy would raise about $4.9 million more annually for the River District throughout its 15-county boundaries. About $4.2 million would be dedicated to partnership projects across the District in one or more of the following five categories laid out in the plan: **productive agriculture, infrastructure, healthy rivers, watershed health and water quality, conservation and efficiency**. The rest would address budgetary reductions caused by the Gallagher and TABOR amendments. No new staff positions would be created with the new funds.

Attachments:
Resolution adopted July 21, 2020
Fiscal Implementation Plan adopted July 21, 2020

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Bonita Peak CAG

Ms. Christina Progess
Superfund Project Manager, EPA, Region 8
1595 Wynkoop Street
Denver, CO 80202-1129

June 22, 2020

RE: Draft Chapters 2 & 4 of the BPMD Site Management Strategy

Dear Ms. Progess:

The Bonita Peak Community Advisory Group (CAG) appreciates the opportunity to review and comment on Chapters 2 and 4 of the Site Strategy Management Plan. In general, we are supportive of EPA's efforts to move forward expeditiously with smaller projects for improving water quality and protecting human health, and to adaptively change management strategies based upon lessons learned through project implementation.

For these two particular chapters, we have several comments and concerns. First, this detailed Site Management Strategy lays out a process-heavy plan for moving forward in five-year increments. It appears to us that EPA is settling in for a twenty-five to thirty-year timeframe for completing and potentially delisting the Bonita Peak Mining District (BPMD). Extensive study and mine remediation have been on-going for the past twenty-five years in the BPMD. Given all the work that has already been accomplished, we feel that we should be moving more quickly to set specific goals and objectives and to address individual mine sites.

Another reason for moving more quickly is related to the lack of designated boundaries for the 48 listed mine sites in the BPMD. Multiple mine claims with multiple property owners surround many of these mines. The owners have been left in limbo, not knowing if their properties are considered part of the listed site and whether or not they have remediation responsibilities. Setting specific goals and objectives are the first steps towards giving these owners clarity as to their potential obligations.

We also realize that the BPMD is currently a high priority site for EPA and is garnering quite a bit of resources. That may not always be the case. We want to be sure that significant progress is made while we remain a high priority.

With regard to setting more specific goals and objectives, our biggest concern with these chapters lies with the structure laid out in Chapter 4 for the roles of the CAG and the BPMD Silverton Planning Group (SPG). First, Section 4.1 states that the initial Site Principles (site goals and objectives) were developed collaboratively by EPA and Site stakeholders. In fact, community stakeholders were not part of that process. Several government agencies developed those Site Principles and presented them to the local community. While these initial Site Principles are reasonable, we are concerned that as they are revisited and potentially become more specific, they will again be developed with little input from community stakeholders. Local stakeholders are directly impacted by the goals and objectives selected at this site. We want our perspectives included in the initial "input" stage in the Site Principles development. Similarly, we are keenly interested in reviewing the Five-Year Strategic Plans, particularly because part of the Five-Year Plan development is a discussion as to whether or not the Site Principles need to be reviewed and revised.

Some members of the CAG and SPG have twenty-five years of experience with water quality and mine remediation in the Animas Basin. As far as we can tell, currently only one EPA person who is heavily involved with the site has more than four years of direct experience in the Animas Basin. EPA should welcome the use of long-term, local experience.

Several more specific comments:

- In Chapter 4, the first figure shows the circular flow path for Adaptive Management. The other four figures in the chapter show one-way, linear process flows. While the four linear diagrams pertain to the first step in the Adaptive Management figure, it is somewhat confusing to show a number of linear processes as part of what is supposed to be a circular, iterative process. It might be useful to both show in the figures and discuss in the text how the Knowledge Integration is to be incorporated into the three distinct decision-making levels outlined in section 4.1.

- In Section 4.4, second paragraph, describes how EPA will review feedback from the CAG and SPG "to determine if the format of the Annual BPMD Task List requires updates." But nowhere in the diagrams or descriptions in Chapter 4 is there any discussion of when and how that feedback will be solicited or provided.

- We have attached the Word documents of the two chapters with some minor "track changes" suggestions and clarifications.

- Finally, we are unclear as to how the public at large will be able to weigh-in on the Site Strategy Management Plan, future changes in the Site Principals, development of the Five-Year plans and Annual Task Lists. Will there be any formal public notice or official comment periods for any of these documents?

When the San Juan County Commissioners first asked Governor Hickenlooper to formally request the listing of the BPMD on the National Priority List, one of their stated conditions was for local interests to have a "seat at the table." The CAG and SPG represent many of those interests, and remain continually vigilant that the chair isn't pushed back into the second row. This is our main concern with these chapters.

We look forward to EPA's response to our concerns.

On behalf of the Bonita Peak CAG,

Peter Butler, Ph.D.

Chair, Bonita Peak CAG
Butlerpeter2@gmail.com
970-317-0584
www.BonitaPeakCAG.org

cc:

Senator Michael Bennet
Senator Cory Gardner
Rep. Scott Tipton
La Plata County Commissioner Clyde Church
San Juan County Commissioner Pete McKay
Silverton Mayor Shane Fuhrman
Durango Mayor Dean Brookie
USFS – Kara Chadwick
BLM- Kris Doebbler
DNR– Tim Mauck

CDPHE-John Putnam
SWCD – Bob Wolff
EPA-Brigid Lowery
EPA- Doug Ammon
EPA-Shahid Mahmud
EPA-Schatzi Fitz-James
EPA- Helen Duteau
EPA-Greg Sopkin
EPA-Patrick Davis

DEEP DEFICIT

Droughts highlighted California's unsustainable use of groundwater. Now, the state is trying refill its aquifers

By **Erik Stokstad**

California's Central Valley—one of the richest agricultural regions in the world—is sinking. During a recent intense drought, from 2012 to 2016, parts of the valley sank as much as 60 centimeters per year. "It isn't like an earthquake; it doesn't happen, boom," says Claudia Faunt, a hydrologist with the U.S. Geological Survey. But it is evidence of a slow-motion disaster, the result of the region's insatiable thirst for groundwater.

For decades, farmers have relentlessly pumped groundwater to irrigate their crops, draining thick, water-bearing clay layers deep underground. As the clays compress, roads, bridges, and irrigation canals have cracked, causing extensive and expensive damage. In 2014, when NASA scientists flew radar equipment over the California Aqueduct, a critical piece of water infrastructure, they found that one section had dipped 20 centimeters over 4 months. Such sagging can leave canals carrying less water—an "ultimate irony," says Graham Fogg, a hydrogeologist at the University of California (UC), Davis, because they were built in part to slacken demand for groundwater. Excessive pumping also jeopardizes water quality, as pollutants accumulate within groundwater and the clays release arsenic. Worst of all, the persistent pumping means that, one day, aquifers might run out of usable water. "If you pump too hard," Fogg says, "you're playing with fire."

Now, California has launched a landmark effort to save its groundwater. In 2014, deep in drought, the state passed a law to protect its aquifers; since then, local water managers have developed sustainability plans for those deemed the most imperiled. The plans for some particularly hard hit regions, just released for public comment, call for ending the groundwater deficit mainly by allowing precipitation to refill aquifers, but also by curtailing demand. The state is funding scientists to gather better data on the crisis; researchers estimate that in the Central Valley, half of the aquifers are dangerously depleted, but they don't know the extent of the damage. Meanwhile, geologists are working to identify the best places to replenish aquifers by flooding farm fields, including some with especially permeable geology.

Groundwater science is taking on a new urgency as California and other regions around the world face growing threats from drought—and are increasingly drilling wells to make up for missing rain and snow. Globally, aquifers are "highly stressed" in 17 countries that hold one-quarter of the world's population, according to the World Resources Institute. Water and food supplies for billions of people are under threat.

PHOTO: ROLF SCHULTEN/ULLSTEIN BILD VIA GETTY IMAGES

Surface water moved by the California Aqueduct (left) hasn't ended overpumping of groundwater.

California is a case study in the challenges of protecting those resources. Farm interests, which use the most groundwater, often resist limiting withdrawals, whereas environmentalists demand more water be returned to rivers and the Sacramento-San Joaquin delta; the first lawsuit challenging California's sustainability plans was filed last month. Demand for groundwater is growing where farms have expanded into areas with little surface water. Across the state, climate change is making precipitation less reliable. "A lot of people are looking to California to see how the law plays out," says Ellen Hanak of the Public Policy Institute of California (PPIC). The hope, she adds, is "there's just so much local innovation in California that it can be a model for folks elsewhere."

CALIFORNIA ONCE SERVED as a global model for another type of innovation: massive water projects. Los Angeles and other cities clamored for more water than they could get locally. The San Joaquin Valley in the southern Central Valley, the state's largest and most lucrative agricultural zone, had fertile soil and plenty of sunshine, but never enough water. Farmers had to make do with what nature provided—and what they could pump from the ground.

In the 1930s, the federal government began to build a network of dams, pipelines, and canals that moved water from the state's wetter north to farms in its semiarid south. Local projects sent water to urban centers. With the taps turned on, California's farms and cities flourished.

But the imported water didn't relieve the pressure on groundwater for long. Thanks to rural electrification, more farmers could pump as much as they wanted. There were no regulations, no limits. And pumps have become ever more powerful, with the best able to guzzle up to 5000 liters per minute from aquifers. Now, in a wet year, about 40% of the water used in the state comes out of the ground; during a drought, the proportion swells to 60%. In some farming areas, the dependence is even greater during dry years (see map, p. 232).

Rates of groundwater extraction are unsustainable in many parts of the state, says Jay Famiglietti, a hydrologist at the University of Saskatchewan. During wet years, enough water from rain and gushing streams sinks into the ground to partially refill aquifers, he says, but levels can fall even lower during the next drought. "It's like a tennis ball bouncing down the stairs, it's just going in one direction," Famiglietti says.

The trend became especially worrisome during the 2012–16 drought. In the San Joaquin Valley, deep irrigation wells lowered groundwater levels—already 250 meters below the surface in places—putting it out of reach of shallower wells that provided thousands of people with drinking water. Elsewhere, environmental groups feared that springs, streams, and rivers would run dry as groundwater levels fell.

In response, state legislators introduced proposals to regulate groundwater withdrawals. The bills were fiercely opposed by farm groups, which worried about declining land values. But the push gained momentum from new satellite radar images that dramatically depicted the state's subsidence problems. "The images really drew attention to a system that's out of balance," says Rosemary Knight, a geophysicist at Stanford University.

Lawmakers were also alarmed by images of water loss (see p. 232) from NASA's Gravity Recovery and Climate Experiment (GRACE), which surveys surface and groundwater by measuring how its mass tugs on a pair of satellites. GRACE measurements, combined with other data, indicated that in 2010 Central Valley aquifers held 20 cubic kilometers less water than they had in 2003.

The Sustainable Groundwater Management Act, which became law in September 2014, was "an incredible step" for a state that had long resisted groundwater regulation, Famiglietti says. But it only requires California's some 260 groundwater sustainability agencies (new organizations set up under the law, often made up of local water districts) to stabilize, not to increase, groundwater levels. And it allows increased pumping if needed during drought, as long as no major problems result. Still, the law has forced a statewide rethink of groundwater policies. In January, the new agencies in 21 basins deemed critically overdrawn had to submit plans for achieving groundwater "sustainability" within 20 years. (Other agencies must submit their plans by 2022.)

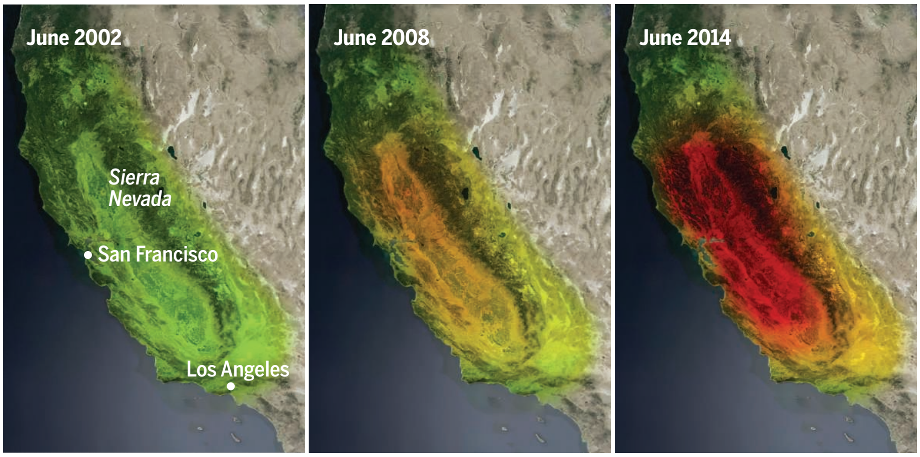
PHOTO: ROBYN BECK/AFP VIA GETTY IMAGES

The push to develop the plans has, in places, revealed an astounding lack of data. Many districts, for instance, aren't sure how much water is being removed from the ground because California doesn't require all pumps to have meters. (Local rules or court orders require metering in some basins to help resolve disputes.) In the absence of hard data, researchers have for years estimated flows by examining electricity records—groundwater pumps are energy hogs—and by mapping the extent and types of irrigated crops. Information on subsidence is also helpful. "It's pretty amazing," says hydrogeologist Andrew Fisher of UC Santa Cruz. "We're in a position now of not knowing what a lot of the big groundwater flows are or how they vary."

REDUCING PRESSURE on groundwater isn't easy or quick. One obvious tactic is to reduce demand. Some parts of California have lessened their reliance on groundwater by incentivizing efficiency and imposing requirements such as water-saving showerheads and toilets. Planting water-efficient crops helps—grapes and young almond trees use much less water than alfalfa, for example. So does leaving fields fallow, a strategy farmers have used to cope with past droughts.

California drying

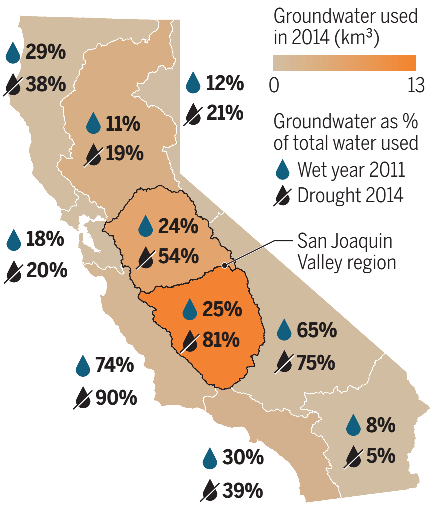
NASA's GRACE satellites detect the gravitational pull of water masses in aquifers, reservoirs, and snowpack. In 2014, GRACE data showing water loss (below, red indicates loss) helped dramatize the draining of aquifers and galvanize state lawmakers to protect groundwater.



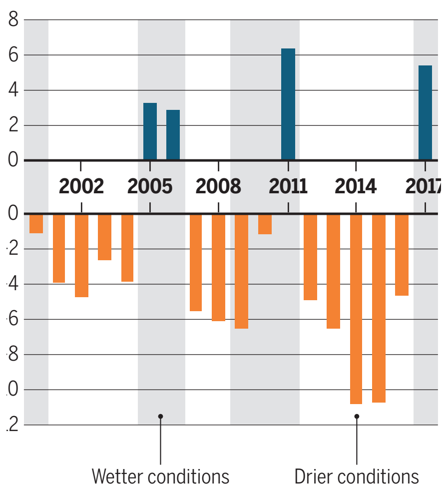
Tallying groundwater losses

California's north receives abundant precipitation, so it relies less on groundwater during droughts than the drier farmland of the San Joaquin Valley to the south (left). In that valley, pumping has taken increasing amounts of groundwater (right), with withdrawals during dry years exceeding replenishment during wet years.

A thirsty valley



Subtraction outraces addition



But for some parts of California, such measures aren't practical, in part because of a massive expansion of profitable vineyards and orchards—tree nut acreage alone increased 85% between 2008 and 2018. The groves and vineyards cannot be fallowed like other fields, although they can survive with less water than normal. And farmers are reluctant to rip them out, because they are expensive to plant, can take years to mature, and have relatively long life spans.

Still, researchers say truly protecting groundwater in California will require cutbacks in agriculture, which on average makes up about 80% of commercial and residential consumption. To stabilize groundwater in the San Joaquin Valley, farmers will likely have to reduce irrigated cropland by more than 200,000 hectares, or 10%, according to a 2019 report from PPIC. Not surprisingly, such prospects worry farmers across the state, says Chris Scheuring, a water lawyer with the California Farm Bureau Federation. "We are absolutely hoping for mitigated outcomes that get us to sustainable management without causing a lot of pain."

To slow the rate of depletion with less pain, a few districts are counting on proven methods for recharging aquifers. For decades, some water districts have filled dedicated ponds in wet years so that the water percolates into the ground. Others flood farm fields when water is plentiful. Vineyards can tolerate spring flooding, and some crops, like alfalfa, do well with flood irrigation. Building culverts and berms to move and hold the water can be expensive, however. In urban areas, where land is scarce or the upper layers of sediment or rock aren't very permeable, officials pump water into the ground instead of removing it.

To expand such practices, researchers have been searching for areas ripe for recharge, based on factors such as soil type, land use, and aquifer geology. A UC Davis team identified 1.5 million promising hectares by reviewing existing data, they reported in *California Agriculture* in 2015. Some of the best places are valleys, now buried, that once existed in the Central Valley and were filled with coarse sediments during the last ice age. These sweet spots may be able to drain 60 times as much water as average sites, Fogg says. Researchers have discovered just three of these buried valleys, but Fogg says many others must exist given the region's geological history.

Knight is using geophysical techniques to find such promising recharge areas. A helicopter-mounted instrument sends electromagnetic signals into the ground, measuring the electrical properties of bur-

CREDITS: (IMAGES) JAY FAMIGLIETTI/NASA JET PROPULSION LABORATORY; CALIFORNIA INSTITUTE OF TECHNOLOGY; UNIVERSITY OF CALIFORNIA, IRVINE; (GRAPHICS) N. DESAI/*SCIENCE*; (DATA) CALIFORNIA DEPARTMENT OF WATER RESOURCES; PPIC

When drought empties reservoirs, such as Lake Cachuma near Santa Barbara, California, in 2015, groundwater can become an even more important source of water.

ied sediment to create 3D maps of geologic formations that are as much as 300 meters deep. After that, smaller devices can be towed through fields or orchards for higher resolution images. The maps can help managers identify areas where water will quickly soak in—avoiding ponding that can lead to crop diseases or undermine trees.

The maps also show where water is most likely to reach deep layers where pumping is causing subsidence. "The level of complexity that we're capturing is amazing," Knight says. California's water resources agency recently committed $12 million to using the helicopter-mounted system in groundwater basins throughout the state.

RESTORING GROUNDWATER could become even more important because of climate change. The state has long relied on abundant mountain snow to provide a reliable, year-round source of surface water. Its many reservoirs were designed to fill with snowmelt by July, and then release the water to satisfy the peak demand during the hot summer. But because of a warming trend, the annual snowpack is already becoming thinner and melting sooner. And climate scientists predict more and more precipitation in California will fall as rain, rather than as snow in the mountains. All that means reservoirs will fill sooner and water will have to be released earlier in the spring, before it's needed. In the summer, farmers would likely have to rely even more heavily on groundwater.

To adapt to that future, officials are pondering a new arrangement in which dam operators would release water ahead of rainstorms. That would make room for the storm water, and the discharge would allow downstream sites to put more into the ground. The idea sounds simple, but involves significant changes in regulations, operations, and in some cases infrastructure, Fogg says. Still, several pilot projects are underway. In the American River watershed, a flood control agency wants to retrofit some upper reservoirs. If the strategy is implemented there and in an adjacent Sierra Nevada river basin, Fogg and colleagues estimate about one-third of a cubic kilometer of water could be stored underground each year. That's 10% to 25% of the annual statewide deficit, Fogg says.

Recharge water that comes from mountain reservoirs often has high quality. But a different source, stormwater runoff from urban or managed landscapes, could pose a problem: preventing contaminants—including farm fertilizers—from seeping into groundwater. Fisher has been studying ways to remove certain contaminants by adding biomatter such as wood mulch and almond shells to the soil at recharge sites. His team has found that the materials can promote the growth of microbes that remove nitrate, a common pollutant. "If we're going to be putting hundreds of thousands or millions of acre feet of water in the ground every year, we should be taking every opportunity to make that water cleaner on the way in," Fisher says.

Recharge isn't the whole solution. In the San Joaquin Valley, scientists estimate recharge alone can eliminate, at best, just 25% of the groundwater deficit—in part because there is so little surface water to begin with in the region. So, any additional savings will likely have to come from reduced pumping, with its political challenges, as well as shifting water to the most productive croplands while leaving others uncultivated. That will require new canals and other infrastructure, and a new level of coordination. Across the state, multiple government and private entities will need to work together on managing supply and demand at the scale of entire basins, in order to minimize the economic cost of using less water. "There has to be policy innovation or financial innovation to get people to move away from this myth that we still have an unlimited groundwater supply and that we're just never going to hit bottom," Famiglietti says.

Bridget Scanlon, a hydrologist at the University of Texas, Austin, is optimistic that innovation will occur. "California has opportunities to move towards more sustainable management, and I think they are," she says. Fogg is hopeful, too, but adds a cautious note. "Civilization has never been very successful at controlling water demand," he notes.

Luckily, California's recent winters have provided enough precipitation to allow aquifers to recover a bit. The state may not find out whether it learned the lessons of the last drought until the next one. ■

PHOTO: SCOTT LONDON/ALAMY LIVE NEWS

ENGINEERING AN EMPIRE

Ingenious water management helped the ancient Wari state expand throughout the Andes. Why couldn't it survive a drought?

By **Lizzie Wade**

When Wari colonists arrived in the Moquegua Valley of southern Peru some 1400 years ago, people already living there were likely nervous. The Wari state, with its capital city of Huari high in the Andes near what is now Ayacucho, Peru, had been expanding its reach. The Wari takeover was violent in places; the invaders sacrificed local people and displayed their heads as trophies.

But this time the Wari colonists did something unexpected. Rather than trying to seize the fertile valley floor, where people already lived, the newcomers occupied high, dry land that no one else had figured out how to use. They constructed their government and religious buildings on top of a high mesa, now called Cerro Baúl, and erected canals and aqueducts that carried water much farther than any previously attempted in the valley. They carved mountain slopes into agricultural terraces, which efficiently trapped and distributed water from rain and snowmelt to plots of maize, quinoa, and peppery berries called molle. People from several other regions moved to the new farms and towns, forming a powerful labor force that helped maintain the sprawling water infrastructure.

