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Who Runs Short in a Drought? Water Rights and Canal Delivery in Arizona*

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November 18, 2026

Abstract

Water rights and seasonal allotments set how much water Arizona farms may use from shared canals. I ask whether farms with the same rights share a shortage equally. I trace the canals to 28,588 fields and measure monthly water use by satellite. I estimate how each district divides its water. In the 2021 drought, fields that usually sit far down a canal were left fallow more often and used less water in districts with junior rights to Central Arizona Project (CAP) water. Where canals rotate water, fields share a shortage. In the Maricopa–Stanfield district, fields far down the canals ran short while CAP water entered at the head. In the 2022–2023 cut, the district relied on wells that pump into its canals, and fields they could not reach ran short. Farmers knew the cut before planting and left land fallow. This first wave caused most of the loss, $8.0–12.1 million a year, or 24 to 40 percent of what the district's farmland normally earns. In a second wave, planted fields these wells could not reach ran short in peak months. Fields near water sources do not take extra water. Who runs short depends on when and where canals can deliver water.

1 Introduction

Laws and rules often decide how much of a shared resource each user may take. In many cases, the resource also reaches those users one after another. When the resource is plentiful, the order in which users are served makes little difference. When it is scarce, the order can matter. A formal right says how much a user may take in total and who is cut first at the source. By itself it does not settle when or in what order users are served when the network cannot meet everyone's demand at once. Even when no one exceeds their legal entitlement, users with the same right can end up with different amounts.

Irrigation water is a clear example of this problem. Water rights and the rules of irrigation districts, the local organizations that run the canals, determine how much water each farm is entitled to. Districts charge each farm's deliveries against a seasonal allotment. Water reaches

*I thank Paul Castañeda Dower (advisor), Corbett Grainger, Daniel Phaneuf, and Laura Schechter for guidance. This research received no external funding. The author has no financial relationships or conflicts of interest to disclose.

farms through branching canals shared with other farms, and along a canal it passes the upstream farms before it reaches the farms below. In the hot months crops need water at the same time, and in a supply cut less water enters. In either case the water entering a canal in a month can fall short of what its planted fields need.

Suppose ten farms on one canal each hold the same right, and a long drought cuts the canal's flow in a peak month by 30 percent below what their crops need. On paper, each farm loses 30 percent. If the district serves orders in sequence down the canal, the upstream farms take what their crops need first out of their seasonal allotments, and the farms at the end lose much more than 30 percent in that month. If the district rotates water among the farms, they share the month's shortfall in proportion. In years without a shortage such gaps can be hidden, because wells and stored water cover most of them. When a drought lasts several years, the buffers run low. I ask whether farms with the same rights then share the shortage equally, and whether the answer follows how their district delivers water.

Arizona is the hard case, because its rights are well defined. Water rights and contracts determine which users lose water first when the Colorado River runs short, and irrigation districts deliver the water to farms through their own canals, each by its own rules (Section 2). In 2022 the first shortage ever declared on the lower Colorado River cut the water of central Arizona's farms, and the cut at the source followed the rules (Reclamation 2021). Any gap between farms with the same rights therefore arises inside the district, in how its canals and wells deliver the water. New federal rules for 2027–2028 cut deliveries to the states on the lower Colorado River by 1.25 million acre-feet a year, and new rules are planned every two years (Interior 2026; Reclamation 2026b). These rules set the cuts for states and their contractors. Who goes short inside a district is left to the district.

The simplest approach would compare farms at the head of a canal with farms at its end. Farms at the end often get less water every year and adjust to it, so in years with enough water they may not look worse at all. So I follow the same fields over time. I trace Arizona's canals from their sources to 28,588 fields, so each field has one route and a known set of upstream and downstream fields (Section 5). Satellites measure each field's monthly water use (its evapotranspiration) and its crop growth, for 2016–2023. I study three outcomes: whether a field is left fallow, how much water a planted field uses in the months its crop grows, and a satellite proxy for crop yield (GCVI) over the season. I proceed in two steps: a test across the whole network that uses only demand (Sections 6 and 7), and a model of canal delivery that adds the water supplied, for the districts with monthly water records (Section 8).