Remote Cerro Baúl is home to some of the best preserved Wari canals and terraces, but the remains of their sophisticated water infrastructure have been found in both the Wari heartland and in several of the state's many colonies, including around the Wari center of Pikillacta near present-day Cuzco and in the Huamachuco region, more than 700 kilometers to the north of Huari. Such innovative hydraulic engineering enabled Wari—which some scholars argue was South America's first empire—to expand and thrive for some 400 years despite an often dry, drought-prone climate, recent studies suggest. (Archaeologists refer to this state as "Wari," not "the Wari," similar to the names of modern nations like Peru or France.) Wari colonists and those who joined their community were able to "settle empty zones and make them productive," says Donna Nash, an archaeologist at the University of North Carolina, Greensboro. Archaeologist Patrick Ryan Williams of the Field Museum calls the Wari strategy "conquest by hydraulic superiority."

Canals, like one near Pikillacta, likely helped Wari establish multiple colonies (map, right) during dry periods.

Those studying the Wari state's rise and fall, however, confront a puzzle. Its end, about 1000 years ago, appears to have coincided with a severe drought. Across history, the pattern might seem familiar; other ancient civilizations, including the Classic Maya and the Old Kingdom of Egypt, appear to have collapsed in a time of drought. But how could drought have doomed Wari, a society that had been built on learning to take maximum advantage of limited water, and had seemingly even expanded through previous dry spells? To find an answer, researchers are trying to reconstruct two intricate, fragmented narratives—the human and the environmental—and weave them together. The history of climate "in the Andes is extremely complicated," says Benjamin Vining, an environmental archaeologist at the University of Arkansas, Fayetteville. "And the only thing more complicated is human behavior."

THE WARI HOMELAND around today's city of Ayacucho is dry, like much of Peru. It sits just 200 kilometers from the Pacific Ocean but nearly 3000 meters above sea level, nestled in the Andes, and the vast majority of precipitation in South America falls far to the east, over the Amazon rainforest. As a result, Peru's mountains and coast depend on rivers fed by mountaintop glaciers, plus what little precipitation falls. "That means water is one of the most valuable commodities," Williams says.

Conditions in the Andes were at least as harsh around 600 C.E., when Wari was expanding beyond the Ayacucho region, recent and ongoing research suggests. Broxton Bird, a paleoclimatologist at Indiana University–Purdue University Indianapolis, is now analyzing a sediment core—drilled from Lake Pumacocha about 250 kilometers north of Ayacucho—that shows cool and relatively dry conditions between 475 and 725 C.E. Those data support evidence of aridity from another high-resolution re-

CREDITS: (PHOTO, OPPOSITE PAGE);MICHAEL LANGFORD/GALLO IMAGES; (GRAPHIC) X. LIU/SCIENCE

cord preserved in a mineral deposit (called a speleothem) from Huagapo Cave, also in the central Peruvian Andes, he says.

Such dry periods certainly stressed prehistoric communities—sometimes intensely, if they tipped into regional droughts. But for Wari, they also appear to have led to innovation, including new and better ways of storing, moving, and using precious water. Their canals were far longer and sturdier than any that came before, and although some other cultures had used agricultural terraces, Wari massively scaled up the technology and brought it to new regions. "In a moment of crisis, they came with the solution," says Francesca Fernandini, an archaeologist at the Pontifical Catholic University of Peru (PUCP). Those technologies likely gave Wari colonists a strategic advantage—and a way to expand into new territories.

Wari's expansion was not always peaceful, however. Wari art often depicts warriors, notes archaeologist Tiffiny Tung of Vanderbilt University. And strontium isotopes preserved in trophy heads uncovered in the Wari heartland site of Conchopata show the victims grew up elsewhere, evidence that Wari warriors captured and sacrificed people from faraway lands, she says. People buried at Conchopata also show more head trauma than people buried in communities controlled by other Andean cultures that existed before and at the same time as Wari.

At first, the Moquegua valley seemed likely to yield signs of a violent Wari takeover. Cerro Baúl was essentially a border outpost, butting up against territory occupied by colonists from Tiwanaku, another expansive Andean state that had its capital near Lake Titicaca in what is now northern Bolivia. But when researchers examined bodies from Tiwanaku cemeteries in the Moquegua area, they found that those buried after Wari colonists arrived showed no signs of increased violence. Instead, the valley's peoples—Wari, Tiwanaku, and local Moquegua communities—appear to have coexisted for 400 years, from about 600 to 1000 C.E., each preserving its own style of pottery, architecture, temples, and burials.

Meanwhile, the Wari community, which Williams estimates numbered about 3000 people, pursued far more ambitious water projects than its neighbors. Whereas people living close to the valley floor typically dug 1- to 3-kilometer-long irrigation canals from the river to their low-lying fields, the Wari community built a 20-kilometer-long canal that snaked high up the mountain slopes and brought water to several settlements built along its path. The earth and gravel terraces on which the Wari farmed—an agricultural innovation independently developed in many hilly, water-stressed ecosystems—retained moisture around crop roots while allowing excess water to drain to the terraces below. Wari leaders living on and ruling from Cerro Baúl were "able to sculpt the landscape and put water where they wanted it," Nash says.

That hydraulic infrastructure required an incredible amount of labor to build and maintain, Nash says. She has excavated in the agricultural settlement of Cerro Mejía, just 2 kilometers away from Cerro Baúl's elite civic and religious center. Based on the variety of domestic pottery and other material, she thinks people from four separate cultures came together under the Wari umbrella in Cerro Mejía, including some Moquegua locals and people from the coast. "I envision this as a multiethnic, pioneering frontier colony," she says. Wari leaders appeared to be able to marshal them all "to perform huge amounts of labor," Williams says.

Formal diplomacy, likely with Tiwanaku representatives, was probably conducted in the form of elite feasts in the palace atop Cerro Baúl, which also housed a brewery. The site is now littered with thousands of molle berries, used for making the typical Wari beer called *chicha de molle*. Tiwanaku-style jewelry found in the Wari palace, as well as a small Tiwanaku shrine tucked into Cerro Baúl's Wari palace, suggest other ties, perhaps formed as elite Tiwanaku women married into the Wari power structure, Nash says.

For many centuries, the system appeared to sustain peace and social cohesion, even during hard times. Between 850 and 950 C.E., for example, excavations show that part of the Wari colony at Cerro Baúl suffered a devastating landslide that buried people, houses, and large swaths of farmland. "It was a massive disaster," Nash says. "But when the Wari government was going strong, they could [cope with] things like this." The terraces were soon rebuilt.

STILL, THE RECONSTRUCTION was flimsy, perhaps reflecting a rush to prevent starva-

PHOTOS: (LEFT TO RIGHT) KENNETH GARRETT/NATIONAL GEOGRAPHIC IMAGE; MATTHEW PISCITELLI; SEARCH, INC./FIELD MUSEUM

tion immediately after the landslide. And in what may be an early sign that support for the Wari government had begun to crack, no one mobilized additional efforts to improve the new terraces. The community appears to have fractured even further by the time a new natural disaster hit: an extreme drought. Paleoclimate records like the core from Lake Pumacocha and the speleothem from Huagapo Cave show this drought was much more severe than the dry period at the beginning of Wari's expansion, Bird says.

By the time the drought reached the Moquegua valley in the 11th century, archaeological evidence suggests the Wari colony at Cerro Baúl was already weakened, Williams says. Around 900 C.E., after centuries of relatively separate coexistence, more Tiwanaku villagers started to move into Wari territory, as shown by the remains of Tiwanaku-style houses, ceramics, and cemeteries. Small Tiwanaku temples appeared on top of abandoned Wari agricultural fields, suggesting parts of the canal system were no longer functioning, which would have weakened the community's ability to cope when the drought arrived. Increasing factionalism and decreasing cooperation to maintain infrastructure "might mean this society is more vulnerable to even the beginnings of a changing climate," Williams says.

Around 1050 C.E., the administrative and religious Wari buildings on top of Cerro Baúl were abandoned, after what Williams calls an "end of times party." The revelers intentionally burned particular rooms, including parts of the *chicha de molle* brewery, then scattered smashed drinking vessels on top, a common offering in Andean societies. Archaeologists can't be sure whether the elite Wari leaders of Cerro Baúl left the region entirely or blended into the new, smaller communities that sprang up in Wari's wake. The more middle-class residents of Cerro Mejía likely retreated into smaller towns located higher on mountain slopes, Nash says; these were easier to defend against attacks and nearer to short segments of the Wari canal that were still functioning.

Cerro Baúl wasn't the only Wari community in trouble around 1050 C.E. Across the Wari state, people appear to have abruptly abandoned settlements they had worked hard to build and maintain. Even the capital of Huari emptied out, with its residents likely moving closer to the coast, Tung says. It remains a mystery, however, whether the collapse of the Wari capital rippled out to weaken colonies like Cerro Baúl, or the colonies gave up first and ceased to send tribute and supplies back to the heartland, eroding the state from the outside in. In any case, Williams says, "The Cerro Baúl colony couldn't sustain itself without being part of the larger whole."

CERRO BAÚL'S STORY is adding to the increasingly nuanced view that scholars have of drought's role in the collapse of ancient societies around the world. Once, it was conventional wisdom that drought had toppled ancient civilizations such as the Maya. Now, scholars rarely see a lack of water as the sole cause. Rather, they say, there is often a complex interplay between the social and natural environments. Sometimes, droughts simply drive wedges deep into existing cracks in political and economic systems.

Elite Wari colonists lived on top of high, dry Cerro Baúl (right). Their administrative center included a brewery for making *chicha de molle*, a beer drunk from decorative ceramic vessels (left).

In Cerro Baúl, for instance, it appears that Wari hydraulic expertise should have enabled the colony to cope with that final drought, Nash says. "But if the politics were bad, if their institutions were unraveling," then the community was vulnerable. "So, you don't blame the drought," she says. "You blame the government."

"The critical moment," says Luis Jaime Castillo, an archaeologist at PUCP, is not necessarily when canals run dry. It "is the moment when people lose confidence in the system."

Ironically, Wari engineering long outlasted the state itself. Beginning in the 1300s, the expanding Inca Empire repurposed Wari canals, roads, and agricultural terraces to feed and connect their far-flung territories. Some of the ancient terraces, with their Incan and Wari roots, are still in use today, Williams says. Indeed, he notes, terracing is being revived as a sustainable and hydraulically efficient way to farm in the Andes, as today's communities confront the ancient problem of drought, but now with a new face: human-caused climate change. ■

DRY TIMES

By **David Malakoff** *and* **Andrew Sugden**

Drought "is the death of the earth," wrote the poet T. S. Eliot. A lack of water withers crops, kills trees, and dries up streams and lakes. Humans have long tried to cope by migrating to wetter regions or inventing new ways of moving water to where it is needed, including by pumping it out of the ground. But as human populations grow, climate change takes hold, and groundwater supplies shrink, droughts pose an increasingly complex challenge to people and the environment.

This special issue examines the science and social impacts of droughts—past, present, and future. Review articles assess our current knowledge of the causes of drought and consequences for forests and soils, how drought relates to political conditions, and options for improving drought resistance in crops. Additionally, three News Features highlight drought's influence on the rise and fall of an ancient South American empire, California's efforts to restore its depleted groundwater, and researchers' methods for predicting the famines that droughts sometimes bring.

Drought is defined by the absence of life-giving water. Some scholars believe that the forbidding presence of a drought that struck the United Kingdom in 1921 helped inspire Eliot's repeated allusions to water and drought in his poetry. That year, less than 260 millimeters of precipitation—one of the lowest levels ever recorded—fell in parts of England, prompting the writer to reflect on a natural force that has long shaped our planet.

Caroline Ash, Pamela Hines, Tage Rai, and Jesse Smith also edited this special section.

PHOTO: JASON EDWARDS/NG IMAGE SALES

SPECIAL SECTION

NEWS

REVIEWS

RELATED ITEMS

An outback field near Deniliquin in New South Wales, stricken by the devastating 2006–2007 Australian summer drought, after hot northerly winds blew away the soils of the farming landscape

REVIEW

On the essentials of drought in a changing climate

Toby R. Ault

Droughts of the future are likely to be more frequent, severe, and longer lasting than they have been in recent decades, but drought risks will be lower if greenhouse gas emissions are cut aggressively. This review presents a synopsis of the tools required for understanding the statistics, physics, and dynamics of drought and its causes in a historical context. Although these tools have been applied most extensively in the United States, Europe, and the Amazon region, they have not been as widely used in other drought-prone regions throughout the rest of the world, presenting opportunities for future research. Water resource managers, early career scientists, and veteran drought researchers will likely see opportunities to improve our understanding of drought.

Unlike most natural disasters, but like a disease, a drought begins before it presents any symptoms (*1*). To understand this, imagine that it is May of 2013 and that you are a farmer in the Caribbean. It has been a little dry recently but otherwise all seems well ahead of the summer rains. The weather is warm, the skies are clear, and the horizon has a yellowish hue from dust carried across the Atlantic from the far-off Sahel (*2*). Although you do not know it yet, the worst drought in at least half a century has already begun (*2*). Before it is over, it will persist for 3 years, push 2 million people into food insecurity, and affect nearly every island in the Caribbean (*2*).

In the United States, drought cost $250 billion in damages and killed nearly 3000 people between 1980 and 2020, making it the costliest natural disaster and the second most deadly one (*3*). Over the last 12 centuries of human civilization, multidecadal megadroughts contributed to the demise of some of the most complex societies of the preindustrial era, including the Khmer and Mayan Empires, the Puebloan cliff dwellers of the southwestern United States, and the Yuan Dynasty of China (*4*). The Old Testament vividly describes drought as a punishment from God that left "Judah wailing, her cities languishing, the land cracked, and wild donkeys standing on barren heights, panting like jackals." Adding, "Even the doe in the field deserts her newborn fawn because there is no grass" (Jeremiah 14).

Droughts of the future may eclipse those of past centuries in their duration, severity, and frequency (*5*, *6*). Although aggressively cutting greenhouse gas emissions reduces these risks, even low levels of warming could amplify drought hazards across much of the world, including the Caribbean, Central America, Brazil, western Europe, central Africa, Southeast Asia, and Australia (*6*, *7*).

Department of Earth and Atmospheric Science, Cornell University, Ithaca, NY, USA. **Email: toby.ault@cornell.edu**

Defining drought

Although the crisis of drought is easily recognized, there is no universally accepted criterion for what constitutes one (*4*, *8*–*10*). Instead, multiple definitions, indices, and metrics exist to meet the particular needs of different research communities or applications (*10*). What they have in common was adroitly articulated by the late Kelly Redmond: They are intervals of time when "the supply of moisture fails to meet its demand" (*9*). Whereas the atmosphere delivers the supply of moisture, the demand for it arises from countless sources—a hot, dry atmosphere demands water vapor from the surface; plants demand water for transpiration; and our infrastructure demands water resources for irrigation, municipal water supply, and hydroelectric power generation, among many other uses.

Droughts are classified according to their impact (*8*, *10*), which imposes an approximate time scale for each type. A meteorological drought stems from rainfall shortages over a period of weeks, whereas an agricultural drought exacts crop losses and may linger for months. A hydrological drought develops on seasonal to interannual time horizons by depleting streamflow or reservoir levels.

Socioeconomic droughts, which affect water resources required for human applications (e.g., municipal drinking water), arise from either a shortage of supply or an excess of demand (*10*). Although the rest of this review will focus on the physics of meteorological and agricultural drought in a changing climate, the basic ideas are broadly relevant to other types of droughts.

An analytical arsenal for drought research

A simple "bucket" model (Eq. 1) builds on the concept of drought as a phenomenon that arises from either a shortage of precipitation supply (P) or an excess of evapotranspiration demand (E) [e.g., (*11*) and references therein]:

$$P - E = \frac{dS}{dt} + R_o + G_w \qquad (1)$$

where the terms on the right are changes in soil moisture storage (dS/dt), runoff (R_o), and groundwater flow (G_w) (*11*).

In principle, if we had observations of precipitation minus evapotranspiration ($P - E$), dS/dt, and R_o going back at least a century, then we could readily characterize drought variability on intraseasonal to multidecadal time horizons. In practice, only precipitation measurements are available from the past few decades, and those records are subject to large uncertainties that affect our understanding of drought (*12*). Measuring E and dS/dt accurately and consistently across space and through time has vexed drought scientists for generations (*8*, *13*).

Drought indices

As an alternative to measuring soil moisture directly, drought indices track relative departures from normal conditions (*14*, *15*). The full palette of drought indices available for researchers and water resource managers is described in other reviews (*8*, *10*), and new indices are routinely added to this collection (*16*). Broadly, they fall into two categories: indices that track the supply of moisture from precipitation alone (*17*) and those that approximate the balance of moisture arising from the combined effects of precipitation, evapotranspiration, and, sometimes, storage (*14*, *15*).

The Standardized Precipitation Index (SPI) (*17*) is designed to track precipitation deficits and surpluses across multiple time scales (e.g., 1, 3, or 12 months), making it ideal for differentiating between different types of drought (e.g., meteorological versus agricultural). However, the SPI's exclusion of evapotranspiration limits its usefulness for some applications and research questions (*15*). The Standardized Precipitation Evapotranspiration Index (SPEI) (*15*) was developed to address this limitation while preserving the robust statistical features of the SPI.

Both the SPI and the SPEI emerged to fill a need for drought indices that was imperfectly carved out by the Palmer Drought Severity Index (PDSI) several decades earlier (*14*). Like the SPEI, PDSI approximates evapotranspiration demand, but it also accounts for moisture storage by different types of soils (*14*). The "self-calibrating" PDSI (*18*) is most appropriate for large-scale studies of drought variability and long-term change (*12*, *19*–*21*). Even so, the magnitude of future change expected from the PDSI depends strongly on its formulation and the historical data used to calibrate it (*21*).

The SPEI and PDSI depend on simplified estimates of potential evapotranspiration (PET) that must be parameterized, and doing so accurately requires meteorological variables beyond precipitation (*12*, *21*). Consider the widely used, physically based Penman-Montieth equation, which approximates PET as a function of net surface radiation (R_n), soil heat flux (G), water vapor pressure deficit ($e_s - e_a$), slope of the temperature-saturation vapor pressure relationship (Δ), psychrometric constant (γ), and two resistance terms (r_s, for surface resistance, and r_a, for atmospheric resistance) (*22*):

$$\mathrm{ET} = \frac{\Delta(R_n - G) + \rho_a c_p \frac{e_s - e_a}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (2)$$

where ρ_a is the density of air and c_p is the heat capacity of dry air.

Use of Eq. 2 requires temperature, humidity, surface pressure, net radiation, and wind speed data (*22*). Of these, only temperature is widely available across large spatial scales and going back more than a few decades (*12*). Using the Penman-Montieth equation (Eq. 2) to study drought at continental scales therefore usually entails merging gridded observational datasets with reanalysis products (*12*); errors in these observational fields will introduce uncertainties into drought indices computed from them (*12*).

Nevertheless, PDSI and SPEI (as well as others) can be computed from observational and model output alike, which, ostensibly, allows projections of the future to be compared against historical conditions using the same indices for both data products (*5*, *12*, *20*, *21*).

piration, including lateral flow and subsoil storage of moisture in the rock layer (*23*, *24*).

More sophisticated land surface models (LSMs) assimilate data from multiple sources to estimate historical variations in land surface hydrology (*25*). However, as with drought indices, observational uncertainties affect the quality of soil moisture data in LSMs (*26*), and appropriate observational boundary conditions only span 1979 to the present (*25*). Consequently, LSM output covers a short and heavily forced period of the recent past, which presents a challenge for detecting and attributing the imprint of climate change in soil moisture (*27*).

An advantage of LSMs, however, is that they simulate the moisture, energy, and biogeochemical fluxes between the atmosphere and the land surface, just as the land surface components of general circulation models (GCMs) do. LSMs therefore also serve as an important bridge between observational data and climate model simulations of the past, present, and future.

Finally, over the past decade, observations of soil moisture from either in situ measurements (*28*) or remote sensing (*29*) have emerged as invaluable tools for validating LSMs and monitoring drought. However, these products cover a relatively short time period; they do not provide much information about interannual, let alone decadal, variations during the historical period.

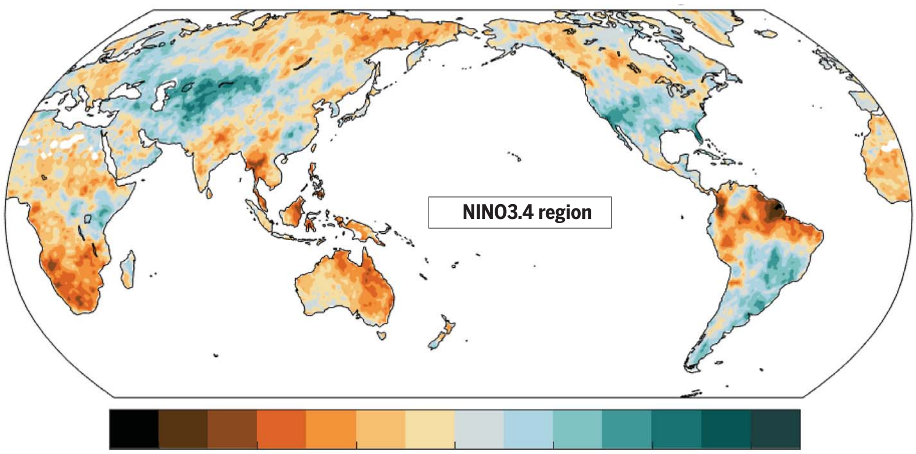


Fig. 1. Correlation coefficients between NINO3.4 SST (ERSSTv3b) and self-calibrating PDSI (*30*). All correlations are computed between boreal winter [January-February-March (JFM)] SSTs with PDSI during the following boreal summer [June-July-August (JJA)].

Modeling soil moisture

Given the apparent simplicity of Eq. 1, one might be tempted to model soil moisture directly using meteorological variables as boundary conditions, thus circumventing the need for drought indices (*11*). For example, the simplified bucket model extends global soil moisture estimates back to 1948 (*11*), but it lacks a number of critical processes that affect evapotrans-

Diagnosing drought dynamics

Atmospheric moisture budgets express the local balance of $P - E$ as a function of specific humidity (q) and horizontal winds ($\vec{V}$) (*30*):

$$P - E = -\frac{1}{g}\left(\frac{\partial \varphi}{\partial t} + \nabla \cdot \int_0^{p_s} q\vec{V}\, dp\right) \quad (3)$$

with total precipitable water, φ, defined as the vertical integral of water vapor:

$$\varphi = \int_0^{p_s} q dp \quad (4)$$

Changes to the $P - E$ balance of Eq. 3 must originate from one of two sources: (i) localized fluxes of precipitation or evaporation (i.e., the first term inside the parentheses on the right) or (ii) the convergence or divergence of vertically integrated moisture flux (i.e., the second term inside the parentheses). This second term can be further decomposed into separate changes originating from the mean flow, transport by transient eddies, divergence of the high-level winds, and advection of moisture gradients by the lower atmosphere (*30*).