In the first step, I test whether a field uses less water in drought when the fields upstream of it use more. A field's place on the canal is fixed, but the water used upstream and downstream of it changes over time as other fields change crops or go fallow. A field's upstream demand is the water its upstream fields use in the month, and its downstream demand is the same for its downstream fields. Because upstream fields respond to the same heat and the same cuts as the field itself, I make three adjustments. First, only fields beyond a distance set for each irrigation district count, where their water use no longer moves with the field's own for local reasons. Second, downstream fields sit on the same canals and face the same weather and cuts, but they cannot take water before the field, so the downstream side tests the direction. I call upstream minus downstream demand the field's *position*, and their sum the *canal total*. Third, I instrument both sides with predicted demand, a field's acres times the typical water use of its crop. Predicted demand moves only when fields change crops or go fallow before the season, so the estimates compare the same field over

time as the demand above and below it shifts. With field-by-month effects, the comparison is the same field in the same month from one year to the next, in drought years and in other years. If the canal delivers in order, position should lower a field's water use. If it shares the shortage, the canal total should. In the CAP districts, position does, and the canal total does not.

The first step uses only demand. It shows where water follows the direction of the canal, but not how much water a field lacked or what rule divided it, because satellites measure water use, not the water delivered to each field. The second step brings in supply. Public records show how much water enters each district's canals each month and where its wells stand. I carry that water down the canals to predict how much reaches each field each month, and I estimate how each district divides it. The model has three free parameters: how much a field with a well claims from the canal, and two weights that set how water splits along a canal and at its branches. I judge each sharing rule by how well its monthly shortfalls predict fields' water use in years left out of the fit, and I test the estimates by shuffling delivery dates and moving fields to other places on the canal.

Water rights and seasonal allotments set how much water each farm may use, and fields near water sources do not take extra water. In Maricopa–Stanfield, planted fields near the sources use at most 8 percent more water over the season than fields far from them with the same crops. What the right does not set is when and where canals can deliver that water. In 2022 Maricopa–Stanfield set allotments at 1.7 to 2.8 acre-feet per acre, depending on where a grower's fields were in the district (Section 2). Where canals rotate water, position on the canal does not matter. Where canals deliver water in order, the fields farthest from the source of the water run short, and when the source moves, the losers move with it. When a cut is announced before planting, farmers answer first by leaving land fallow, which keeps the season's water on the fields they plant near normal. In a second wave, those fields still go short in the peak months (Section 8).

I report three findings. First, across the state, position on a canal matters only where canals run short and do not rotate water (Section 7). That is the case in the CAP districts with junior rights in drought. In the 2021 drought, fields that usually sit far down a canal were left fallow more often and used less water. The share left fallow rose 4.1 percentage points in the furthest third of fields and fell 3.3 in the nearest. Delivery in order can cost a field water only if the field has no other water sources (Section 3). Some fields have no backup source of groundwater. Their owner has no well, and no canal pump stands within 2 kilometers above them. In 2021, among these fields, one at the 75th percentile of position used 7 to 10 percent less water, relative to its crop's need, than one at the 25th. This holds whether 2021 is compared with 2019–2020, with 2017–2018, or with all other years. Fields below a canal pump are protected by a large groundwater source, and there position did not lower water use. The average over all fields mixes exposed and protected fields, so it is smaller: about 5 percent in a drought month, and half that against 2019–2020 alone. In the 2022–2023 cut, position from the head no longer lowers water use in the CAP districts, because CAP water in the canals was cut and district wells fed the canals along their length. Where canals rotate water, in the Upper Gila, position does not leave fields fallow or lower water use. The same holds in senior-rights districts, and position did not lower water use in the droughts of 2008–2015, when CAP supply was full.

Second, inside a district, which fields run short depends on the sharing rule, where water enters, and who runs the wells (Section 8). Equal sharing is rejected where canals deliver water in order and fits best where they rotate. Where districts run short and record their water, fields without a well use less water in the months the model predicts a shortfall. In Maricopa–Stanfield, they use 27 to 31 percent less water in months when the canal leaves 35 percent or more of their claim

unmet than in months when it meets nearly all of it. There, which fields ran short followed the water source (Figure 11). While CAP water entered at the head, among the fields that depend most on CAP water, those farther from the head used less water. Maricopa–Stanfield has records of its canal pumps and wells, so I test the pumps there. In the cut, fields without a well used less water and farmed less land where the model predicts their shortfall rose more: 5.6 percent less water and 4.9 percentage points less land farmed, per standard deviation. If the model spreads the same pump water evenly over all fields, it no longer finds which fields used less water. Where farmers run their own wells, in Harquahala and New Magma, the loss falls on fields without a well. In Central Arizona and Hohokam, the records leave out too much to tell: which wells ran in Central Arizona, and water that reached fields in Hohokam.