In addition to atmospheric moisture budgets, idealized numerical modeling experiments serve as invaluable tools for investigating the origins of drought (*31*). These experiments typically force a free-running atmosphere with prescribed sea surface temperature (SST) anomalies that are hypothesized to cause drought (*31*). Running multiple atmospheric simulations, all of which are forced with the same SST field, and then averaging these simulations together disentangles the SST "signal" in droughts from the atmospheric "noise."

Causes of drought

The general circulation of the atmosphere delivers moisture from the world's oceans to its continents. Some of that moisture becomes trapped in glaciers, aquifers, and lakes; the rest flows through soils, plants, and rivers. Drought occurs from aberrations to the flow of moisture through these terrestrial systems.

The largest disruptions to the global hydrological cycle occur during the El Niño and La Niña events (Fig. 1) (*31*–*33*). For example, El Niño displaces tropical rainfall in northeast Brazil, Central America, and the Caribbean, causing drought in those regions (*32*). Meanwhile, the areas that normally see strong convection, such as Indonesia and northern Australia, also experience rainfall shortages, crop losses, and wildfires (*34*, *35*).

Although the El Niño–Southern Oscillation's (ENSO's) impacts on the global climate were recognized decades ago, moisture budgets and idealized SST-forcing experiments have now revealed key details of the dynamical processes responsible for those teleconnections (*31*, *33*). Winter storms shift equatorward during El Niño years (*36*) because deep convection modifies the structure and flow of the storm tracks and hence the transport of moisture (*36*). This in turn can trigger drought in the Pacific Northwest and the southeastern United States owing to additional downstream effects (*36*).

On shorter time scales, seasonal modes of variability such as the North Atlantic Oscillation (NAO) can modify storm tracks crossing the Atlantic (*37*). During the positive phase of the NAO, winter storms crossing the Atlantic tend to make landfall at higher latitudes (e.g., the United Kingdom and Scandinavia), which in turn favors drier conditions across France, Spain, Italy, and the Mediterranean region in general (*37*, *38*).

Over longer time scales, decadal SST variability appears to be connected to drought (*31*), although it can be difficult to disentangle such long-term effects from anthropogenic forcing (which may also affect decadal SST variations) (*31*).

Atmospheric moisture budgets also serve as invaluable tools for evaluating the realism of GCMs and for diagnosing their predictions of future aridity (*39*), although this remains a relatively underexplored area for future research.

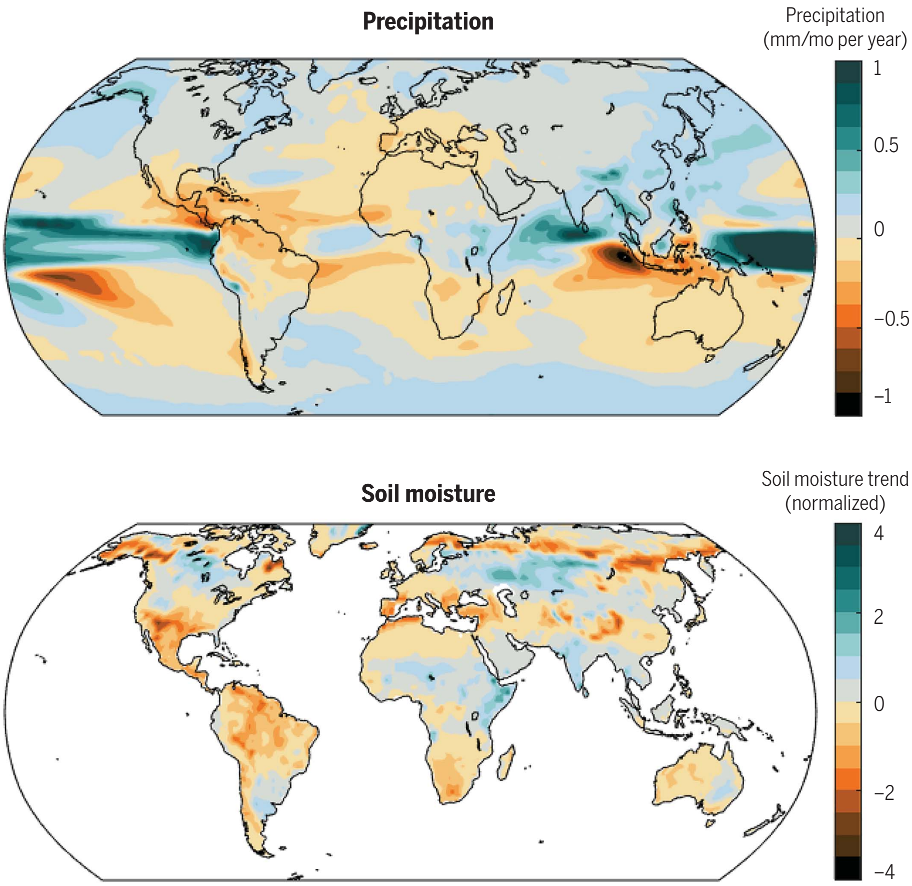


Fig. 2. Annual precipitation totals (blue) and JJA volumetric soil moisture averages (brown) from the CESM large ensemble (*50*).

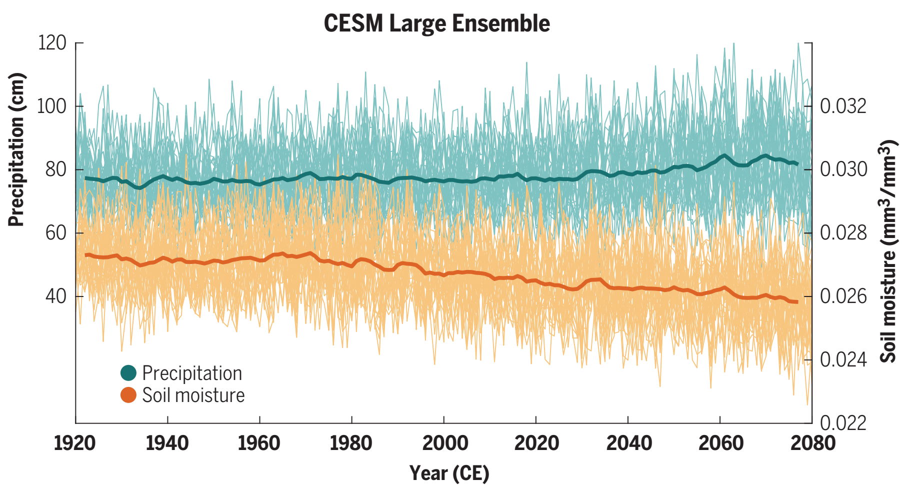


Fig. 3. Ensemble-averaged 21st-century Climate Model Intercomparison Project V (CMIP5) trends computed from annual precipitation (top) and column-integrated soil moisture (bottom).

Back to the future

If you are a water resource manager and you remember just one thing from this review, it should be this: Cutting CO_2 emissions reduces drought risk (*6*, *7*). In many regions, including Central America, the Caribbean, the Amazon, Western Europe, and southern Africa, avoiding even just half a degree of warming makes a difference: Regional drying is more severe if global warming reaches 2.0°C than if it is curtailed at 1.5°C (*6*, *7*).

Climate change alters the balance of moisture throughout the world by disrupting its supply through changes in the general circulation (*39*, *40*). Meanwhile, higher temperatures can increase moisture demand from the land surface (*12*, *41*) for the same reason that a sauna will dry out a towel faster than a steam room (see Eq. 2). Accordingly, regions seeing both a decrease in supply and an increase in demand are very sensitive to even low levels of warming (*6*).

Plants, however, may use water more efficiently as CO_2 concentrations increase in the atmosphere (*42*), and this "CO_2 fertilization effect" might partially offset a portion of future drying predicted for some regions (*42*–*44*). Nevertheless, there are several examples of models that predict reductions in soil moisture despite increases in overall precipitation and an increase in water use efficiency by plants (*5*, *42*, *44*). That is, the improvements in efficiency from higher CO_2 concentrations reduce the total amount of drying, which is substantial, but they do not reverse it (Fig. 2).

Finally, ENSO will likely continue to disrupt hydroclimate across vast spatial scales (*32*). When it does, the impacts of El Niño on drought could be even more severe than they are today for two reasons: (i) We expect climate change to strengthen ENSO events (*45*, *46*), and (ii) a hotter atmosphere demands more moisture from the land surface when droughts occur (*41*, *47*). Even now, higher temperatures may already be worsening aridity beyond anything seen in the past few centuries (*27*).

The future of drought research

Legions of studies have used the analytical arsenal described earlier to confront fundamental questions about the physics, dynamics, and risks of drought in a changing climate. For example, they have asked:

1) How do future droughts and long-term changes in aridity compare with modern-day

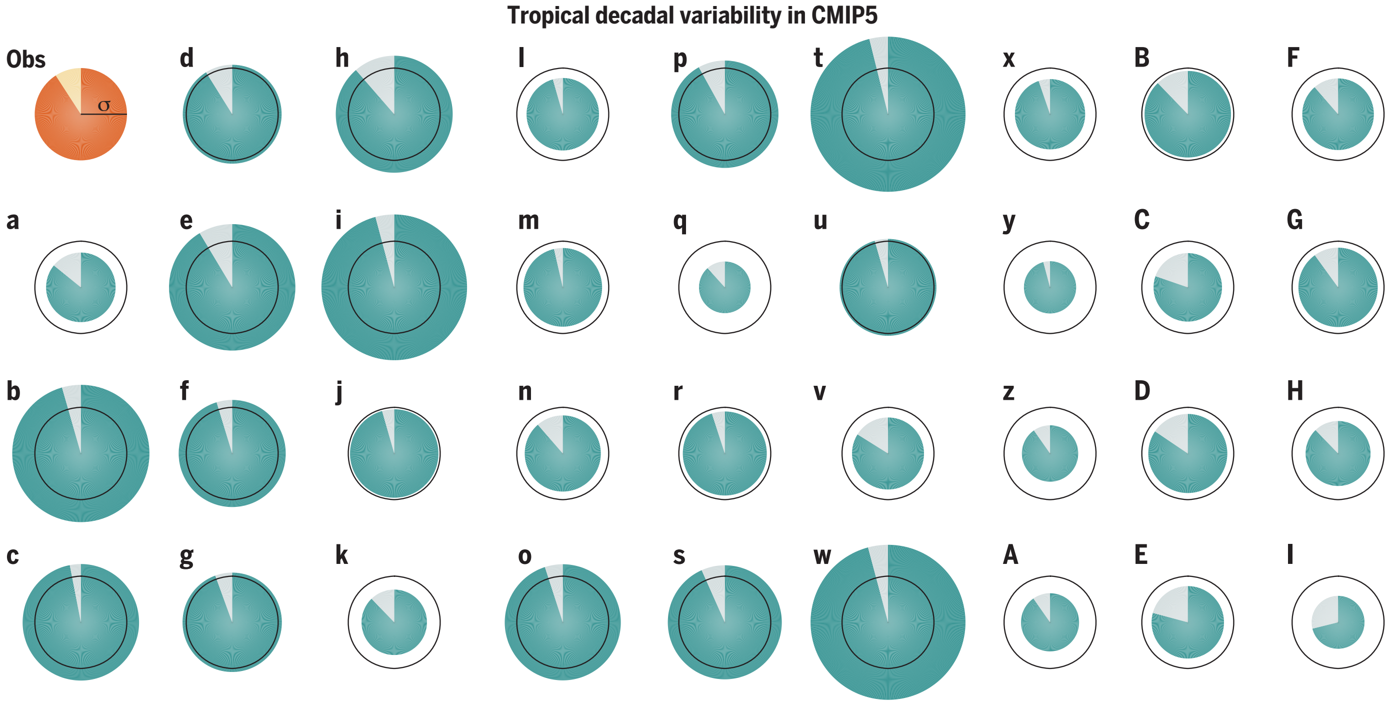


Fig. 4. Summary of tropical Pacific variability in observations and models. The circle in the topmost left is derived from observational data, with the radius being proportional to the standard deviation (±1.5°C) of NINO3.4 and the lighter color representing the fraction of the total variance that occurs on decadal time scales in the NINO3.4 region (~8.5%). The remaining charts summarize this same information for individual members of the CMIP5. Again, the radii of each circle are proportional to the standard deviation of a given model, and the lighter color represents the fraction of total variance occurring on decadal time horizons. For reference, the outline of the observational NINO3.4 chart is included on each model diagram. Variability in circle size emphasizes the now well-known differences in El Niño and Southern Oscillation amplitudes across the CMIP5 archive. Differences in the fraction of variance occurring on decadal time scales, in conjunction with differences in ENSO amplitudes, have received less attention. The models are identified by a single letter as follows: (a) ACCESS1.3; (b) BNU-ESM; (c) CCSM4; (d) CESM1-BGC; (e) CESM1(CAM5-FV2); (f) CESM1(CAM5); (g) CESM1(FASTCHEM; (h) CESM1(WACCM); (i) CMCC-CESM; (j) CMCC-CMS; (k) CMCC-CM; (l) CNRM-CM5-2; (m) CNRM-CM5; (n) CSIRO-Mk3.6.0; (o) CanCM4; (p) CanESM2; (q) EC-EARTH; (r) FGOALS-g2; (s) FIO-ESM; (t) GFDL-CM2.1; (u) GFDL-CM3; (v) GFDL-ESM2G; (w) GFDL-ESM2M; (x) GISS-E2-H-CC; (y) GISS-E2-H; (z) GISS-E2-R-CC; (A) GISS-E2-R; (B) HadCM3; (C) HadGEM2-AO; (D) HadGEM2-CC; (E) HadGEM2-ES; (F) IPSL-CM5A-LR; (G) IPSL-CM5A-MR; (H) IPSL-CM5B-LR; and (I) MIROC-ESM-CHEM. When multiple realizations were available, only the first simulation was used.

conditions (*19–21*, *41*)? Which indices and models should be used to characterize future droughts (*21*, *42*, *43*)? Is there already a *detectable* imprint of anthropogenic climate change on global drought (*19*, *20*, *27*)?

2) How will regional changes in temperature affect moisture demand from the atmosphere through evapotranspiration (*42*, *43*)? What role does vegetation play in coupling the land surface to the atmosphere (*42–44*)?

3) How will the supply of moisture to land evolve in response to large-scale changes in the general circulation (*39*)? How will ENSO and other seasonal variations influence drought in the future (*46*, *48*)?

In addressing these questions, researchers have begun assembling the puzzle of drought risks in a changing climate. Many regions may face events that are more severe, frequent, and long-lasting than those of the recent past (*13*, *21*, *26*) or even the last millennium (*4*, *5*, *27*). However, not all of the pieces fit together.

Wet, hot American summer drought

Perhaps the most contentious debate among drought researchers stems from differences between drought indices (as described above) computed from GCMs and soil moisture simulated by those same models. Drought indices depict unprecedented drying throughout much of the United States (*5*, *20*, *21*), but these indices do not account for biological processes (such as CO_2 uptake) that may alter the surface moisture balance in the future (*42*, *43*). They are also sensitive to the length and quality of historical data used to calibrate them (*12*, *21*) and may distort the magnitude of future changes if they are not calibrated appropriately (*12*, *19–21*). Finally, their reliance on the Penman-Montieth equation might overestimate future PET rates (*43*).

Soil moisture projections from LSMs help to characterize some limitations of drought indices, although they have their own pitfalls. For example, soil moisture data are not widely available in most regions, making it difficult to directly compare LSM output against the historical record (*26*). LSMs typically overestimate evapotranspiration rates (*49*), which in turn makes them too strongly coupled to the atmosphere, and artificially enhance precipitation in some regions (*49*). Although they can simulate CO_2 "fertilization" in plants, their modules for representing ecological interactions among plants, soil moisture, and runoff all introduce new uncertainties that propagate into their projections of the future (*26*, *44*).

Although GCM-based drought indices and soil moisture variables do not paint an entirely consistent picture of future drying, their differences may be superficial (*44*) (Fig. 2). In the case of the Community Earth System Model (CESM) "large ensemble" (*50*), the apparent paradox of increased drought risk in a wetter climate is easy to reconcile from the perspective of soil moisture balance: The increase in demand for evaporation from higher temperatures exceeds the increase in supply from precipitation. Future research could elaborate on these details in other models and other parts of the world.

Expanding outward

Quantifying how uncertainties in the large-scale circulation of GCMs are manifest in regional predictions of drought presents a harder problem for researchers (*51*). For example, GCM simulations of the 21st century depict a scenario in which the subtropics become drier but wet equatorial regions become rainier (*40*) (Fig. 3). In a general sense, this subtropical drying is a robust thermodynamic response to higher temperatures: A warmer atmosphere can "hold" more water vapor, yet the rate at which water vapor increases in the atmosphere outpaces the rate of precipitation increase (*39*, *40*). Accordingly, less moisture evaporates from the ocean to meet the demand for precipitation, which slows tropical circulation (*40*).

Most of the slowdown in tropical circulation occurs in the meridional Hadley cells, causing them to widen (*40*), which dries the subtropics. GCMs predict a similar outcome over the tropical Pacific Ocean because the east-west Walker circulation should also slow in conjunction with the Hadley cells (*52*). However, this is not happening (*53*)—or if it is happening, recent trends in the historical record are being dominated by other processes. One possible cause for this discrepancy is that the Walker circulation is responding differently in reality than it does in models to greenhouse gas forcings (*48*). That is, the recent observed changes are a forced dynamical adjustment in the coupled ocean-atmosphere system that the GCMs do not capture (*48*).

Alternatively, substantial internal *decadal* variability in the equatorial Pacific Ocean may be overshadowing the forced response of the Walker circulation (*54*). On this point, models do not agree with each other, let alone with the observations, on the relative importance of decadal variability in the tropical Pacific (Fig. 4).

For the time being, the issue must be regarded as unresolved. However, its resolution is vital to our portrait of 21st-century drought risk because the structure of the Walker circulation affects rainfall throughout the world (*39*).

The issues described above will manifest in the mean moisture balance of the tropics and subtropics, but droughts of the future will be caused by both the long-term changes in the general circulation and short-term deviations during El Niño and La Niña events (in addition to other modes of climate variability). Again, GCMs do not agree with one another, nor the historical record, on the amplitude of ENSO fluctuations and the relative importance of decadal variability (Fig. 4) (*55*, *56*). Because the tropical Pacific exerts a major influence on global precipitation patterns (*32*) (Fig. 1), frequency biases in this region likely affect the statistics of precipitation in regions with strong ENSO teleconnections. Quantifying the relationship between ENSO frequency biases in GCMS (as well as potential changes in ENSO frequency) and drought presents an important area for future research.

New additions to the analytical arsenal

During the past 30 years, intellectual and technological breakthroughs accelerated the pace of drought research. In the 1990s, personal computers enabled scientists to develop, analyze, and deploy our current generation of drought indices. In the early 2000s, investments in high-performance computing and land surface models helped lay the foundation for the sophisticated LSMs used today. In the 2010s, satellites began making unprecedented global measurements of surface soil moisture (*29*). Although all these technologies brought powerful tools into our analytical arsenal, they are not very egalitarian. Most farmers living in the Majority World must confront the hazards of drought in a changing climate with little, if any, access to the technological advancements of recent decades.

Encouragingly, the late 2010s also introduced very low-cost soil moisture sensors, which are already being deployed through public partnerships with local communities (*57*). These sensors transmit information about the state of the land surface continuously and nearly instantaneously, and researchers can use this data to validate satellite retrievals, initialize near-term predictions, or study the flow of moisture through the land surface with an unprecedented density of in situ measurements. At the same time, local communities are able to use data from those devices to gain insight into current conditions. During the 2020s, this emerging "Internet-of-things" technology could become the new frontier of drought monitoring and modeling.

Imagine, again, that you are a farmer in the Caribbean during a drought, but this time, the year is 2035. It is exceptionally hot (*7*), aquifers are depleted (*58*), and there are frequent blackouts because reservoir levels are so low at the hydroelectric power plant (*59*). What would you ask us—the people alive today—to do now to ensure that you are resilient in the face of drought in a changing climate?

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A carcass of an elephant that succumbed to drought is seen under a tree in Hwange National Park, in Zimbabwe, on 12 November 2019.

REVIEW

Hanging by a thread? Forests and drought

Timothy J. Brodribb[1]*, Jennifer Powers[2], Hervé Cochard[3], Brendan Choat[4]

Trees are the living foundations on which most terrestrial biodiversity is built. Central to the success of trees are their woody bodies, which connect their elevated photosynthetic canopies with the essential belowground activities of water and nutrient acquisition. The slow construction of these carbon-dense, woody skeletons leads to a slow generation time, leaving trees and forests highly susceptible to rapid changes in climate. Other long-lived, sessile organisms such as corals appear to be poorly equipped to survive rapid changes, which raises questions about the vulnerability of contemporary forests to future climate change. The emerging view that, similar to corals, tree species have rather inflexible damage thresholds, particularly in terms of water stress, is especially concerning. This Review examines recent progress in our understanding of how the future looks for forests growing in a hotter and drier atmosphere.

No tree species can survive acute desiccation. Despite this unambiguous constraint, predicting the death of trees during drought is complicated by the process of evolution, whereby the fitness of tree species may benefit equally from traits that either increase growth or enhance drought resilience. Complexity arises because improving either of these two beneficial states often requires the same key traits to move in opposite directions, which leads to important trade-offs in adaptation to water availability. This conflict promotes strategic diversity in different species' adaptations to water availability, even within ecosystems. Understanding how the diversity of tree species will be affected by future droughts requires a detailed knowledge of how the functions of different species interact with their environment. Temperature and atmospheric CO_2 concentration are fundamental elements that affect the water relations of all tree species, and the rapid rise in both of these potent environmental drivers has the potential to markedly change the way trees behave during drought. The future of many forest systems will be dictated by how these atmospheric changes interact with tree function.

[1]School of Biological Sciences, University of Tasmania, Hobart, TAS 7001, Australia. [2]Departments of Ecology, Evolution and Behavior and Plant and Microbial Biology, University of Minnesota, 140 Gortner Laboratory, Saint Paul, MN 55108, USA. [3]Université Clermont Auvergne, INRAE, PIAF, 63000 Clermont-Ferrand, France. [4]Hawkesbury Institute for the Environment, Western Sydney University, Penrith, NSW 2751, Australia.
*Corresponding author. Email: timothyb@utas.edu.au

Is rising CO_2 good for trees?