Third, in Maricopa–Stanfield, land left fallow caused most of the 2022–2023 cut's cost, while on planted fields water use and the yield proxy fell with the shortfall (Sections 8.5 and 8.8). In the first wave, leaving land fallow cost $8.0–12.1 million a year in returns over operating costs, 24 to 40 percent of what the district's farmland would normally earn. Had every field stayed planted and shared the water, the loss would have been about three times as large. Farmers knew their cuts before planting, so under equal sharing or pooled canal pumps they would have left different fields fallow, not less land. Before the cut, a planted field offset a short month with more water in the season's other months. The season's water use did not always fall, and the yield proxy did not fall. In the second wave, planted fields could no longer offset a short month. Their season's water use and, less precisely, their yield proxy then fell with the shortfall. On average, planted fields without a well lost 1.2 percent of their gross revenue in 2022 and 3.1 percent in 2023. In the model, in July 2022 more than half of the planted fields received their full claim, and the shortfall fell on the fields the district's canal pumps could not reach. An even delivery, the same shortfall on every planted field, would have saved none of that loss if yield falls in a straight line with water. It would have saved less than a fifth under seasonal field-trial responses and most of it under my estimated monthly response. That even delivery is a benchmark the district could not reach by changing its rule alone, because canal pumps cannot send water upstream.

The paper shows what well-defined property rights in water leave undefined. Burness and Quirk (1979) show that, when rights cannot be traded, serving senior users first is less efficient than sharing water equally. Libecap (2011) and Leonard and Libecap (2019) study how prior appropriation and irrigation districts emerged. Ayres, Meng, and Plantinga (2021) show that tradable groundwater rights raise land values over open access. Barzel (1989) separates the legal right, which the state assigns, from the economic right, which is what the holder can actually get. In a resource delivered in sequence, the gap between the two has a spatial order, and the water right leaves that order to the district. There, the district's delivery rules and who runs its wells decide who goes short.

The paper also contributes to the study of common-pool resources with sequential access, in which irrigation is the main example (Ostrom 1990; Ostrom and Gardner 1993). Theory and field studies show that farms at the head of a canal have an advantage over farms at the end, and that enforcement and local institutions affect its size (Wade 1988; Ray and Williams 2002; Mekonnen, Channa, and Ringler 2015; Akram and Mendelsohn 2017; Jacoby and Mansuri 2020; Jacoby, Mansuri, and Fatima 2021; Das and Dutta 2026). Most of that evidence comes from developing countries, where water rules are often weakly enforced, and most of it compares fixed locations. In the western United States, Cody (2018a) studies 60 irrigation systems in Colorado's San Luis Valley during the drought of 2011–2014. Fields at the head and at the end grow about equally

where farms take turns, and under some rules the end does worse where farms take water at the same time. Cody (2018b) finds that seniority and catchment size predict what ditches divert far better than a ditch's place on the stream. In Maricopa–Stanfield, farms at the end of long laterals had worse service in the 1990s (Bautista et al. 2000). That evidence comes from one valley and one district, and it compares fixed locations.

Earlier studies show that fields at the end of a canal can lose water. This paper shows which fields lose it, in which months, and why. To my knowledge, this is the first study to follow the same fields over time, each placed on its canal by the water used above and below it each month, across the canal networks of a whole state. The head-end advantage appears when deliveries are cut, in districts that deliver water down their canals in order. The advantage goes to the fields the water reaches first, which in the 2022–2023 cut were the fields below the districts' canal pumps. For the same shortfall, fields that the district's canal pumps can supply lose at most half as much water as fields the pumps cannot supply. In the Upper Gila, whose canals rotate water, position does not matter, as on Cody's ditches that take turns. There, fields without a well are left fallow more often when water is short.

Akram and Mendelsohn (2017) estimate that an efficient division of canal water among farms in Pakistan would raise welfare by 12 to 14 percent. Here the gain from equal sharing depends on the wave of the cut. Before the season, equal sharing would have changed which fields were left fallow, not how much land, because farmers knew the cut before planting. On planted fields during the season, the gain depends on how yield responds to water (Section 8.8; Table 8).