A primary example of conflicting selection pressures on trees can be seen in the basic operation of photosynthesis. Achieving a higher photosynthetic rate requires higher leaf porosity to CO_2, but a higher leaf porosity causes a parallel increase in water loss, which is detrimental during an environmental water shortage. This trade-off plays a fundamental role in structuring terrestrial plant evolution and ecology (*1*), emphasizing the potential for rising CO_2 levels and temperatures to affect forests during drought conditions. There has been a change in perspective over the past 10 years, from expectations of enhanced forest growth under enriched atmospheric CO_2 to the more sobering prospect of damage or decimation of standing forest caused by an increase in the drying rates of leaves and soil in a hotter climate (*2*).

Early discussions of plant responses to rising atmospheric CO_2 (*3*) focused largely on CO_2 fertilization, a concept that refers to the potentially beneficial effects of atmospheric CO_2 enrichment on plant growth. Under controlled conditions, elevated CO_2 can theoretically increase plant growth by stimulating photosynthesis or by increasing the water use efficiency (WUE) of plants (the ratio of carbon intake to water lost by leaves). Both of these behaviors depend on the active response of stomata (microscopic valves on the leaf surface that regulate gas exchange) to CO_2 (*4*). Long-term studies of tree growth under artificially enhanced atmospheric CO_2 suggest that improved photosynthetic performance at elevated CO_2 can translate into increased growth (*5*, *6*), but there is little evidence of any CO_2-associated growth enhancement in natural forest conditions (*7*, *8*). This is thought to be either because of colimiting resources for plant growth, such as water and nitrogen (*9*–*11*), or because stomatal closure in response to rising CO_2 increases WUE (*12*, *13*) at the cost of enhanced assimilation and growth. Controversially, it has been suggested that the impacts of future drought stress may be ameliorated by higher atmospheric CO_2 if WUE is sufficiently enhanced (*14*, *15*). The validity of this concept depends largely on the effects of rising temperature on WUE and plant survival during extended rainfall deficits.

Rising temperature and drought

Ultimately, the impact of elevated CO_2 on forest trees is likely to come down to the intensity of the CO_2-associated temperature rise and its effect on trees' water use. This is because the distributions of tree species, in terms of water availability, broadly reflect their intrinsic tolerance of water stress (*16*–*18*). In other words, species from rainforests to arid woodlands face similar exposure to stress or damage during periods of drought (*19*). Hence, any increase in the rate of soil drying caused by elevated temperatures is likely to lead to increasing damage to standing forests during drought. Improved tree WUE could ameliorate the temperature effect, but this argument remains highly debatable because most reports of improvements in tree WUE with rising atmospheric CO_2 refer to intrinsic WUE, a value that converts to real plant water use only with a knowledge of leaf temperature and atmospheric humidity (*20*). Thus, rising atmospheric temperature and the associated increase in evaporative demand is likely to reverse the improvements in tree WUE that are proposed to result from higher CO_2. Recent evidence suggests that this is the case, with observations of reduced global tree growth and vegetation health associated with enhanced evaporative gradients and warming temperatures (*21*, *22*).

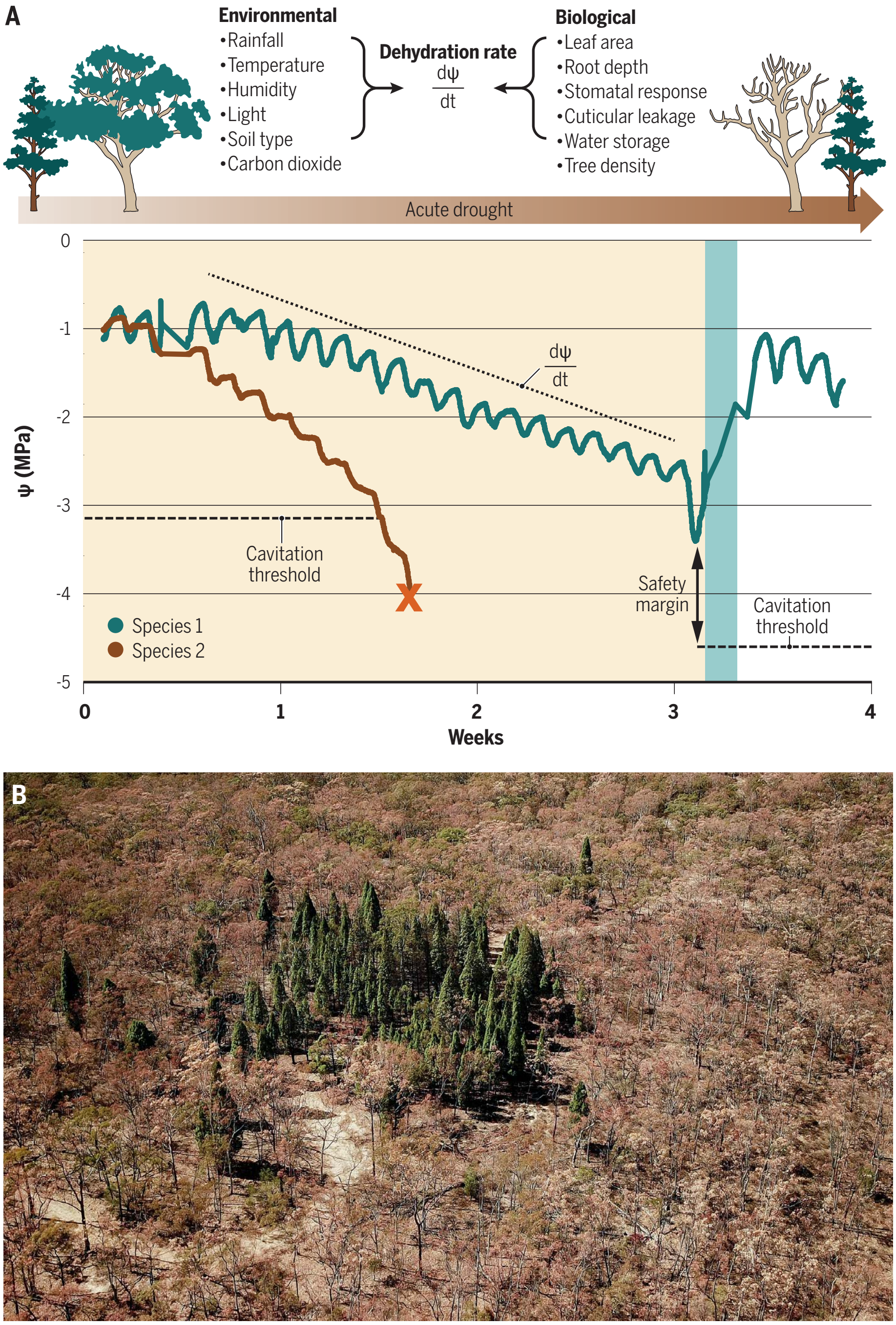


Fig. 1. Theoretical and observed impacts of drought on co-occurring tree species. (**A**) A representation of the impact of drought on two tree species with different thresholds for drought-induced vascular damage. Different xylem cavitation thresholds determine the water potential (Ψ: water stress intensifies as water potential becomes more negative) causing tree mortality. Two lines indicate the oscillating water stress between day and night as the two species (indicated by small tree icons) dehydrate after the cessation of rainfall (data are from two trees from a dry forest site in Tasmania, Australia). The cavitation threshold and the rate of drying (dΨ/dt) both determine how many days into an acute drought each species will die. The taller species, which is more vulnerable to cavitation and faster drying, dies (indicated by an orange X) in week 2, whereas the shorter species survives until rainfall (indicated by the blue rectangle in week 3), enabling the tree to recover hydration. The proximity between the cavitation threshold and the lowest water potential during drought is known as the hydraulic safety margin. The dehydration rate is a product of a set of environmental and biological factors, many of which interact. Increasing temperature increases the rate of drying both directly and by interaction with biological factors, whereas CO_2 has the potential to reduce dehydration by its biological interaction with stomata and the photosynthetic rate. (**B**) Recent (2019) drought-induced mortality of native forest in eastern Australia. Large-scale mortality of *Eucalyptus* trees (seen as recently killed dry canopies) contrast with the more cavitation-resistant conifer species (*Callitris*). The observed pattern of mortality can be explained by the processes described in (A).

ILLUSTRATION: JOSHUA BIRD/*SCIENCE*; PHOTO: MATT HERBERT

In combination with the size and allometry of trees, the dynamic behavior of stomata and their regulation of water loss from tree canopies largely dictates the course of plant and soil dehydration. During atmospheric or soil water deficit, stomatal closure limits transpiration, preserving water content in the soil and tree (*23*). However, this well-characterized behavior becomes unpredictable when leaf temperatures are substantially elevated, with stomata permitting greater water loss than expected during both day (*24*, *25*) and night (*26*–*28*). Additionally, plants continue to lose some residual water after the stomatal valves are closed, and this residual leakiness also appears to increase with elevated temperatures (*29*–*31*). Herein lies perhaps the greatest threat for forests subjected to warming atmospheric temperature, because warmer plants not only consume water faster when soils are hydrated, but they also have a diminished capacity to restrict water loss during drought, thereby exhausting soil water reserves.

Tree mortality is most commonly observed when drought and high temperature are combined (*32*–*34*), likely owing to the compounding effects of the increased evaporative gradient and the increased porosity of leaves at high temperature. The inevitable rise in the intensity and/or frequency of such events as global temperatures climb (*35*) has already been associated with an increase in tree mortality globally (*36*), especially in larger trees (*37*), which raises a grave concern about the capacity of existing forests to persist into the future. Establishing the magnitude of this threat is an important challenge that requires a fundamental understanding of how water deficit leads to tree mortality.

Much research has focused on the possible mechanisms behind tree death during drought. Possible mechanisms primarily include vascular damage, carbon starvation, and enhanced herbivory (*38*–*42*). These studies reveal the complex nature of tree death, where the moment of death is difficult to pinpoint or even define (*43*). Although it remains difficult to connect cause and effect at the point where drought injury becomes lethal, strong and consistent correlational data from trees suffering mortality or growth inhibition across the globe point unequivocally to the plant water transport system as a fundamental axis dictating the long-term survival of trees (*44*–*47*).

Forests on a thread

The massive woody structure of trees provides mechanical support for their photosynthetic crowns; however, the matrix of microscopic threads of water that is housed within the porous woody cells of the xylem is even more fundamental to tree survival. These liquid threads provide a highly efficient mechanism to transport large quantities of water over long distances under tension, from the roots to the leaves. Relying on this passive pathway to replace the water transpired by leaves has the major drawback that the internal water column in trees becomes increasingly unstable during times of water stress, as the tension required to draw water from the soil increases. Rising xylem water tension (conventionally described as an increasingly negative water potential) during intensifying soil water deficit exposes a universal vulnerability in trees to xylem cavitation during drought (*48*). This occurs when the water potential in the xylem becomes sufficiently negative to draw minute bubbles through the cell wall into the lumen of the xylem cells, at which point the small bubbles trigger a very rapid formation of voids (in a process termed xylem cavitation), which subsequently become air bubbles or embolisms that block water flow. The vulnerability of a species to cavitation is conventionally quantified as a P50, which is the water potential that causes 50% of the xylem to cavitate. The most extreme form of xylem damage occurs when a feedback develops, as increasing xylem water tension caused by soil water deficit leads to xylem cavitation and blockage, further exacerbating the tension in the xylem, and ultimately killing the plant by completely severing the connection between soil and leaves. This process is likely to occur under acute water shortage (*49*, *50*), killing plants (*51*) before the return of rainfall. Although this type of acute drought-induced mortality may not describe all instances of tree death during water shortage, the existence of quantifiable biophysical thresholds defining specific survival limits for different tree species has greatly enabled our capacity to understand tree mortality and distribution (*42*) and provides a robust basis for modeling future effects of drought (*52*, *53*). Many aspects of the xylem cavitation process remain uncertain because of difficulties associated with measuring water flow in a system that operates under high tension (*54*); however, new methods are providing more clarity and confidence to our understanding of the critical sensitivity of plant vascular systems to damage under water stress (*55*, *56*).

The water transport system in plants lies at the center of interactions between rainfall, soil water, carbon uptake, and canopy dehydration, which makes xylem hydraulics an obvious focus for understanding and predicting the thresholds between tree death or survival during exposure to drought and heat stress. Xylem vulnerability to cavitation varies markedly among species (*19*), not only indicating sensitivity to water deficit but also enabling the quantification of functional impairment if trees are not immediately killed by drought (*43*, *50*). Although a knowledge of cavitation thresholds informs the triggering of tree damage, the rate of tree dehydration indicates how quickly that damage threshold is approached during drought. The characteristics of tree species that are classically associated with adaptation to water availability—such as rooting depth, water storage, stomatal behavior, root and canopy area, and leaf phenology—can be predictably integrated to determine how plant water content will respond to environmental conditions. The combination of environmental conditions with biological attributes results in a highly tractable framework (Fig. 1) for understanding the dynamics of mortality or survival during slow dehydration (*57*).

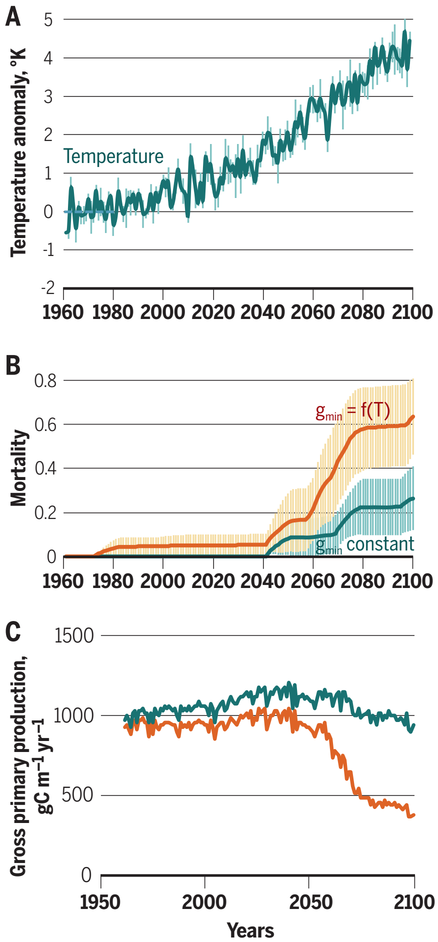
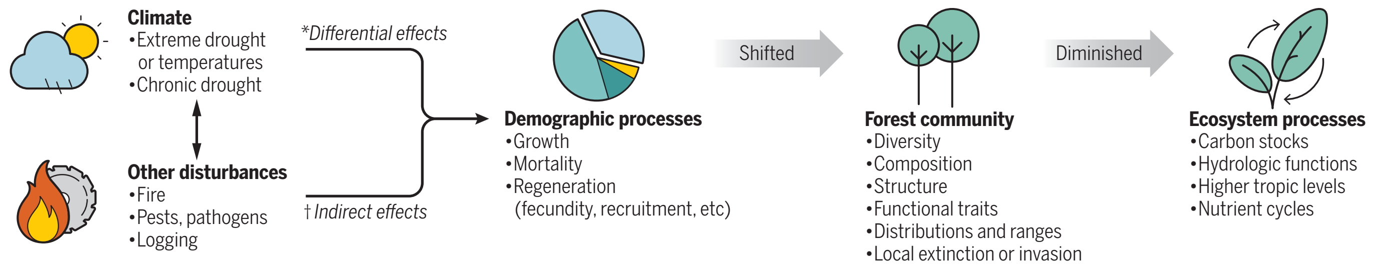


Fig. 2. A mechanistic hydraulic model of future drought-induced tree mortality. (**A** to **C**) Sensitivity of a process-based hydraulic model to predict tree mortality and gross primary production (GPP) under the representative concentration pathway (RCP) 8.5 climatic scenario. The model was parametrized with data for a population of a typical temperate coniferous tree, displaying a Gaussian distribution of cavitation resistance (mean xylem vulnerability of P50 = –3.5 MPa, variance = 0.3). Daily climatic data from five Eurocodex climate models were used to simulate tree transpiration, soil water content, xylem water tension, and xylem cavitation. The lethal threshold of cavitation was set to 88%. The model forecasts an increase in tree mortality with the rise of temperature caused by predicted climate change. The predicted collapse of the tree population and forest GPP was more drastic when a more realistic temperature-dependent increase in the cuticular leakage (g_{min}) (*108*) was implemented in the model [g_{min} = f(T); orange line] compared with a static cuticular leakage [g_{min} constant (gC); green line]

Despite the existence of sharp xylem cavitation thresholds, post-drought legacies of damage and mortality of trees are often protracted over months or years after peak drought intensity (*58*), which implies that more-complex interactions between plant water and carbon status are also important in the recovery process. Post-drought rainfall enables trees that have not suffered catastrophic xylem failure to replace drought-damaged xylem by woody regrowth (*50*), but this is highly costly and can lead to rapid depletion of tree carbon reserves (*59*), leaving them vulnerable to insect attack [although insect interactions remain unpredictable (*60*)] unless conditions remain favorable. Recovering, drought-damaged trees may invest disproportionately in new leaves rather than xylem growth (*61*), potentially making them more sensitive to subsequent water shortage because of reduced xylem water delivery. Although much remains to be learned about the physiology of plant hydraulics, the principles of hydraulic failure provide a solid framework for understanding and predicting mortality, damage, and recovery under a diversity of drought scenarios.

Modeling forest mortality in the future

Diverse approaches have been employed to predict how forests are likely to respond to hotter and potentially drier and more-variable conditions in the future. Progress toward understanding the mechanisms that lead to tree mortality has seen a movement away from traditional correlative niche models (*62*) in favor of more process-based modeling. Incorporation of theoretically derived mortality modules into dynamic vegetation models has the potential to capture drought mortality, but these models are currently rather unsophisticated and unreliable, particularly when applied outside the domain of calibration (*63*, *64*). At the more functional end of the modeling spectrum are recent attempts to explicitly model drought mortality triggered by hydraulic failure (or associated carbon starvation) (*52*). In particular, the combination of tree hydraulics with the principles of stomatal optimization (assuming that stomatal behavior regulates assimilation and transpiration to achieve a maximum difference between photosynthetic gain and the risk of hydraulic damage) is emerging as a promising structure for models of land surface gas exchange (*65*–*67*). Although the mathematical rendering of physiological processes to predict forest productivity and tree survival provides a powerful approach for modeling the performances of species or genotypes in a range



* Differential effects mediated by intra- and interspecific variability in hydraulic traits, tree size, community composition and structure, landscape context.
† Indirect effects mediated by interactions between drought and other disturbances.

Fig. 3. Interactions between climate and forest community. Schematic of how climatic variability interacts with disturbance to affect tree demographic processes, which may result in shifted community diversity and species distributions as well as ecosystem processes.

ILLUSTRATION: JOSHUA BIRD/*SCIENCE*

of future climates, a limitation in using these mechanistic formulations is that relatively small changes in parameterization or biological assumption can substantially change predictions (Fig. 2). To capture this uncertainty, recent studies have spanned a range of assumptions, particularly with regard to how trees might acclimate to drought, in order to reveal a range of possible scenarios (*15*, *68*).

Modeling provides the most credible view of how forests may cope with different intensities of future global warming, with most models suggesting large-scale mortality, range contraction, and productivity loss through this century under the current warming trajectories (Fig. 2). Greater precision as to the nature and pace of forest change is urgently needed, requiring dedicated work on key knowledge gaps (*69*) that limit model precision accuracy. These gaps are apparent in even the basic physiological processes of trees, such as stomatal behavior, tree water acquisition (*70*), and interactions between water and carbon stores in trees (*67*). Critical components such as the dynamic connection between trees and the soil are highly simplified in models owing to a lack of knowledge about water transfer and storage in the roots under conditions of water stress. The triggering of mortality is also highly oversimplified because the negative feedbacks likely to operate during acute tree stress are difficult to capture in a model. Avoiding this complexity, a commonly used proxy for lethal water stress is the point of 50% xylem cavitation in stems (Fig. 2). Although this threshold is not strictly correct (because trees can survive with a 50% impairment of water transport capacity), it does provide a readily measurable indication of rapid vascular decline incipient to complete failure of the vascular connection between roots and leaves. More-precise understanding of the post-drought transition to recovery or tree death is needed to accurately represent the legacy effects of drought in large-scale models.

Acclimation of forest in situ

The long generation time and slow growth of trees present a formidable challenge to survival in the face of rapid environmental change, particularly increases in aridity and the frequency of extreme-drought events. Avoidance of local extinction (extirpation) in tree species is possible by two non–mutually exclusive mechanisms: (i) migration tracking the ecological niches to which they are adapted or (ii) adaptation and acclimation to novel climate conditions and persistence within their current range. Species distribution models based on climatic envelopes have predicted pronounced range shifts in tree populations over the next century; however, this mechanism of survival is contingent on the capacity of species to achieve rapid migration (*71*), and few tree species are likely to disperse rapidly enough to keep pace with the current rate of climate warming (*72*). The persistence of tree populations exposed to increased aridity in their current range will depend on adaptation and acclimation to higher intensities of plant water stress. Given the rapid pace of climate change, adaptation of organisms with such long generation times appears unlikely to enable persistence in most species.

The potential for rates of adaptation to keep pace with environmental change depends on a number of factors, including the levels of genetic diversity present in critical traits, differentiation between leading and trailing edge populations, and gene flow between populations. Very few studies have examined the genetic diversity present in important plant hydraulic traits, with the most-comprehensive studies focused on temperate deciduous and conifer species (*73*–*75*). The results of these studies suggest that genetic diversity of traits, such as cavitation resistance, is low in pine species (*74*) but may be higher in temperate angiosperms such as beech (*73*, *76*). Overall, genetic diversity in hydraulic traits appears to be limited relative to the changes in intensity of water stress that are expected over the coming decades. This lack of genetic diversity across populations may limit the capacity for adaptation to increasing aridity in current distributions.

Acclimation by means of phenotypic plasticity presents another mechanism by which trees may adjust to novel climate regimes (*77*). Acclimation is dependent on trait plasticity in individuals and may occur over much shorter time scales than evolutionary processes such as adaptation. The acclimation of some physiological and morphological traits in response to changes in temperature and drought stress is well documented. This includes the acclimation of photosynthesis, respiration, and leaf thermal tolerance to temperature (*24*, *71*) and changes in resource allocation, such as sapwood-to-leaf ratio (*78*). For example, leaf shedding allows trees to rapidly reduce the leaf surface area available for transpiration and is a primary mechanism limiting water loss during drought. Studies examining intraspecific variation across precipitation gradients have shown that populations adjust to greater aridity through increasing sapwood-to-leaf ratios (*79*–*81*), increasing hydraulic capacity relative to leaf area deployed.

Acclimation in physiological traits related to drought tolerance is less well studied. However, the available data suggest that there is limited plasticity in key mechanistic traits. This is borne out in common-garden and reciprocal transplant experiments as well as throughfall exclusion experiments and studies of natural populations growing across aridity gradients (*80*, *82*, *83*). Low plasticity in hydraulic safety has also been observed with tree size (*84*), although the behavior of seedlings remains unknown. Pine species exhibit particularly low variation in cavitation resistance, with available evidence suggesting canalization of hydraulic traits, which constrains the capacity of pines to acclimate or adapt to drier conditions (*74*). Common-garden studies suggest that traits associated with hydraulic safety (Fig. 1) appear to be under strong genetic control (*16*, *81*). This may be one reason why partial leaf shedding is a commonly observed response to drought, because higher plasticity in leaf area may assist trees in maintaining levels of water stress within the functional limits set by inflexible hydraulic failure thresholds. However, reducing leaf area comes at the cost of lowered productivity and growth rates, and it may adversely affect survival in trailing edge populations exposed to intense interspecific competition.

Communities and consequences

Although hydraulic failure may be sudden and pronounced, predicting the consequences of drought for tree populations and communities is more challenging than simply extrapolating from models of hydraulic processes. This is because drought may also affect demographic processes beyond tree mortality and may interact with other disturbances. Stand-level interactions among individuals and species may attenuate or exacerbate drought impacts, and landscape-scale variations in topography, edaphic conditions, or forest-patch characteristics can modulate drought effects (Fig. 3). Moreover, current forest communities are responding to both extreme events, such as El Niño–Southern Oscillation (ENSO)–related droughts (*85*), and to directional changes in rainfall, such as decadal-long decreases in rainfall (*86*). What does seem certain is that these changes in forest composition and tree species distributions will have important consequences for the diversity and structure (*69*), hydrologic function (*87*), and carbon-storage potential (*88*) of future forests.

Interspecific variation in hydraulic and other traits is clearly linked to differential damage and mortality rates during extreme drought (*47*, *89*, *90*). However, other demographic processes or life history stages—such as fecundity, seedling recruitment, and tree growth—may also be affected, and species- or functional group–specific responses to drought may change community composition and functional traits over decadal time scales or even result in shifts among biomes, such as forests being replaced by shrublands (*91*). Regeneration dynamics are especially critical in mediating shifts between vegetation types or biomes (*91*), but, at this point, the data are too limited to generalize about how the likelihood of such shifts differs among forest types. For example, an extreme drought during the 2015 ENSO reduced seed rain of drought-deciduous tree species relative to evergreen trees and lianas in a seasonally dry tropical forest in Costa Rica (*92*). By contrast, in a semimoist tropical forest in Panama, a 30-year record of leaf and fruit production showed elevated seed production during ENSO years that mirrors seasonal patterns, suggesting that the sunnier conditions that accompany ENSO favor fruit over leaf production (*93*).

Predicting or modeling the impacts of drought on forest communities is also complicated by interactions between changes in climate and interactions with other disturbance agents, such as fire (*94*), insects and pathogens (*95*), or logging (*96*). The catastrophic wildfires that have affected Australia in 2019 and 2020, after years of extreme drought, is just one such example of drought-fire interactions. Such interactions are also affecting forests in North America (*97*), Amazonia (*94*), and elsewhere (*98*). Increases in vapor-pressure deficit and temperature during drought dry out fuel, thereby increasing fire activity and the area that is burned (*97*). Drought-fire interactions may also cause tipping points and shifts among vegetation types in areas such as the southwestern Amazon (*94*). There, tree mortality is elevated during intense fires experienced in drought years (*94*), resulting in altered microclimatic conditions and grass invasion into the understories, which further increases flammability and fire risk (*94*).

The identification of which trees and species within stands are most vulnerable to drought (*37*, *99*) and of the factors that render certain stands within landscapes more susceptible to changing climates (*100*, *101*) may inform both basic science and management strategies (*69*). Meta-analysis and theoretical models suggest that large trees are more likely than smaller trees to die during and after drought (*37*, *59*). However, simple predictions of which size classes of trees die during drought may not hold in mixed-species forests, where different sizes of drought-weakened trees experience different levels of attack by host-specific bark beetles in idiosyncratic ways (*102*). Additional knowledge of community composition beyond tree size—i.e., size-species distributions—may help bridge predictions from the individual to the stand scale (*69*). Forest density may be an indication of competition for water, and trees growing at low densities may experience lower mortality rates (*101*) and less-pronounced reductions in growth during drought compared with those in higher density stands (*103*).

Advances in the remote sensing of proxies of plant stress, like canopy water content, may help us to monitor and map patterns at coarse geographic scales (*104*). These findings may guide silvicultural actions, such as selective thinning to reduce vulnerability to drought in managed forests (*103*). Finally, the diversity of hydraulic traits in forests has emerged as a property that helps explain ecosystem responses to climatic variability (*105*). Ecosystem fluxes inferred from eddy covariance measurements of forests with higher trait diversity of hydraulic traits appear more buffered against changes in soil water and vapor-pressure deficit compared with forests with low trait diversity (*105*), presumably because catastrophic failures of canopy dominants (Fig. 1B) are reduced. This underscores the idea that building large databases of hydraulic traits, rather than morphological traits such as specific leaf area and wood density, is a high priority to advance our understanding of forest vulnerability to drought (*106*).

Outlook

Drought is a natural phenomenon that plays a major role in limiting the distributions of species. However, the extremely rapid pace of climate change appears to be introducing enormous instability into the mortality rates of global forests (*107*). Instability and unpredictability are intrinsic aspects of the physiological processes that are linked to the drought-induced mortality process, whereby vascular damage is prone to failure and positive feedback, leading to tree death. Most models predict major damage to forests in the next century if current climate trajectories are not ameliorated. Debate still remains as to the magnitude of stabilizing forces, such as tree acclimation and positive CO_2-associated effects on water use, but most observational data suggest that forest decline is well under way. Future improvements in physiological understanding and dynamic monitoring are needed to improve the clarity of future predictions; however, changes in community structure and ecology are certain, as are extinctions of tree species by the direct or indirect action of drought and high temperatures.

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REVIEW

The physiology of plant responses to drought

Aditi Gupta, Andrés Rico-Medina, Ana I. Caño-Delgado*

Drought alone causes more annual loss in crop yield than all pathogens combined. To adapt to moisture gradients in soil, plants alter their physiology, modify root growth and architecture, and close stomata on their aboveground segments. These tissue-specific responses modify the flux of cellular signals, resulting in early flowering or stunted growth and, often, reduced yield. Physiological and molecular analyses of the model plant *Arabidopsis thaliana* have identified phytohormone signaling as key for regulating the response to drought or water insufficiency. Here we discuss how engineering hormone signaling in specific cells and cellular domains can facilitate improved plant responses to drought. We explore current knowledge and future questions central to the quest to produce high-yield, drought-resistant crops.

Drought is a misfortune for agriculture, humanity, and livestock alike (*1*). Climate change is leading us toward a hotter, more parched world (*2*). There is an urgent need to produce high-yielding plants that use water more efficiently than their present-day counterparts (Fig. 1A). In the past decade, global losses in crop production due to drought totaled ~$30 billion. Global population rose from 5 billion inhabitants in 1990 to more than 7.5 billion presently and is predicted to rise to 9.7 billion to 10 billion by 2050 (*3*), at which time 5 billion people are projected to be living in water-scarce regions (Fig. 1B) (*4*). Despite the moderate increase in global arable land, an additional 1 million ha will be needed to ensure food security (Fig. 1C) (*5*). In addition, water demand for agriculture could double by 2050, whereas the availability of fresh water is predicted to drop by 50%, owing to climate change (Fig. 1D) (*6*). Certainly, plant biotechnology holds one of the promises to meet the societal demand for increased global crop production.

Water is crucial for plant survival, and water deficits limit plant growth. However, plants have strategies to prevent water loss, balance optimal water supply to vital organs, maintain cellular water content, and persevere through periods of drought. The ability of a plant to sense the water-deficiency signal and initiate coping strategies in response is defined as drought resistance. Drought resistance is a complex trait that proceeds through several mechanisms: (i) escape (acceleration of plant reproductive phase before stress that could hinder its survival), (ii) avoidance (endurance with increased internal water content and prevention of tissue damage), and (iii) tolerance (endurance with low internal water content while sustaining growth over the drought period) (*7*). After a period of drought, the percentage of viable plants upon rewatering is referred to as the drought survival rate. From the perspective of molecular biology, cellular water loss marks the first event of drought stress. At the cellular level, drought signals promote production of stress-protectant metabolites such as proline and trehalose, trigger the antioxidant system to maintain redox homeostasis, and deploy peroxidase enzymes to prevent acute cellular damage and membrane integrity. Factors such as the extent of water stress and the plant organ in which the stress is sensed also trigger specific signaling responses, including but not limited to abscisic acid, brassinosteroids, and ethylene phytohormone pathways (*8*–*11*).

Drought's impact on agriculture depends on the degree and duration of the reduced precipitation and soil water gradients, as well as on plant species and developmental stages (*8*). In most instances, crops experience moderate droughts caused by prolonged precipitation deficits, reduced groundwater levels, and/or limited access to water supplies, leading to substantial losses in overall yield. Therefore, investigating the mechanisms of how a plant sustains its growth during moderate drought and devising strategies to improve plant health during such periods can provide solutions for future food security. Understanding the response of cellular signaling to water shortage is key for shedding light on these modern agricultural problems (*12*). Here we explore how water availability cues cell and tissue growth patterns and how these patterns are coordinated in the whole plant to improve drought resistance without loss of yield. Overexpression of drought-responsive genes often results in growth deficits and yield loss. Tissue- or time-specific expression of drought-response traits may improve drought response without depressing yield. A combination of strategies may boost agricultural yields despite increased water insecurity.

Traits for improving drought resistance

During drought spells, plant systems actively maintain physiological water balance by (i) increasing root water uptake from the soil, (ii) reducing water loss by closing stomata, and (iii) adjusting osmotic processes within tissues (*13*). Activated stress response pathways include phytohormone signaling as well as antioxidant and metabolite production and mobilization (*11*).

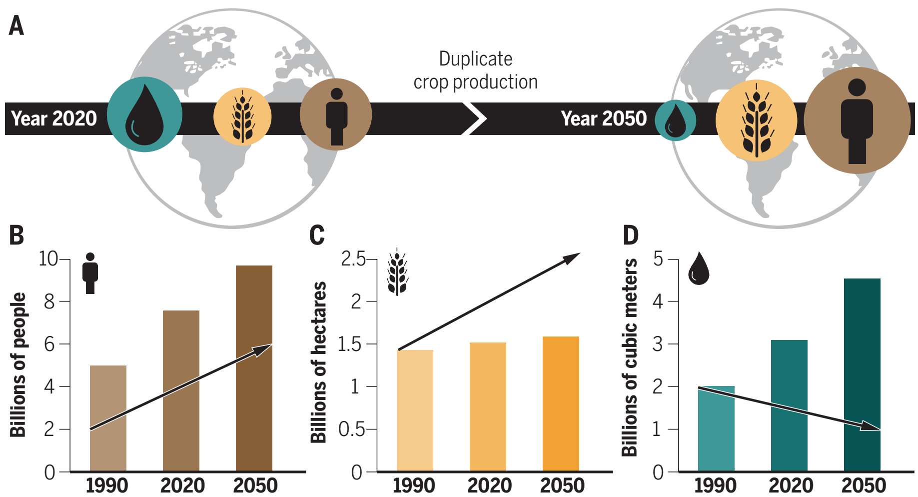

Fig. 1. Past, present, and future of global climate, agriculture, and food security. (**A**) Most scenarios predict that water scarcity will increase in the coming years. With the world's population continuously growing, crop production must also increase to fulfill civilization's basic needs. For this purpose, plants must become more water efficient. (**B**) Estimated world population for the 1990–2050 time period. The arrow indicates the estimated number of people living in water-scarce areas. (**C**) Global arable land for agriculture for the 1990–2050 time period. The arrow indicates the predicted demand for arable land to ensure food security, given the current rates of crop production per hectare. (**D**) Global freshwater demand for agriculture for the 1990–2050 time period. The arrow indicates the predicted decline in freshwater availability for agriculture, given the current trends for climate change and precipitation.

Department of Molecular Genetics, Centre for Research in Agricultural Genomics (CRAG), CSIC-IRTA-UAB-UB, Campus UAB (Cerdanyola del Vallès), 08193 Barcelona, Spain.
*Corresponding author. Email: ana.cano@cragenomica.es

Roots respond to changes in soil moisture at the cellular scale and with the entire root system architecture. The root stem cell niche, meristem, and vasculature each coordinate responses to drought (Fig. 2, A and B). During periods of water scarcity, the root system architecture undergoes morphological changes to enhance its ability to absorb water and nutrients (*9*, *10*). These modifications can be traced to coordinated cell division, elongation, and differentiation events in the root apex. In the pursuit of moisture, root systems grow differentially and adapt their architecture to be either deep or shallow (Fig. 2C). Longer and deeper roots with reduced branching angles can efficiently capture water from soil that is dry at the surface but retains moisture in deep layers. By contrast, shallower root architectures are more beneficial for maximizing water capture from the soil surface in regions of low precipitation (*9*). Roots that encounter a soil environment with nonhomogeneous water distribution display hydropatterning by favoring lateral root emergence toward soil patches with higher water content, a process that is also mediated by auxin signaling (*9*, *14*). Another adaptive response to nonhomogeneous distribution of moisture through soil is hydrotropism (Fig. 2D), in which root tips grow toward zones with higher water content to optimize the root system architecture for water acquisition (*15*).

Stomatal closure is a more rapid defense against dehydration (Fig. 2, D and E). Stomatal pores on leaf surfaces open or close according to the turgidity of the surrounding guard cells. The turgor-driven shape changes of guard cells are affected by the cell wall structure, plasma membrane, tonoplast properties, and cytoskeletal dynamics (*16*). Plant vascular tissues, the xylem and phloem, transmit water availability signals from roots to shoots and transmit photoassimilates from shoots to roots, respectively (*17*). Development of these inner vasculature tissues also affects drought resistance. Crop yield becomes most vulnerable if the drought occurs during a plant's reproductive phase. In *Arabidopsis thaliana*, early flowering associated with drought escape is linked to phloem loading and transport of the photoperiod-dependent protein FLOWERING LOCUS T (FT) from leaves to the shoot apical meristem (*18*).

Phytohormones to combat drought

The hormone abscisic acid (ABA) regulates plant responses to dehydration and optimizes water use. Dehydration signals stimulate local production of ABA in different plant organs. However, ABA production is more efficient in the leaf mesophyll cells than in the root tissues (*19*). The accumulated ABA then activates downstream signaling components (*20*). ABA executes its function during stress by mediating signal cross-talk with other pathways (Fig. 3) (*21*). Many existing schemes to improve water use efficiency and drought resistance engage the ABA pathway.

Genetic engineering to improve the function of PYR/PYL/RCAR (Pyrabactin Resistance 1/PYR1-Like/Regulatory Component of ABA Receptors) and SnRK2 (SNF1-related protein kinase 2) and repress the negative regulator PP2C (clade A type 2C protein phosphatase) has resulted in improved water use efficiency in plants such as *A. thaliana* and wheat under controlled laboratory growth conditions and greenhouses (*22*–*25*). A regulatory network of ABA pathway genes, a hierarchy of ABA-related transcription factors, and signaling feedback were identified among ABA-mediated stress responses to drought (*26*). Engineering the ABA receptor PYR1 for heightened sensitivity toward the preexisting agrochemical mandipropamid resulted in improved drought resistance in *A. thaliana* and tomato (*22*). Virtual screening for ABA receptor agonists led to the identification of a bioactive ABA mimic called opabactin. This small molecule can enhance ABA receptor activation and downstream signaling to improve water use efficiency and drought resistance in *A. thaliana*, tomato, and wheat (*27*). Thus, computational design combined with experimental biology led to identification of a small molecule that can mitigate the effects of drought on crop yields.

Brassinosteroid hormones also regulate drought response through signaling components linked to the ABA response pathway (Fig. 3) (*28*, *29*). Brassinosteroid signaling negative regulator BRASSINOSTEROID-INSENSITIVE 2 (BIN2) is dephosphorylated by ABA INSENSITIVE1 (ABI1) and ABI2. ABA activates BIN2 by inhibiting the activity of ABI1 and ABI2 (*30*). BIN2 phosphorylates SnRK2s and activates the downstream pathway (*31*). ABA signals can also converge with the brassinosteroid pathway at the level of downstream transcription factors (Fig. 3). BRI1-EMS-SUPPRESSOR 1 (BES1) inhibited ABA induction of a drought-related transcription factor RESPONSIVE TO DESICCATION 26 (RD26) (*32*). RD26 shows reciprocal antagonism with brassinosteroid by modulating BES1-regulated transcription and inhibiting brassinosteroid-regulated growth (*33*). WRKY46,

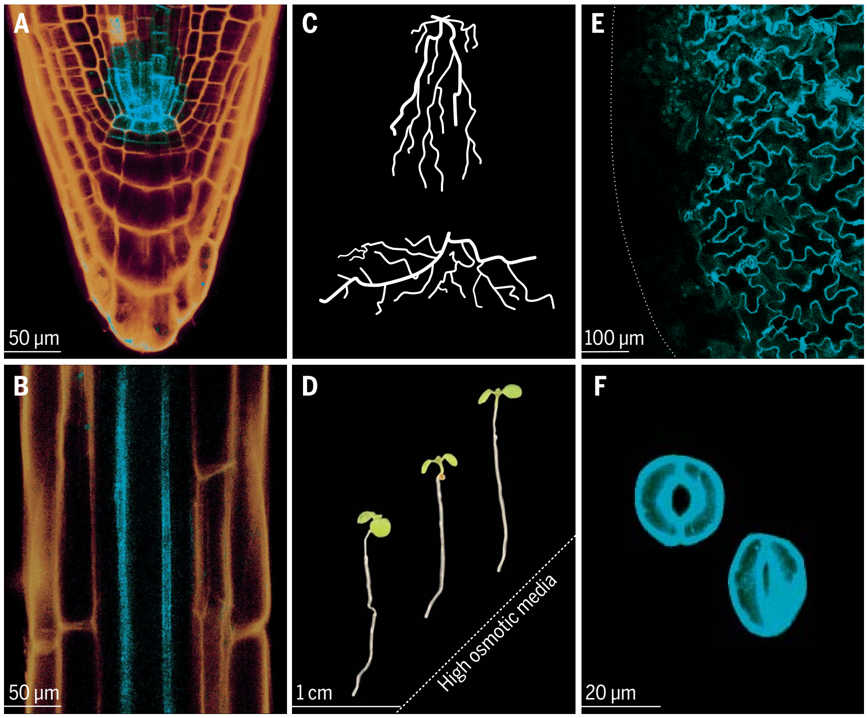

Fig. 2. Root and shoot traits that account for drought resistance. (**A** and **B**) Plants initially sense drought through their roots, where particular cell types (shown in blue)—such as stem cells, cortical cells, and vascular cells—mediate adaptive responses toward water limitations. Roots can modulate their system architecture to (**C**) maximize access to superficial humidity or delve into deep humid soil layers, as well as to (**D**) bend toward more humid soil zones (hydrotropism). (**E** and **F**) In aboveground plant organs such as leaves and stems, stomata work actively against dehydration. In water-limiting conditions, stomata remain closed to reduce water loss.

-54, and -70 belong to another class of transcription factors that interact with BES1 to promote plant growth while repressing drought responses (*34*). BIN2 can phosphorylate and destabilize WRKY54 to negatively regulate its effect on the BES1-mediated brassinosteroid response (*35*). BIN2 phosphorylates and activates the ubiquitin receptor protein DSK2, which leads to BES1 degradation via autophagy and coordinates plant growth and survival under drought conditions. (*36*). An AP2/ERF transcription factor called TINY is another candidate that balances brassinosteroid-mediated stress adaptation with growth. TINY interacts with BES1 and antagonizes brassinosteroid-regulated growth. BIN2, on the other hand, phosphorylates and stabilizes TINY to promote ABA-induced stomatal closure and drought resistance (*37*). Thus, brassinosteroids as well as ABA aid drought resistance.

Tissue-specific responses for drought resistance

Stomatal closure preserves water in the plant. ABA content in leaves regulates stomatal movement in response to water availability (*25*) (Fig. 3). Because stomatal movements control CO_2 influx and transpiration, efforts to reduce water loss via stomatal closure occur at the cost of photosynthesis, growth, and yield (*13*). Therefore, most strategies to improve water efficiency and drought resistance in plants focus on fine-tuning stomatal conductance and manipulating ABA signaling via stomata-specific promoters (*38*). With optogenetics, scientists have improved the responsiveness of the stomata and overcome the coupling of CO_2 uptake with water vapor loss. Upon introducing BLINK1 (a light-activated synthetic K^+ ion channel) into guard cells, stomata became more synchronized with fluctuating light conditions (*39*). This manipulation improved the performance of the stomata and, consequently, growth and productivity of the plant. Thus, water use efficiency was improved by engineering the stomata to maximize the amount of carbon fixed per unit of water lost.

Improving water acquisition by roots can also improve plant performance upon drought. In *A. thaliana*, the auxin pathway modulator EXOCYST SUBUNIT EXO70 FAMILY PROTEIN A3 (EXO70A3), which regulates root system depth, was identified through genome-wide association mapping (*40*). EXO70A3, a component of the exocytosis system, is expressed in root tips. EXO70A3 regulates local auxin transport by affecting the homeostasis of the auxin efflux carrier PIN-FORMED 4 in root columella cells (Fig. 3). Natural variation in EXO70A3 was correlated with seasonal precipitation and conferred different adaptive root system architecture configurations under different rainfall patterns. In areas with high temperatures and irrigated soils, deeper root architectures proved better for drought adaptation. In rice, the auxin-inducible gene *DEEPER ROOTING1* provides drought resistance by promoting a more vertical and deeper root system architecture (*41*). Although auxin modulates root architecture under stress (*40*, *41*), hydrotropic root responses function relatively independent of auxin and involve ABA signaling in root elongation zones. Coordinated activity of ABA-inducible MIZU-KUSSEI1 (MIZ1) and SNF1-RELATED KINASE 2 (SnRK2.2) in root elongation zone cortical cells interprets water potential gradients in soil environments (*15*, *42*).