The paper also shows how to learn the way a district divides its water when the water delivered to each field is not observed. It starts from a measure of who is upstream of whom. Studies of irrigation rarely observe which fields take water before which others, and comparing farms near the head with farms near the end misses how canals branch (Manero et al. 2019). A correlation among neighbours does not show that one affects another, because neighbours share their surroundings (Manski 1993). Water on a canal moves one way, so the fields downstream of a field give a comparison. Garg et al. (2018) use downstream villages in the same way on rivers, and Keiser and Shapiro (2019) compare waters above and below a treatment plant. Splitting demand into position and canal total separates rationing by order from a limit that the whole canal shares. The delivery model then estimates, from satellite water use, how each district actually divides its water. In Ostrom's terms these are the rules in use, and Appendix Table A18 sets them beside the rules on paper (Ostrom 1990). The network rests on public data on canals, land elevation, and field boundaries, and satellites supply the outcomes, as in other work on canal performance (Peña-Arancibia and Ahmad 2021; BenYishay et al. 2025). The first step can therefore be applied to other irrigated regions. The delivery model also needs monthly records of the water entering each canal. With a year's water and each field's usual demand, the delivery model predicted which fields lost water and went fallow in the 2022–2023 cut.

Finally, the paper adds to recent work on how scarce water is allocated by looking inside a district's canals, once the water has reached the district. Most of this work stops at the district. Rafey (2023) measures the value of reallocating water through markets in Australia's Murray–Darling Basin, and Rafey (2026) measures water misallocation across water rights in California. Li, Xu, and Zhu (2019) find that junior rights holders irrigate less of their land, and Cobourn et al. (2022) find that they fallow more land and switch crops. Harris (2024) studies how Arizona farmers changed their crops and planted acreage when CAP deliveries were cut, and cannot observe how water moves within a district. Ryan and Sudarshan (2022) show that a fixed ration

of power for pumping misallocates groundwater across farmers in India, and Burlig, Preonas, and Woerman (2026) show that higher pumping costs cut groundwater use and shift crops. Garcia and Belmar (2025) show that river water boards in Chile limit upstream extraction and raise yields downstream. The boards allot water to whole canals and leave the division inside each canal to its canal association. Studies that reach the district take it to divide its water evenly among its farms (Ji and Cobourn 2018; Hagerty 2022). I test that. Equal sharing fits best where canals rotate water. Where the district delivers water in order, farms with the same rights do not share a shortage equally.