Brassinosteroid receptors regulate root hydrotropic responses (Fig. 3). Overexpression of the vascular-enriched brassinosteroid receptor BRI1-Like3 (BRL3) promotes root hydrotropic bending. The *brl1brl3bak1* triple mutant of the BRL3 signalosome shows a reduced hydrotropic response, suggesting a role for the vascular BRL3 receptor complex in regulating hydrotropic responses (*43*) (Fig. 3). Activation of the BRL3 pathway in vasculature triggers accumulation of osmoprotectant metabolites such as proline, trehalose, and raffinose family oligosaccharides in plant roots in response to water withdrawal, which improves drought resistance without penalizing growth (*43*) (Fig. 3). Phloem-specific localization of BRL3 is likely to be the determining factor for promoting drought resistance without impairing yield (*29*, *43*).

In drought conditions, roots sense water scarcity from soil. The aboveground segments of plants respond by closing stomata in leaves, implicating a systemic communication system. In times of drought, the CLE25 peptide is produced in the roots and moves through the vasculature to plant leaves to drive ABA production by activating the biosynthetic enzyme NCED3. This burst of ABA synthesis leads to stomatal closure and improved water balance, thereby promoting drought survival (*44*) (Fig. 3). This insight into small-peptide signaling in *A. thaliana* may help with identification of similar mechanisms in crop plants for root-to-shoot mobilization of stress signals.

A view to the future

Genetic traits that sustain crop plant growth under moderate drought may come from multiple sources, including natural genetic variation in wild relatives or bioengineering. Traditional breeding has been the main strategy for exploiting the genetic diversity of adaptive traits in natural alleles. The advent of genomic

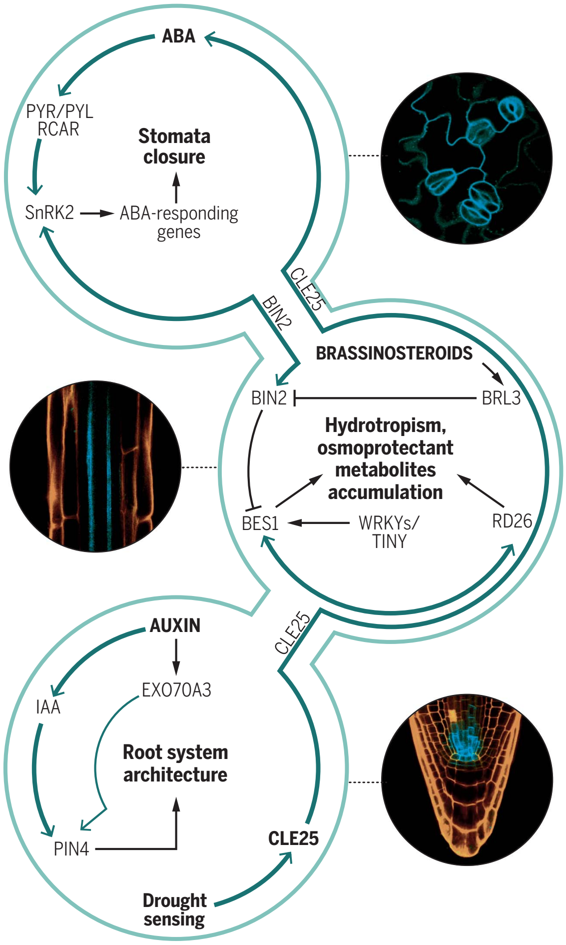

Fig. 3. Hormone signaling events underpinning drought. Schematic representation of hormone signaling modules that control drought adaptation. Plants work against dehydration in organs such as leaves, vasculature, and roots. ABA, through SnRK2, activates a variety of genes that trigger stomata closure and improve water balance. When roots sense drought, the CLE25 peptide moves through the vasculature to the leaves, where it locally controls ABA biosynthesis and stomata closure. Brassinosteroids also play roles in regulating plant drought response. Brassinosteroid pathways converge with ABA by activating SnRK2 through downstream pathway component BIN2 and vice versa. Independently of ABA, brassinosteroid receptors (BRI1, BRL1, and BRL3) modulate hydrotropic responses in the roots. The vascular BRL3 receptor coordinates plant growth and survival under drought stress by promoting the accumulation of osmoprotectant metabolites in the root tissues. Furthermore, noncanonical auxin responses via EXO70A3 and PIN4 can modulate root architecture patterning and depth to boost water absorption from the soil, thereby improving drought tolerance.

technologies and gene mapping tools such as genome-wide association study (GWAS) and precision genome editing with the CRISPR-Cas9 system has been instrumental for the generation of alleles that can improve plant yield and performance under various stresses. Molecular studies that use tissue- or cell-specific promoters coupled with live microscopy techniques for real-time visualization of cellular processes are paving the way for analysis of drought response networks that can be targeted by various approaches (Fig. 4). Small molecules such as peptides or hormone agonists may be useful for fine-tuning drought response pathways while preserving yield in agriculture. Together, research efforts aimed at uncovering the physiology of plant responses to drought in model systems and translating these findings to crops will deliver new strategies to combat water scarcity. Discovering ways to ameliorate agriculture's "thirst" will ease competition for freshwater resources, even as the world's population grows.

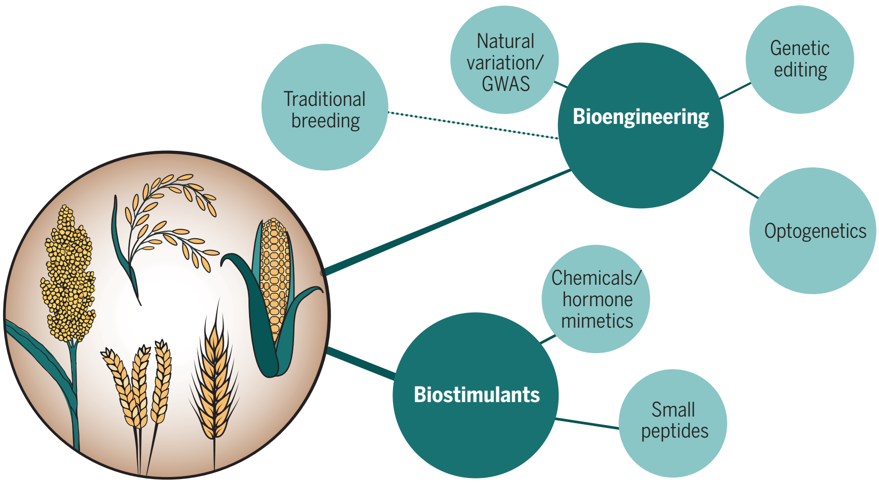

Fig. 4. The promise of overcoming drought in agriculture. Genetic strategies provide solutions to counteract drought and can be used to develop drought-smart crops. Natural allelic variations in plants can be selected to improve drought resistance and yield. Traditional breeding approaches have selected drought characteristics to obtain more-resistant crops. Advancements in gene mapping tools such as GWAS can explore the genetic diversity of drought resistance traits in natural alleles with nucleotide-level precision. Genetic engineering of drought response markers at the spatiotemporal scale and precise genome editing with tools such as CRISPR-Cas9 have opened new horizons for developing crops with improved drought resistance, without sacrificing yield. Emerging techniques such as optogenetics allow fine manipulation of cell- and tissue-specific responses to signaling and therefore increase growth and plant resistance to drought. Small peptides, hormone mimics, and receptor agonists can be used to design better agrochemicals and fine-tune drought resistance while preserving yield.

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REVIEW

The effects of drinking water service fragmentation on drought-related water security

Megan Mullin

Drought is a critical stressor that contributes to water insecurity. In the United States, an important pathway by which drought affects households' access to clean, reliable drinking water for basic needs is through the organization and activities of community water systems. Research on the local political economy of drinking water provision reveals the constraints on community water systems that affect their performance when confronting drought hazards. Fragmentation in responsibility for drinking water contributes to disparities in drought vulnerability, preparation, and response across households and across communities. The nature and extent of these disparities require further investigation to identify strategies for expanding water security in the face of drought and other water hazards.

By global standards, most Americans are water-secure with respect to drinking water, meaning that they have reliable access to affordable and safe drinking water in adequate supply for basic needs. Yet important gaps remain, especially in rural and impoverished communities, and overall risk to drinking water security is on the rise (*1*). Drought is a key contributor to the growth in water insecurity (*2*). Climatic and hydrologic conditions play a role in intensifying drought hazards for water consumers, as do social and political conditions, including water management regimes (*3*). In parts of the United States, especially the Southwest and interior West, droughts have become more frequent and severe over time, while changes in land use are producing increased water demand (*4*, *5*). Warming temperatures reduce water storage in reservoirs and snowpack, and climate-induced pumping has contributed to widespread groundwater depletion (*6*). Deteriorating physical infrastructure for water storage, treatment, and delivery and inadequate technical, managerial, and financial capacity to adapt to changing conditions all heighten vulnerability to drought-related hazards.

Drought can push communities to the brink of their water supplies. U.S. states regularly declare drought emergencies and release funds for communities to drill new wells, repair existing facilities, or connect to a neighboring system. Loss of pressure in water distribution systems triggers boil-water advisories. Sometimes water systems completely run dry, making it necessary to turn to tanker trucks or even fire hoses to bring water into the community for weeks or months, until infrastructure can be improved or water supply augmented. Households whose private wells dry up or those receiving unreliable service from a water system purchase bottled or hauled water for drinking, cooking, and bathing. These events occur not just in the arid West but throughout the country, because many water systems lack the capacity to withstand added stress from drought.

A growing body of research examines drinking water provision as it relates to drought, focusing on water managers' perceptions of scarcity (*7*–*9*), policy and management responses (*10*–*15*), and broader sociotechnical and socioecological relationships undergirding regional water resource governance (*16*–*18*). Other literature draws attention to the wide disparities in the quality and availability of drinking water service in the absence of drought (*1*, *19*–*21*). An important link connecting drought hazards to household water security is the local political economy of drinking water provision. Nationwide, an estimated 87% of Americans receive their drinking water from a community water system (CWS) (*22*). Thus, for most households, the impact of drought on drinking water is mediated by the activities and responses of their CWS (Fig. 1). Understanding the political organization of drinking water delivery is critical for identifying strategies to expand water security in the face of drought and other water hazards.

Water security for drinking water systems during drought

Drought presents numerous challenges for drinking water management. Reduced water availability jeopardizes the ability to meet basic water needs in communities without surplus water supply. Drought also has negative impacts on water quality. Effects on water resources include microbial growth, increased organic load, saltwater intrusion, and leaching of natural and anthropogenic contaminants. Depending on local water management approaches and the condition of infrastructure, drought may further affect treated drinking water quality by way of pipe damage, increased water age in distribution systems, and changes in source mix (*23*).

The effects of drought on a CWS vary widely according to natural and physical features that determine exposure to drought hazard, local policies and management practices, and the CWS's position within a regional water allocation system. Drinking water providers compete with other water users, including farms, power plants, and neighboring cities, for access to surface and groundwater resources, and environmental regulations limit overall water withdrawals. An institutional framework that includes water rights, contracts, allocation and purchase agreements, and collaborative management of water sources shapes a water system's ability to access adequate supply to meet its customers' basic needs when resources dwindle. These institutional constraints tend to be more long-standing and binding in regions with ongoing water stress because of feedbacks between water rights and infrastructure (*24*).

Even when a CWS is relatively unconstrained by the demands of other users, its ability to maintain water security during drought depends on historical policies and management practices that contribute to land-use and settlement patterns as well as the extent and condition of built infrastructure. Because neither drought nor drinking water are well integrated into local government land-use planning processes, communities miss opportunities to incorporate conservation and water resource protection into development decisions (*25*–*27*). Instead, water often gets used as a pretense in broader political conflict over growth management (*28*). Within the realm of water management, a CWS can improve its drought resilience through investments to diversify water sources, expand pumping capacity and storage, or build system interconnections. These types of investments require access to capital and the ability to generate stable and adequate revenue. Ongoing maintenance also can reduce drought vulnerability. Water loss through leaking distribution pipes exacerbates drought effects, and drought response can be delayed if unused intakes have been allowed to clog or emergency supply lines have been left to deteriorate. Rising drought frequency and rising drought severity may require distinct management responses.

Absent adequate long-term resilience planning and investment, short-term drought response can help protect water security within a CWS's service area. Water systems use a variety of instruments to encourage reductions in water use in order to stretch limited resources, sometimes with great success. For example, in response to a statewide mandate in 2015, California water systems were able to reduce water use by an average of 25% (*13*). Instruments adopted as short-term drought response sometimes become part of a CWS's portfolio of strategies for managing demand in the long term (*11*), but they can be costly to implement. The two strongest instruments—pricing and mandatory use restrictions—are politically unpopular, harmful to water-intensive businesses and industry, and potentially deleterious to a community's growth goals (*12*, *15*). Successful efforts

Nicholas School of the Environment, Department of Political Science, and Sanford School of Public Policy, Duke University, Durham, NC, USA. **Email:** megan.mullin@duke.edu

to induce conservation can undermine a CWS's fiscal health by reducing the user fee revenue that funds water system operations. Drought response also requires a high degree of capacity to monitor shortage conditions, implement appropriate policies, and then monitor and enforce those policies (*29*).

Some large CWSs are tackling the challenges of drought preparation and response and transitioning toward more-adaptive management to cope with changing climatic and hydrological conditions (*8*, *12*, *16*–*18*). However, apart from the very large systems, typically located in water-scarce regions, that most commonly receive research attention, there is limited evidence that CWSs more generally are expending effort to seek out information about their water supply or improve their drought preparedness (*30*, *31*). Drought planning can challenge the dominant mindsets of decision-makers: CWS personnel, who prioritize avoidance of political conflict and the ability to meet customers' water demands, and elected politicians, who benefit more from disaster response than from disaster preparation (*32*, *33*). The capacity to protect water quality and ensure adequate quantity during drought is not evenly distributed across CWSs. Some limitations are legacies of water allocation rules or infrastructure age, but many disparities are attributable to the political organization of CWSs and the demographic features of the communities they serve.

Water service is highly fragmented: of the 50,000-plus CWSs delivering drinking water year-round, more than 80% provide service to fewer than 3300 people (Fig. 2). Small water systems face myriad challenges in delivering safe drinking water under normal conditions: They cannot take advantage of economies of scale in drinking water production and delivery; they have less access to private capital and other funding; and their technical, managerial, and operational capabilities are often inadequate to maintain regulatory compliance (*34*). Small systems also are less likely to engage in drought preparation and to respond quickly when drought conditions arise (*10*, *15*, *35*, *36*). Institutional design makes a difference for drought response. Many water systems, especially small ones, are privately owned, often functioning as independent not-for-profit entities or ancillary to another business, such as a mobile home park (*37*). These systems, along with publicly owned special districts that lack broader authority beyond drinking water, have weak enforcement tools and operate outside the public view, which reduces their ability to influence water use behavior through education and outreach. Among the many data gaps on drinking water systems is a clear accounting of the distribution of ownership and governance structures across systems.

Small water systems are already at a disadvantage when it comes to protecting water security during drought, but the fragmentation of drinking water provision creates an additional problem: it differentiates between populations served by water systems along economic and racial lines. Several factors contribute to this differentiation. First, underlying residential segregation by race and income produces more homogeneity within geographic units as the number of units rises. Second, where water system service areas correspond with municipal boundaries, they replicate patterns of racial and economic segregation that exist across local jurisdictions (*38*). Third, where water service areas are not aligned with local government boundaries, service extension is the outcome of political decision-making and reflects power distributions in the community. In metropolitan areas, local policies guiding service provision historically have served to protect wealthy white residents from the spread of disease and to boost their property values (*39*, *40*). In rural areas, the development of water institutions favored irrigation over provision of drinking water for domestic use (*20*, *41*). The result in both cases is patterns of drinking water provision that systematically disadvantage communities of color and communities with low ability to pay (*19*, *21*, *37*, *42*). These communities may be left without water service altogether or be made to depend on a small water system without an adequate revenue base to support its operation. Disparities in water and other local services subsequently undergird inequalities in growth, economic development, and political incorporation (*43*, *44*). The nature and extent of demographic disparities between water systems is not well understood empirically, because few states have reliable, up-to-date maps of water system service areas that allow calculation of demographic attributes (*45*).

The effects of drinking water fragmentation have received attention in research and policy conversations with respect to water quality and affordability outcomes but less so for their impacts on drought resilience. Disparities in the size and composition of water service areas result in unequal vulnerability to drought hazards. CWSs with smaller, lower-income customer bases have less political influence in the state-, regional-, and watershed-level institutions that determine allocation priority, even when those institutions are designed to plan more proactively for drought contingency (*46*). Resource and information constraints can hinder participation in allocation processes, and decision-makers at these CWSs might perceive a stronger tension between sustainable management of the water resources and the imperatives of economic development. Because water service provision is funded overwhelmingly through user fees, small systems and those serving disadvantaged communities have less fiscal capacity to maintain robust infrastructure that minimizes leakage and protects water quality during periods of scarcity, especially if their customer base does not include major commercial users. These systems are also less able to make investments in response to detection of operational weaknesses (*47*). The challenges compound to put entire water systems at risk. During the 2011–2017 drought in California, nearly 150 CWSs serving an estimated 480,000 Californians experienced water shortages or requested emergency funding from the state in order to maintain water service. Most of these were small systems serving low-income populations, including many farmworker communities in the San Joaquin Valley (*48*).

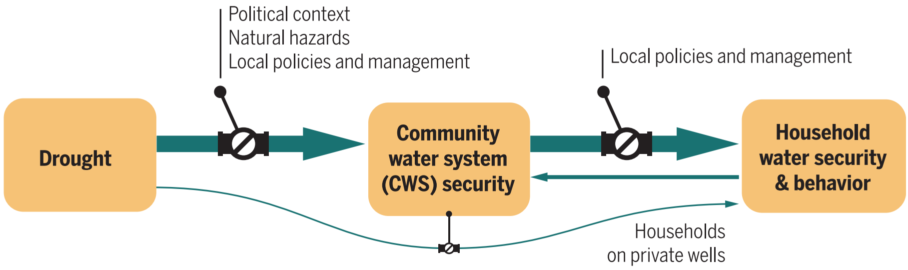

Fig. 1. Pathways for drought impacts on drinking water security. For most Americans, their local community water system mediates the impact of drought on drinking water security.

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Household water security during drought

Drought creates further disparities in drinking water security at the household level. Deteriorating infrastructure and low water pressure introduce variations in service within a CWS, with more-remote households and those in areas with older development more likely to experience problems with reliability and drinking water quality. Price increases intended to encourage conservation or those adopted to compensate for conservation-induced revenue shortfalls create an economic burden for low-income customers that could result in failure to pay and subsequent service shutoff. The difficulty associated with reducing water use depends on a variety of factors, including income, employment status, the proportion of typical water use that is dedicated to basic needs, and the extent to which one's livelihood is water-dependent. Commercial users that can help provide revenue stability for a CWS may end up competing for scarce resources with households. The organizational form of a CWS—its boundaries, decision-making processes, and relationship to local government—influences the capacity of different users and groups to make claims and influence policy choices (*24*, *28*, *41*). Patterns of variation in water delivery that emerge within CWSs then feed back into overall CWS security by affecting the system's revenue base, its political influence in regional water allocations, and the salience and political framing of water issues in the media (*17*, *49*).

For households that access drinking water from domestic wells, drought impacts are not directly mediated by a CWS but are indirectly affected by decisions of nearby CWSs about where to extend service. Those households that rely on domestic wells are particularly vulnerable to drought-induced groundwater depletion, especially in agricultural areas where drought induces additional pumping nearby (*50*). Service extension decisions may be influenced by a CWS's own vulnerability to drought hazards, but also they are the product of political conflict shaped by existing power distributions. In South Texas, along the United States–Mexico border, irrigated agriculture dominates the institutional landscape for water decision-making, resulting in limited and inconsistent water service to the unincorporated *colonias* populated by low-income Mexican Americans (*41*). Residents' legal claims seeking greater participation in water-governing institutions have been unsuccessful, and patchy and precarious water service has left large communities with little drinking water security.

Tackling the challenge of drinking water fragmentation

Drought amplifies risks to drinking water security that are rooted in the local political organization of drinking water delivery. Two commonly cited solutions to fragmentation in water service are consolidation and collaboration. Full consolidation of water systems—integration of CWS management, operations, and facilities through merger or absorption—has long been viewed by regulators and policy analysts as an effective, and sometimes necessary, intervention for struggling water systems. For some water systems, consolidation can reduce risks associated with drought and other unpredictable events (*51*). However, this solution is, by nature, piecemeal and typically faces substantial political opposition stemming from community pride and concerns about local autonomy.

The second solution, collaboration, is a broader set of structures and processes for managing the problems of fragmented governance. Various forms of watershed, river basin, and groundwater basin authorities aim to coordinate the activities of multiple users to address common challenges, including drought. By bringing CWSs

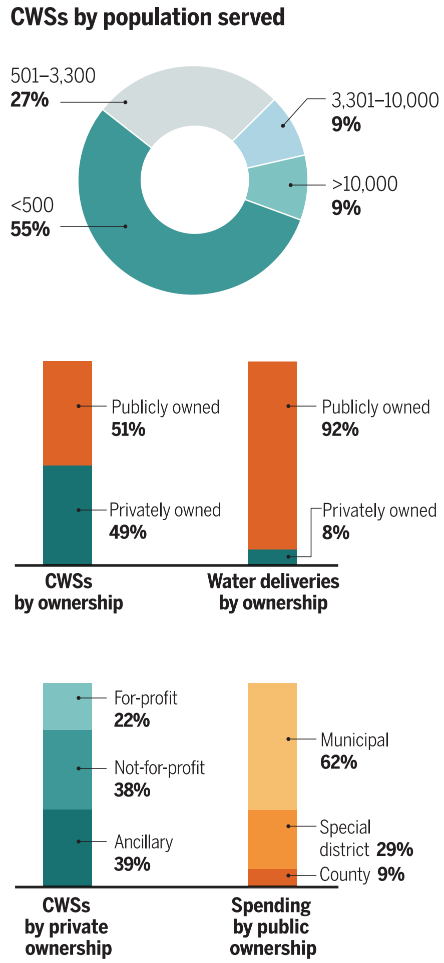

Fig. 2. Fragmentation in U.S. drinking water provision. A large majority of U.S. water systems serve fewer than 3300 people (*64*, *65*). Ownership type affects a CWS's capacity for drought preparation and response.

into conversation with other regional water users and one another, collaboration can promote information sharing, build social capital, and help CWSs reach agreements that balance short-term drought response with long-term supply planning (*52*). California has recently sought to promote collaboration among local water agencies to address problems related to water scarcity through programs for integrated regional water management and sustainable groundwater management. Participation in these efforts is costly, however, and representation in collaborative settings tends to reflect underlying power distributions (*53*, *54*). Where collaborative processes are tied to funding, these uneven patterns of participation can have a meaningful impact on resource distributions (*55*). Collaboration could therefore aggravate rather than ameliorate disparities, and empirical evidence is lacking about trade-offs between collaboration and other dimensions of water resilience (*56*).

Water system governance beyond U.S. borders

The United States is not alone in facing challenges created by fragmentation in drinking water governance. In Canada and many European nations, small water systems are prevalent and share many of the same financial and operational limitations that can put drinking water security at risk (*34*, *57*). In the developing world, the consequences of fragmentation are more stark. Access to piped water from any type of provider is much less common—an estimated 31% of the population in the world's least-developed countries has piped water, compared with 96% of the population in Europe and North America (*58*). Lower rates of connection create more opportunities for selective extension of water service, often driven by wealth and electoral considerations. Emphasis on provision of new infrastructure to garner political support rather than maintenance of existing pipes contributes to widespread water loss and unreliable service. Informal water providers fill service gaps, playing an important role in providing water access for daily needs, but do so through a mechanism that becomes precarious in times of drought. Recent decades have seen widespread reform of water services in developing countries that favors local control and corporatization, or the separation of water finances and management from other government activities (*59*). Decentralization to small jurisdictions raises concerns about equity in water security, as the financial and management capacity of local water providers is a key factor in water delivery performance, especially under conditions of scarcity (*60*). The demands on water systems to self-finance their operations, typically through user fees, is a challenge in all settings, and substantial numbers of water systems in both developing and developed nations report that they are unable to cover basic operations and maintenance expenses (*61*).

Whereas large water systems in the United States have thus far avoided large-scale drought-induced water security crises, the same is not true internationally. In 2018, local officials in Cape Town, South Africa, warned of a looming "day zero," when the city of four million people would run out of municipal water. By implementing severe restrictions, the water system managed to avoid turning off taps completely. The same was not true in surrounding Eastern Cape communities, where smaller water systems ran dry for months, requiring residents to spend hours in line waiting for periodic water deliveries and exposing them to grave public health risks. Those towns struggle to provide minimal levels of water to this day.

Pathways for policy and research

The challenges faced by U.S. CWSs demand a political analysis that extends beyond the boundaries of individual water systems. At the core of disparities in drinking water security is the reliance on local funding—in particular, user fees—to support drinking water provision. Rising threats to water security from drought and other stressors call for research into the impacts of this governance and financial model. Not all political contributors to drinking water insecurity at the CWS or household level are funding-related: historic rights and allocations play a role, as well as ongoing power inequalities. But many drinking water system vulnerabilities relate to capacity. State-level policies for sharing revenue and resources across CWSs could enable more-vulnerable CWSs to invest in infrastructure repair, interconnectivity, supply adjustments, and demand management that reduce long-run vulnerabilities to drought. Reforms that reduce reliance on user fees may help buffer insecure CWSs from the fiscal costs associated with conservation. Designing appropriate policies requires that attention be paid to inequalities at multiple scales. Legal and fiscal analysis of policy options should consider lessons from school finance reform, where decades of efforts to equalize funding have been effective in reducing between-district, but not within-district, disparities in education outcomes (*62*).

As states increasingly take up the challenge of confronting climate change impacts, a high priority should be to enable local water systems to withstand drought. Many states support or require drought planning (*11*, *25*), but these efforts do little to address the core vulnerabilities in water systems. A first step toward protecting water security during drought is to build a richer understanding of the distribution of vulnerabilities. Recent efforts in several states to develop maps of water system service areas should be replicated nationwide and integrated with data on drinking water finance, built infrastructure, and water supply and use. Systematic reporting on supply shortages, low-pressure events, and use of backup water supplies would help identify water systems at risk. Although states have expanded their collection and distribution of water data, many gaps remain, especially in relation to water use and the finances and performance of drinking water utilities (*63*). As drought hazards intensify, addressing weaknesses in drinking water management becomes all the more important to ensure universal water security.

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DROUGHT

Large contribution from anthropogenic warming to an emerging North American megadrought

A. Park Williams[1]*, Edward R. Cook[1], Jason E. Smerdon[1], Benjamin I. Cook[1,2], John T. Abatzoglou[3,4], Kasey Bolles[1], Seung H. Baek[1,5], Andrew M. Badger[6,7,8], Ben Livneh[6,9]

Severe and persistent 21st-century drought in southwestern North America (SWNA) motivates comparisons to medieval megadroughts and questions about the role of anthropogenic climate change. We use hydrological modeling and new 1200-year tree-ring reconstructions of summer soil moisture to demonstrate that the 2000–2018 SWNA drought was the second driest 19-year period since 800 CE, exceeded only by a late-1500s megadrought. The megadrought-like trajectory of 2000–2018 soil moisture was driven by natural variability superimposed on drying due to anthropogenic warming. Anthropogenic trends in temperature, relative humidity, and precipitation estimated from 31 climate models account for 47% (model interquartiles of 35 to 105%) of the 2000–2018 drought severity, pushing an otherwise moderate drought onto a trajectory comparable to the worst SWNA megadroughts since 800 CE.

Southwestern North America (SWNA; western United States and northern Mexico: 30°N to 45°N, 105°W to 125°W) has been anomalously dry and warm in the 21st century relative to the 20th century (*1*–*3*). The 21st-century drought severity has been reflected in reduced snowpack (*4*), reduced river flow and lake levels (*5*), declines in groundwater availability (*6*, *7*), shifts in agricultural activities (*8*), forest drought stress (*9*), increased wildfire activity (*10*), and reduced vegetation carbon uptake (*11*).

Paleoclimatic proxies indicate that SWNA experienced many severe swings in hydroclimate before the observed period. In particular, tree-ring records reveal several megadrought events during the Medieval era and subsequent centuries (~850–1600 CE) that dwarfed all droughts in the following 400 years in intensity and duration (*12*). These megadroughts were likely associated with cool eastern tropical Pacific sea surface temperatures, which promote an atmospheric wave train that blocks Pacific storms from reaching SWNA (*13*–*15*). Any attribution of recent drought to anthropogenic climate change must consider this region's capacity for large internal hydroclimatic variability (*16*, *17*). Although 21st-century drought conditions have been clearly promoted by natural Pacific Ocean variability (*18*–*20*), certain elements are also consistent with projected drying due to anthropogenic radiative forcing (*21*–*23*). Cold-season precipitation deficits across the southwestern United States and northern Mexico are consistent with modeled poleward expansion of the subtropics, albeit with large uncertainties in models and observations (*24*, *25*). Observed warming since the early 1900s is more uniformly consistent with model simulations of anthropogenic trends, decreasing SWNA runoff and warm-season soil moisture by reducing snowpack and increasing evaporative demand (*26*–*28*). Models project that 21st-century SWNA summer droughts will intensify owing to declining spring precipitation in the southern portion of the region and continued warming-induced reductions of summer runoff and soil moisture (*22*–*24*, *29*).

Here, we use 1586 tree-ring chronologies to reconstruct 0- to 200-cm summer (June to August) soil moisture and snow water equivalent (hereinafter termed "soil moisture" collectively) anomalies on a 0.5° latitude-longitude grid back to 800 CE across western North America [(*30*); Fig. 1]. Soil-moisture anomalies are standardized relative to the entire 800–2018 CE period, and the magnitude of negative anomalies indicates drought severity. The soil-moisture record targeted in the reconstruction covers 1901–2018 and is referred to as Noah-calibrated soil moisture (*31*). Because true observations of soil moisture do not exist, this soil-moisture record is modeled based on observed climate. Monthly precipitation, temperature, humidity, wind speed, and radiation data are used to force a bucket-type water-balance model with intermonth persistence tuned to emulate the Community Noah land-surface model (*32*) (fig. S1). The reconstruction method is the same method that has been used to develop previous continental drought atlases (*16*). Reconstruction skill is evaluated as the squared Pearson's correlation (R^2) between observations during the 1901–1983 calibration period and out-of-sample reconstruction values that were calculated by using leave-10-out cross-validation (*30*). Reconstruction skill is highly significant ($P < 0.01$) across much of SWNA (Fig. 1A). The cross-validated R^2 for the SWNA regionally averaged reconstruction is 0.86 back to 1700 CE (Fig. 1B). Skill reduces back in time owing to loss of tree-ring chronologies but remains above 0.73, even when using the subset of tree-ring chronologies extending back to 800 CE (Fig. 1B).

We evaluated 19-year running means of reconstructed and observed soil-moisture anomalies for explicit contextualization of the dry 2000–2018 period. Running-mean values are assigned to the final year in each 19-year window. During 800–2018 CE, there were 40 prolonged drought events with more than one negative SWNA 19-year running-mean soil-moisture anomaly. We rank the severity of each prolonged drought event based on the event's most negative 19-year soil-moisture anomaly. Definitions of megadrought vary, but in North America, they generally refer to multidecade drought events that contained periods of very high severity and were longer lasting than any event observed in the 19th or 20th centuries (*12*). Here we identify the strongest SWNA megadroughts in the reconstruction as the prolonged drought events that contained at least one 19-year anomaly that was 0.25 standard deviations (σ) more negative than any observed in the 20th century. The regionally averaged SWNA reconstruction (Fig. 1C) reveals four megadroughts that satisfy this criterion in the late 800s, mid-1100s, 1200s, and late 1500s.

The 21st-century prolonged drought event (still ongoing as of 2020 given our definition) registered its first negative SWNA 19-year anomaly in 1996–2014, and its most negative anomaly (2000–2018) was −0.74 σ; the late-1500s megadrought was the only reconstructed event with a more negative 19-year soil-moisture anomaly than that in 2000–2018 (Fig. 1C). The most severe SWNA 19-year soil moisture anomaly during the late-1500s megadrought was −0.80 σ in 1575–1593. The 2000–2018 drought severity was nevertheless within the uncertainty ranges of several other 19-year drought severities, and the late-1500s event contained six 19-year anomalies more negative than that in 2000–2018. Within SWNA, local drought rankings during the 21st-century event were generally not as high as the ranking of the regionally averaged drought (Fig. 1D). Only 37% of SWNA experienced a local 19-year drought severity that ranked among the top five since 800 CE, a smaller aerial extent of high-ranking drought than occurred

[1]Lamont-Doherty Earth Observatory of Columbia University, Palisades, NY 10964, USA. [2]NASA Goddard Institute of Space Studies, New York, NY 10025, USA. [3]Department of Geography, University of Idaho, Moscow, ID 83844, USA. [4]Management of Complex Systems Department, UC Merced, Merced, CA 95343, USA. [5]Department of Earth and Environmental Sciences, Columbia University, New York, NY 10027, USA. [6]Cooperative Institute for Research in Environmental Sciences, University of Colorado Boulder, Boulder, CO 80302, USA. [7]Universities Space Research Association, Columbia, MD 21046, USA. [8]NASA Goddard Space Flight Center, Greenbelt, MD, USA 20771, USA. [9]Civil, Environmental, and Architectural Engineering, University of Colorado Boulder, Boulder, CO 80309, USA.
*Corresponding author. Email: williams@ldeo.columbia.edu

during any of the four most severe reconstructed megadroughts (Fig. 1D). Notably, the four megadroughts in Fig. 1 were longer than the 21st-century drought thus far, giving grid cells more chances to register high-ranking 19-year drought severities. Conversely, the 21st-century drought is the only event in which all SWNA grid cells registered at least one below-average 19-year soil-moisture anomaly.

The above results are consistent across alternate reconstructions with longer calibration periods that extend beyond 1983 (using fewer tree-ring records), with 2000–2018 always ranking second driest (fig. S2A). The above results are also consistent with alternate reconstructions of the self-calibrated Palmer Drought Severity Index [scPDSI; (*33*)] and soil moisture simulated by the Variable Infiltration Capacity hydrological model [VIC; (*34*)], but the reconstruction targeting VIC soil moisture has considerably less skill than the reconstructions targeting Noah-calibrated soil moisture or scPDSI [(*30*); fig. S2, B and C]. The alternate reconstructions of scPDSI and VIC soil moisture agree with our primary reconstruction in placing 2000–2018 within the two most severe prolonged SWNA droughts in at least 1200 years (fig. S2, B and C).

To address the contribution of anthropogenic climate change, we evaluated 1901–2018 trends in precipitation, temperature, and relative humidity simulated with 31 climate models in the fifth phase of the Coupled Model Intercomparison Project (CMIP5). During 2000–2018, the multimodel mean anthropogenic warming in SWNA was 1.2°C [model interquartiles (IQs): 1.0° to 1.5°C], with all models simulating warming (Fig. 2A). Anthropogenic warming increased the annual mean atmospheric vapor-pressure deficit by 9.6% (IQs: 8.4 to 11.3%), which increased the mean annual total evaporative demand (as estimated by the Penman-Monteith reference evapotranspiration) by 59 mm, or 4.5% (IQs: 53 to 73 mm, 4.1 to 5.5%) (Fig. 2, B and C). Models disagree on anthropogenic precipitation trends, with a slight multimodel mean increase in the SWNA annual total (6 mm, 1.2%; IQs: −6 to 12 mm, −2.5 to 2.2%) (Fig. 2D).

In Fig. 2, E to H, we estimate the effect of these anthropogenic climate trends on soil moisture as the difference between observed soil-moisture anomalies and those recalculated after removing model-estimated anthropogenic trends from the observed climate records [e.g., (*3*, *10*)]. The positive effect of the slight multimodel mean precipitation increase in northern SWNA (Fig. 2E) is overwhelmed by the spatially ubiquitous drying effect of increasing vapor-pressure deficit simulated by all models (Fig. 2F). Notably, the high intermodel spread in anthropogenic precipitation trends causes high spread among estimated soil-moisture trends (Fig. 2, D and E), and the true uncertainty may be even larger than suggested here owing to systematic model biases (*25*, *35*). Combined, the multimodel mean estimates of anthropogenic trends in precipitation, temperature, and humidity force a 2000–2018 SWNA regionally averaged summer soil-moisture anomaly of −0.35 σ (IQs: −0.26 to −0.78 σ) (Fig. 2G). This accounts for 47% (IQs: 35 to 105%) of the observed anomaly (Fig. 2H). Of the 31 CMIP5 models considered, 28 (90%) simulated climate trends that promoted SWNA drought during 2000–2018 based on our water-balance estimates. Twenty-five models (81%) indicated that this altered baseline in mean climate

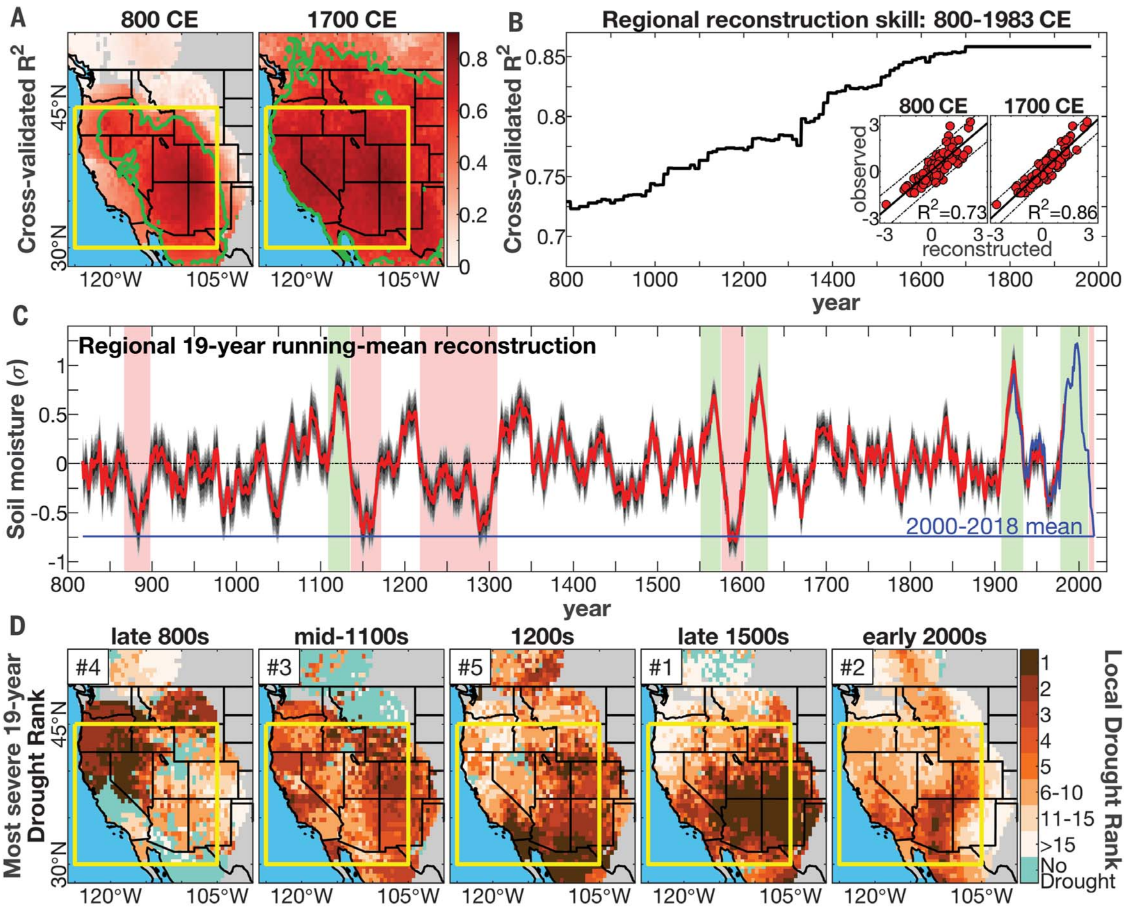

Fig. 1. Summer soil-moisture reconstruction for SWNA. (**A**) Cross-validated reconstruction skill (R^2) using tree-ring records that extend to 800 and 1700 CE (green contour: $R^2 \geq 0.5$; gray: reconstruction does not extend to 800 CE; yellow box: SWNA). (**B**) Time-resolved cross-validated R^2 of the SWNA regional reconstruction. The inset shows observations versus cross-validated reconstructions during the 1901–1983 calibration interval using tree-ring records extending back to 800 and 1700 CE. (**C**) Time series of reconstructed (red) and observed (blue) 19-year running-mean standardized SWNA soil moisture (gray: 95% reconstruction confidence interval; blue horizontal line: 2000–2018 mean; pink and green shading: the five drought and pluvial periods with the most-negative and most-positive 19-year soil-moisture anomalies, respectively). (**D**) Maps of the local rank of the most negative 19-year anomaly to occur during each of the five drought events highlighted in (C). In the maps, the aqua color indicates no negative 19-year anomaly, and numbers in the top left corners indicate the rank of the most negative regionally averaged 19-year anomaly during each drought event.

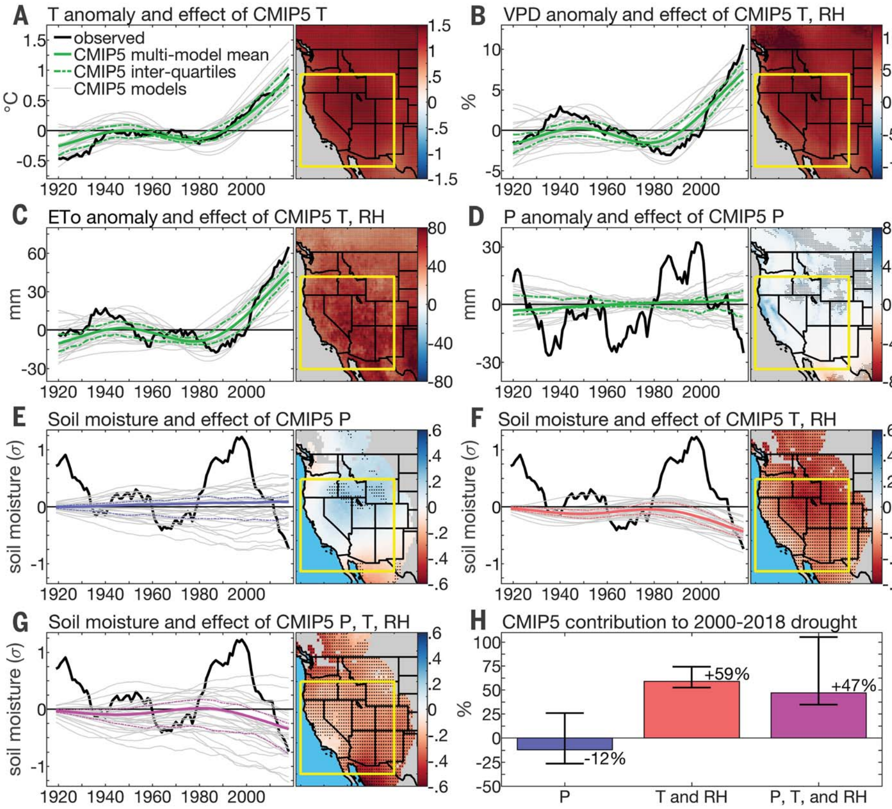

Fig. 2. Effects of anthropogenic climate trends. (**A** to **G**) Time series plots showing the 19-year running-mean observed anomalies (black lines) in SWNA (yellow box in maps) for mean annual temperature (T) (A), mean annual vapor pressure deficit (VPD) (B), annual reference evapotranspiration (ETo) (C), annual precipitation (P) (D), and soil moisture [(E) to (G)]. Solid and dotted colored lines represent 19-year running-mean CMIP5 multimodel mean and IQ trends, respectively (gray lines: trends from 31 models). CMIP5 trends are evaluated for P, T, and relative humidity (RH). In (E) to (G), CMIP5 trends show contributions to observed soil-moisture anomalies since 1901. The maps show CMIP5 multimodel mean contributions to 2000–2018 anomalies (dots: >75% model agreement on sign; gray: masked out because reconstruction does not extend to 800 CE). (**H**) Percent contribution of CMIP5 (bars) multimodel mean climate trends to the 2000–2018 SWNA soil-moisture anomaly (whiskers: model IQs). Anomalies are relative to 1921–2000 in (A) to (D) and 800–2018 CE in (E) to (G).