2 How Arizona Divides Water in a Shortage

2.1 Rights at the Source

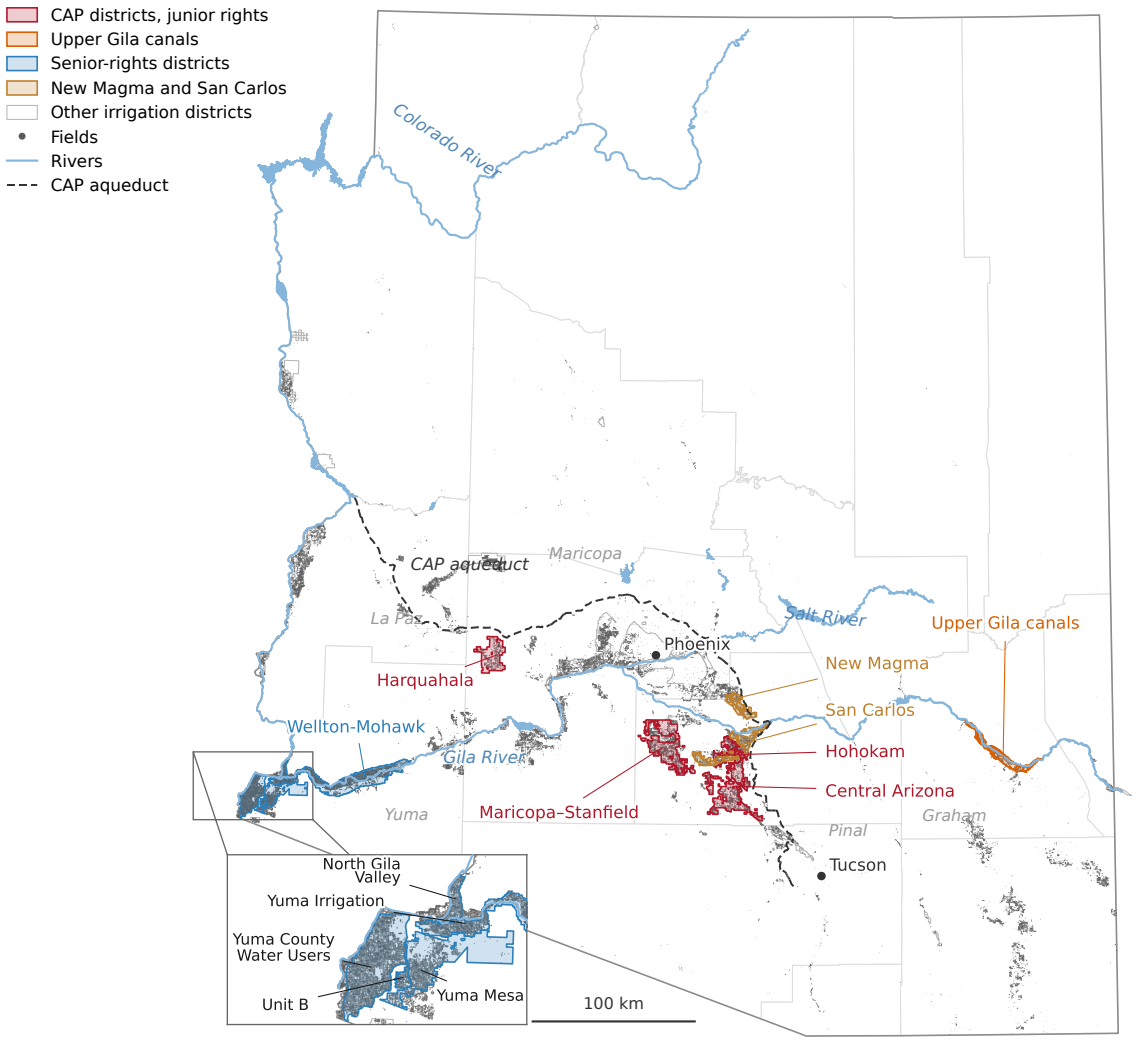
Irrigated agriculture in Arizona concentrates along three surface-water corridors (Figure 1): the Colorado River and its diversion canals in the western border counties (Yuma, La Paz), the Salt–Gila system feeding Phoenix (Maricopa, Pinal), and the upper Gila Valley (Graham). The 540 km Central Arizona Project (CAP) aqueduct connects the Colorado to central Arizona. The paper's three groups of districts lie one in each corridor: senior rights on the Colorado River, CAP districts with junior rights in the center, and the Upper Gila canals in the east.

Several layers of law govern different steps between the source and the field. The first is priority on the river. Under prior appropriation, Arizona ranks surface-water rights by their age, "first in time, first in right," and in a shortage the newest rights are cut first (Arizona Department of Water Resources and Central Arizona Project 2023). A senior user can place a "call on the river," and junior users upstream must then cut what they divert until the senior user has its water (The Nature Conservancy Arizona and Friends of the Verde River 2020; Feldman 2004). On the Colorado River, CAP holds a junior right, and the Yuma districts and Wellton-Mohawk hold senior ones. Inside CAP there is a second ranking. CAP sets aside a low-priority block of its water, the Agricultural Settlement Pool, for central Arizona's irrigation districts, and a 2004 settlement made the pool junior. The districts also take in-lieu water, CAP water delivered in place of pumping.

The years 2000–2021 were the driest 22-year period in southwestern North America since at least 800 CE (Williams, Cook, and Smerdon 2022). In 2008–2014, CAP agricultural deliveries stayed within 1 percent of schedule and no shortage was declared. The 2015 reduction was voluntary and compensated (Appendix Table S9). In August 2021 Reclamation announced the first shortage ever declared on the lower Colorado River, known as Tier 1, for 2022 (Reclamation 2021). The cuts of 2022–2023 were made at the source and followed the rules, so the users with the weakest claims lost water first. In 2022 the CAP districts lost about two-thirds of their CAP water even after replacement water (ADWR and CAP 2021), and realized pool deliveries fell 88 percent. In 2023 the pool received no water at all (CAP 2023). I find no record of a mandatory cut to the senior Yuma users in 2021–2023.