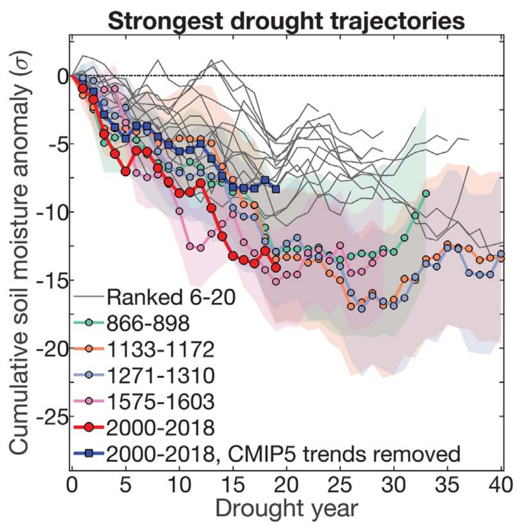

Fig. 3. Development of the most severe 19-year droughts since 800 CE. Time series of cumulative SWNA summer soil-moisture anomalies for the 20 prolonged droughts with the most-negative 19-year soil-moisture anomalies. The drought periods analyzed here begin 18 years before the most-negative 19-year anomaly. The dark blue line shows 2000–2018 cumulative anomalies after removing CMIP5 multimodel mean climate trends. The shaded regions represent 95% confidence intervals for the four reconstructed megadroughts shown with the light colored lines.

accounted for >25% of the observed 2000–2018 SWNA soil-moisture anomaly. This net anthropogenic drying effect is corroborated by the tree-ring records themselves. Reconstruction of an alternate summer soil-moisture record recalculated after removal of CMIP5 ensemble mean temperature and relative humidity trends reduces validation skill because the recalculated soil moisture is too wet relative to the reconstruction in recent decades (fig. S3).

When repeated for scPDSI and VIC soil moisture, the CMIP5 multimodel mean contribution to SWNA 2000–2018 drought severity was 47 and 30%, respectively (fig. S4). The weaker anthropogenic drying effect in the VIC simulation was primarily due to desert areas: (i) In high desert, warming reduces winter snow sublimation and increases infiltration; (ii) where vegetation is sparse, increased winter precipitation and minimal transpiration enhance deep moisture storage; and (iii) in more vegetated desert areas, soils dry to the wilting point in summer regardless of anthropogenic climate trends, erasing all soil-moisture memory of warming-induced drying in spring (supplementary text S1 and figs. S5 to S10). Outside of deserts, and particularly in forested areas, the VIC model simulates summer soil drying driven by anthropogenic warming through enhanced evapotranspiration and early loss of snowpack (fig. S11).

Given known disagreement among land-surface models in deserts where small anomalies are substantial relative to dry climatologies (*36*) and the inherently better representation of forested areas by the tree-ring network, we repeated our reconstructions to target forested areas only. All forest-only reconstructions still estimate 2000–2018 to be among the two driest 19-year drought periods since 800 CE for SWNA (fig. S12, A to C). Considering SWNA forested areas only, the contribution of anthropogenic climate trends to 2000–2018 drought severity increased slightly for Noah-calibrated soil moisture and scPDSI (to 57 and 51%, respectively) and dramatically (to 83%) for VIC soil moisture (fig. S12, D to F). This stronger anthropogenic effect in the VIC simulation is likely due to the additional effect of warming-driven snowpack loss, which is not accounted for directly in the Noah-calibrated soil moisture or scPDSI. The VIC simulations indicate a steady warming-driven reduction to SWNA spring snowpack over the past century that accounts for the majority of the simulated spring snowpack anomaly in 2000–2018 (fig. S13).

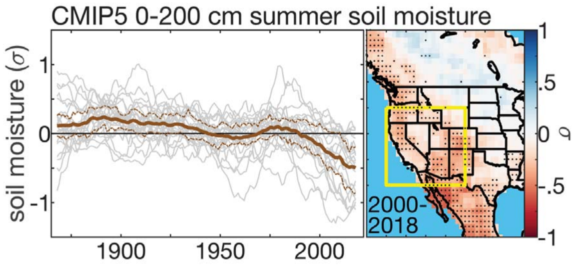

Fig. 4. Trends in summer soil moisture simulated directly from coupled models. (**Left**) CMIP5 19-year running-mean 0- to 200-cm summer soil-moisture anomalies for historical (1850–2005) and 21st-century (2006–2018) scenarios (standardization relative to 1850–2018; gray represents 26 models; brown represents multimodel mean, IQs). (**Right**) Multimodel mean anomalies in 2000–2018 (dots represent >75% model agreement on sign; yellow box indicates SWNA).

The 2000–2018 drought was preceded by the wettest 19-year period (1980–1998) in at least 1200 years (Fig. 1C). Climate models project enhanced precipitation variability across much of the globe as a result of anthropogenic climate change, and this includes a slight 21st-century trend toward greater decadal precipitation swings in SWNA (*37*). This tendency is also apparent in model simulations of summer 0- to 200-cm soil moisture, but this simulated effect does not emerge until the second half of the 21st century (fig. S14). Regardless of the anthropogenic impact on multidecadal variability, the 1980–2018 wet-to-dry transition was hastened by the background drying forced from anthropogenic warming.

Figure 3 shows that the 2000–2018 drought was on a megadrought-like trajectory throughout its development. In the absence of anthropogenic climate trends, 2000–2018 would still rank among the 11 most severe prolonged droughts in the reconstruction (dark blue line in Fig. 3), but anthropogenic warming was critical for placing 2000–2018 on a trajectory consistent with the most severe past megadroughts. These results are robust regardless of the drought metric used or whether only forested areas are considered (fig. S15).

The results above do not account for the possibility that increased atmospheric carbon dioxide concentration ([CO_2]) has ameliorated soil-water loss by allowing plants to reduce stomatal conductance and use water more efficiently through increased surface resistance (r_s) to transpiration (*38*). Although the effects of enhanced [CO_2] on vegetation and surface water fluxes are highly uncertain (*39*), we explore how our results would be affected by a r_s response to [CO_2] as simulated by current Earth system models. Repeating our study with an adjusted calculation of reference evapotranspiration that assumes the CMIP5 multimodel mean r_s response to [CO_2] (*40*) reduces 2000–2018 drought severity by about 20% (to −0.61 σ). This prolonged drought ranks fifth in the revised reconstruction, still in line with the megadroughts (fig. S16). Even with the assumed increase in r_s, 30% of the 2000–2018 drought's severity is attributed to anthropogenic climate trends, with 81% of models simulating some degree of anthropogenic drying. Importantly, the potency of the [CO_2] effect on r_s varies by a factor of three among CMIP5 models (*40*), highlighting considerable uncertainty in this effect.

Our relatively simple hydrological modeling approach also does not account for coupled land-atmosphere interactions or dynamic vegetation responses to climate. It has been argued that hydrological effects of anthropogenic climate change are better addressed with coupled Earth system models that directly simulate land-atmosphere coupling and vegetation responses to changes in climate and [CO_2] (*38*, *41*). Figure 4 shows that, of the 26 CMIP5 models with soil-moisture data available for historical and 21st-century climate scenarios, 23 (88%) simulate negative soil-moisture anomalies in SWNA during 2000–2018, with a multimodel mean of −0.50 σ (IQs: −1.38 to −0.17 σ) relative to a 1850–2018 CE baseline. Because each model simulation has its own internal climate variability, intermodel agreement on dry soil during 2000–2018 arises from the common anthropogenic forcing. The multimodel mean 2000–2018 anomaly derived directly from CMIP5 soil-moisture simulations is somewhat larger than the anthropogenic effect of −0.41 σ found when the previously calculated anthropogenic effect shown in Fig. 2G is rescaled relative to 1850–2018 CE. The stronger anthropogenic soil drying simulated by the CMIP5 models is likely due to reduced spring-summer mountain snowpack and enhanced vegetation water use caused by lengthened growing seasons and increased leaf area due to CO_2 fertilization (*39*). Notably, the simulated ability for vegetation to survive and perpetuate these modeled soil-moisture declines may be unrealistic because current Earth system models inadequately represent nutrient and moisture limitations on vegetation activity (*42*–*44*).

The tree-ring record serves as an ominous reminder that natural climate variability can drive SWNA megadroughts that are as severe and longer than the 21st-century drought thus far. The atmosphere and ocean anomalies that drove past megadroughts very likely dwarfed those that occurred during 2000–2018, but superposition of the 2000–2018 climate dynamics on background anthropogenic soil drying put an otherwise moderately severe soil-moisture drought onto a trajectory characteristic of the megadroughts of 800–1600 CE. Critical to the megadrought-like trajectory of the 21st-century event were enhanced evaporative demand, early snowpack loss, and a broad spatial extent, all promoted by anthropogenic warming. Natural variability may very well end the early 21st-century drought in the coming years, and this transition may be under way after a wet 2019. However, our work demonstrates that the magnitude of background anthropogenic soil drying is already substantial relative to the range of natural multidecadal variability. Furthermore, anthropogenic global warming and its drying influence in SWNA are likely still in their infancy. The magnitude of future droughts in North America and elsewhere will depend greatly on future rates of anthropogenic greenhouse gas emissions globally. The effects of future droughts on humans will be further dependent on sustainable resource use because buffering mechanisms such as ground water and reservoir storage are at risk of being depleted during dry times.

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SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/368/6488/314/suppl/DC1
Materials and Methods
Supplementary Text
Figs. S1 to S21
Tables S1 and S2
References (*46*–*90*)

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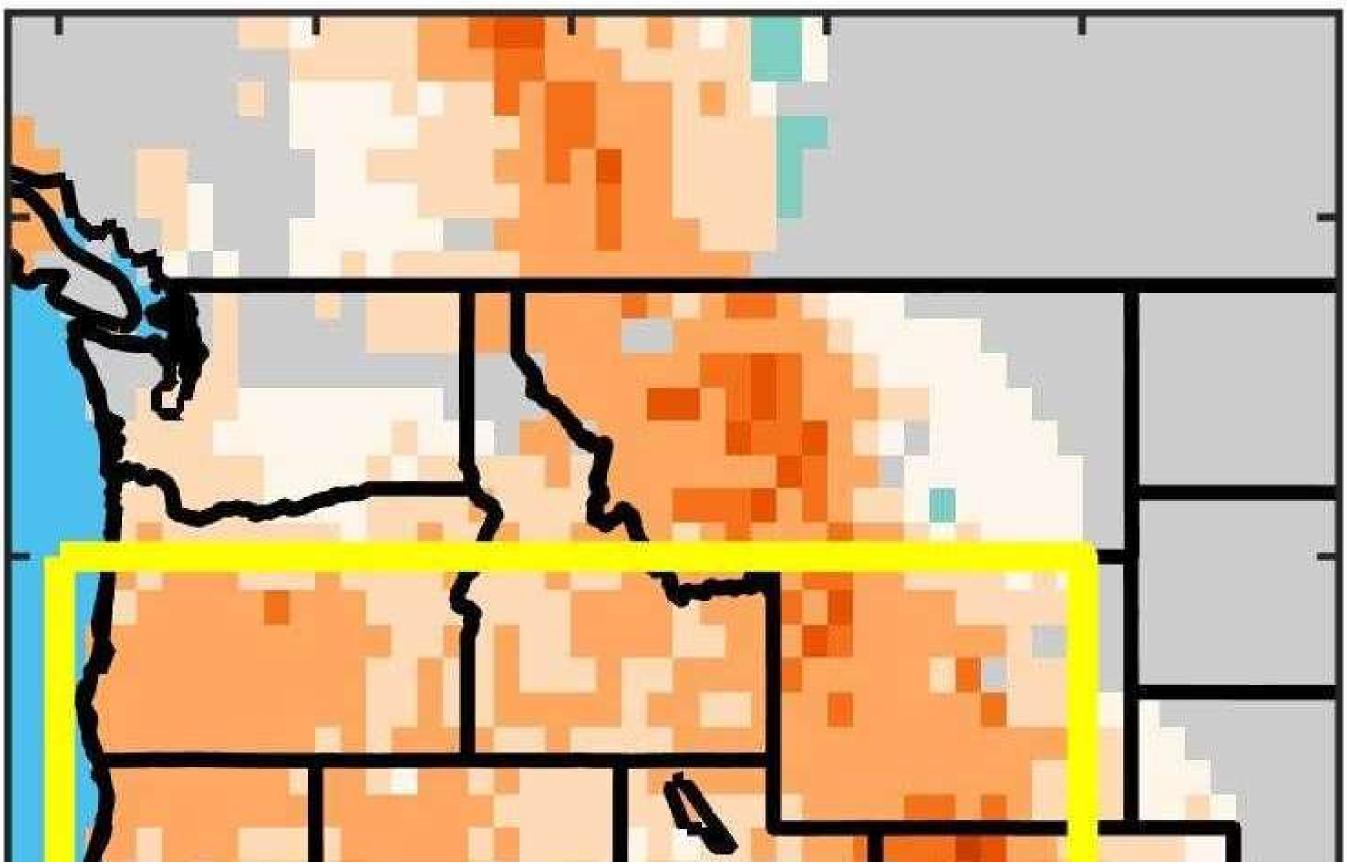
Climate-driven megadrought is emerging in western US, study says

by Kevin Krajick, Columbia University



Areas of southwestern North America affected by drought in the early 2000s; darker colors are more intense. Yellow box shows the study area. Credit: Adapted from Williams et al., Science, 2020

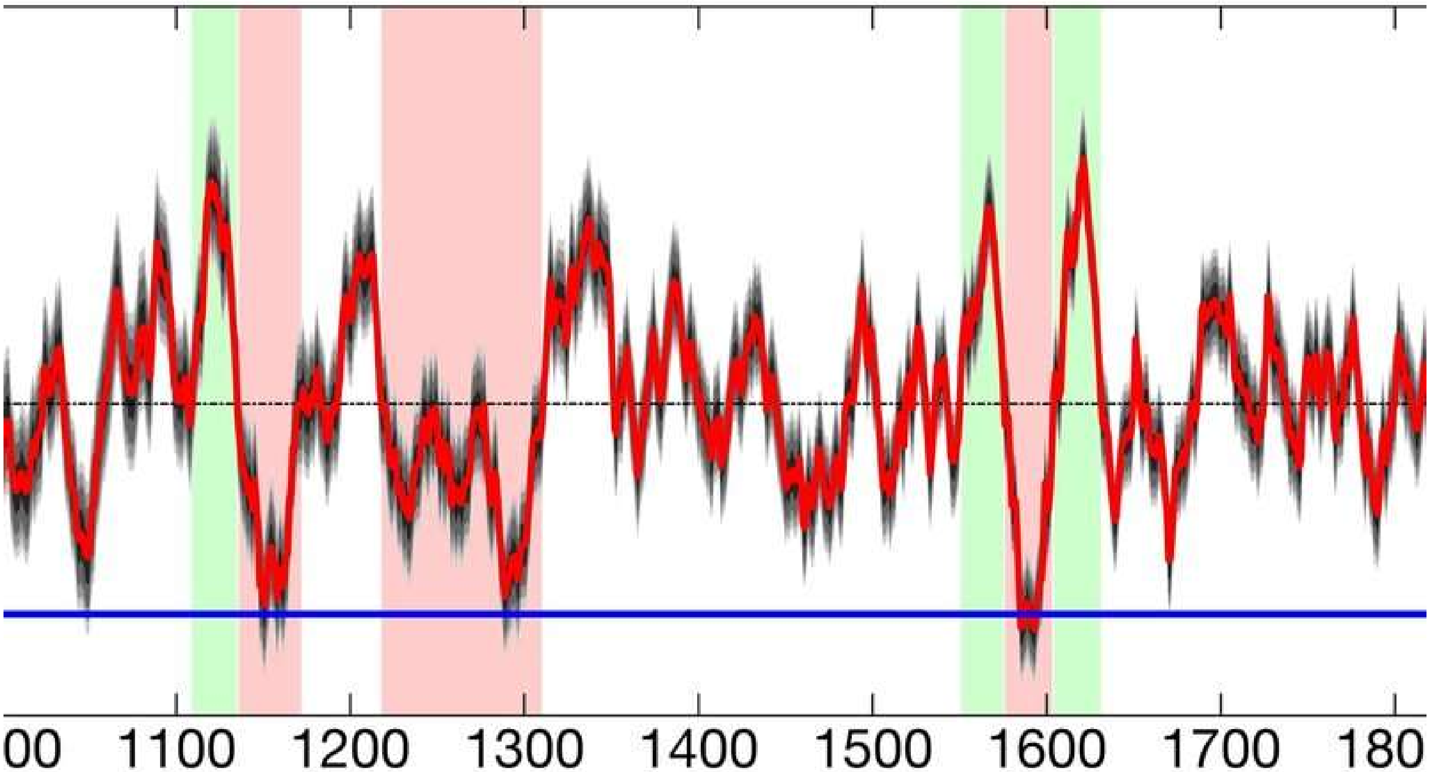
With the western United States and northern Mexico suffering an ever-lengthening string of dry years starting in 2000, scientists have been warning for some time that climate change may be pushing the region toward an extreme long-term drought worse than any in recorded history. A new study says the time has arrived: a megadrought as bad or worse than anything even from known prehistory is very likely in progress, and warming climate is playing a key role. The study, based on modern weather observations, 1,200 years of tree-ring data and dozens of climate models, appears this week in the leading journal *Science*.

"Earlier studies were largely model projections of the future," said lead author Park Williams, a bioclimatologist at Columbia University's Lamont-Doherty Earth Observatory. "We're no longer looking at projections, but at where we are now. We now have enough observations of current drought and tree-ring records of past drought to say that we're on the same trajectory as the worst prehistoric droughts."

Reliable modern observations date only to about 1900, but tree rings have allowed scientists to infer yearly soil moisture for centuries before humans began influencing climate. Among other things, previous research has tied catastrophic naturally driven droughts recorded in tree rings to upheavals among indigenous Medieval-era civilizations in the Southwest. The new study is the most up-to-date and comprehensive long-term analysis. It covers an area stretching across nine U.S. states from Oregon and Montana down through California and New Mexico, and part of northern Mexico.

Using rings from many thousands of trees, the researchers charted dozens of droughts across the region, starting in 800 AD. Four stand out as so-called megadroughts, with extreme aridity lasting decades: the late 800s, mid-1100s, the 1200s, and the late 1500s. After 1600, there were other droughts, but none on this scale.

The team then compared the ancient megadroughts to soil moisture records calculated from observed weather in the 19 years from 2000 to 2018. Their conclusion: as measured against the worst 19-year increments within the previous episodes, the current drought is already outdoing the three earliest ones. The fourth, which spanned 1575 to 1603, may have been the worst of all—but the difference is slight enough to be within the range of uncertainty. Furthermore, the current drought is affecting wider areas more consistently than any of the earlier ones—a fingerprint of global warming, say the researchers. All of the ancient droughts lasted longer than 19 years—the one that started in the 1200s ran nearly a century—but all began on a similar path to to what is showing up now, they say.



Varying soil moisture in southwestern North America, 800-2018. The straight horizontal center line indicates average moisture; blue line at bottom shows 2000-2018 mean. Green bars indicate abnormally wet periods, pink ones abnormally dry. The fluctuating red moisture line is based on tree-ring data until it converts to blue at the start of modern instrumental observations. Credit: Adapted from Williams et al., Science, 2020

Nature drove the ancient droughts, and still plays a strong role today. A study last year led by Lamont's Nathan Steiger showed that among other things, unusually cool periodic conditions over the tropical Pacific Ocean (commonly called La Niña) during the previous megadroughts pushed storm tracks further north, and starved the region of precipitation. Such conditions, and possibly other natural factors, appear to have also cut precipitation in recent years. However, with global warming proceeding, the authors say that average temperatures since 2000 have been pushed 1.2 degrees C (2.2 F) above what they would have been otherwise. Because hotter air tends to hold more moisture, that moisture is being pulled from the ground. This has intensified drying of soils already starved of precipitation.

All told, the researchers say that rising temperatures are responsible for about half the pace and severity of the current drought. If this overall warming were subtracted from the equation, the current drought would rank as the 11th worst detected—bad, but nowhere near what it has developed into.

"It doesn't matter if this is exactly the worst drought ever," said coauthor Benjamin Cook, who is affiliated with Lamont and the Goddard Institute for Space Studies. "What matters is that it has been made much worse than it would have been because of climate change." Since temperatures are projected to keep rising, it is likely the drought will continue for the foreseeable future; or fade briefly only to return, say the researchers.

"Because the background is getting warmer, the dice are increasingly loaded toward longer and more severe droughts," said Williams. "We may get lucky, and natural variability will bring more precipitation for a while. But going forward, we'll need more and more good luck to break out of drought, and less and less bad luck to go back into drought." Williams said it is conceivable the region could stay arid for centuries. "That's not my prediction right now, but it's possible," he said.

Lamont climatologist Richard Seager was one of the first to predict, in a 2007 paper, that climate change might eventually push the region into a more arid climate during the 21st century; he speculated at the time that the process might already be underway. By 2015, when 11 of the past 14 years had seen drought, Benjamin Cook led a followup study projecting that warming climate would cause the catastrophic natural droughts of prehistory to be repeated by the latter 21st century. A 2016 study coauthored by several Lamont scientist reinforced those findings. Now, says Cook, it looks like they may have underestimated. "It's already happening," he said.

In the Catalina Mountains in southern Arizona, forests struggle to keep up with recent increases in drought and wildfire activity, which are expected to continue due to human-caused climate change. Credit: Park Williams/Lamont-Doherty Earth Observatory

The effects are palpable. The mighty reservoirs of Lake Mead and Lake Powell along the Colorado River, which supply agriculture around the region, have shrunk dramatically. Insect outbreaks are ravaging dried-out forests. Wildfires in California and across wider areas of the U.S. West are growing in area. While 2019 was a relatively wet year, leading to hope that things might be easing up, early indications show that 2020 is already on a track for resumed aridity.

"There is no reason to believe that the sort of natural variability documented in the paleoclimatic record will not continue into the future, but the difference is that droughts will occur under warmer temperatures," said Connie Woodhouse, a climate scientist at the University of Arizona who was not involved in the study. "These warmer conditions will exacerbate droughts, making them more severe, longer, and more widespread than they would have been otherwise."

Angeline Pendergrass, a staff scientist at the U.S. National Center for Atmospheric Research, said that she thinks it is too early to say whether the region is at the cusp of a true megadrought, because the study confirms that natural weather swings are still playing a strong role. That said, "even though natural variability will always play a large role in drought, climate change makes it worse," she said.

Tucked into the researchers' data: the 20th century was the wettest century in the entire 1200-year record. It was during that time that population boomed, and that has continued. "The 20th century gave us an overly optimistic view of how much water is potentially available," said Cook. "It goes to show that studies like this are not just about ancient history. They're about problems that are already here."

More information: "Large contribution from anthropogenic warming to an emerging North American megadrought" *Science* (2020). https://science.sciencemag.org … 1126/science.aaz9600

Journal information: Science

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