Trade could undo an unequal division by moving water to the fields that value it most. In Arizona, water markets remain thin. Volumes are low, and a transfer across districts is arranged by the districts themselves. For most of the period a right that went unused could be lost, under "use it or lose it" provisions (Brocious 2021). The rule gave its holder a reason to take the whole entitlement even when the water was worth little. A 2021 reform relaxed that rule, but it covers only the last three years of the sample.

Figure 1: Arizona's Fields and the Three Groups of Districts



Notes: Grey dots: the 54,946 fields of the panel (Section 4.1). In colour: the districts of the three groups of Section 2.4, the CAP districts with junior rights (red), the Upper Gila canals (orange), and the senior-rights districts on the Colorado River (blue). New Magma and San Carlos (ochre) are in none of the three groups and enter in Section 8. Thin grey outlines: other irrigation districts. Dashed line: the Central Arizona Project aqueduct. The inset enlarges the area around Yuma.

Priority usually stops at the gate of the district. The district holds the right, and its farms share it. In my audit of 30 districts, the districts with 77.8 percent of the audited fields hold one priority that covers the surface water of every member farm. In nine districts, with 15.8 percent of the fields, farms differ in priority, at least on paper. The remaining 6.4 percent are in three groundwater-only systems and one single-farm entity (Appendix S8). Priority therefore ranks districts on the river. It does not rank the farms on one canal, and it says nothing about canal capacity or turnout scheduling.

2.2 How Water Reaches a Field

Each district divides its water among its own fields. CAP water enters a district at a few turnouts, the gates through which it leaves the CAP canal. From there it flows through main canals to the laterals that serve the farms. Maricopa–Stanfield, the district with the fullest records, shows the

scale. Its system has over 362 km of lined canals and pipelines, 180 farm turnouts, and nearly 400 wells (Bautista et al. 2000, 143). A farm turnout is the gate where a farm takes water from a lateral. It serves about 600 acres and is normally not shared between farms (144). Below it, the farm carries the water to its fields in its own ditches.

Delivery is on order. During the season a farm orders water when its crops need it. Bautista et al. (2000) call the system arranged delivery. Under the rules they describe for 1991, the farmer places an order one day ahead and names a flow rate and a duration. District staff then set the gates along the canal and open the farm turnout, and the farmer or an irrigator must be present to take the water (145, 149). In 2022 ditch riders still ran manual gates (Maricopa–Stanfield Irrigation and Drainage District 2022c). Water takes time to travel down a lateral. Staff filled orders within an eight-hour working day, so a farm at the end of a long lateral had a shorter window than a farm near its head (Bautista et al. 2000, 145). The district sets no schedule of turns, so in hot weeks the orders come together.

A farm cannot take water without limit. Districts give each farm an allotment for the season and charge its deliveries against it, so a farm that takes more in one month has less later. Maricopa–Stanfield's long-term allotment is about 4 acre-feet for every acre a grower has a water right on (Evancho 2022). The district meters each farm turnout and charges by the acre-foot (Bautista et al. 2000). Central Arizona cuts each farmer in proportion under what it calls "the mandated reduced allotment" (CAIDD 2022). Districts differ in how well they measure. Metered Reclamation turnouts in Yuma and Wellton-Mohawk report per-device accuracy near ±3 percent (Stringam, Sauer, and Pugh 2003). Smaller systems allocate per acre with no volumetric measurement, and Arizona imposes no statewide metering requirement. The allotment counts water at the farm turnout, and the crop consumes only part of it. In Maricopa–Stanfield a field needs about 1.4 acre-feet at its turnout for each acre-foot its crop consumes (Section 8.1). By water use I mean the water the crop consumes.

Wells are the second source of water, and who controls a well decides which fields it can reach. District wells pump into the canals, so their water serves the fields below them. Private wells serve their owners' fields. In Maricopa–Stanfield and Central Arizona, farmers mostly do not run their own wells. Maricopa–Stanfield took over the operation of the wells that serve its land in 1989, on 40-year leases, and it has "operational control of over 350 wells" (Betcher 2013; Maricopa–Stanfield Irrigation and Drainage District 2020, 2024). By 1990, "all groundwater wells within the district boundaries were leased to CAIDD for a period of 40 years" (Strand and Clemmens 2010, 28). In 2017 the state counted 132,238 acre-feet of groundwater used on Maricopa–Stanfield's farms, and the district's own wells delivered 132,322, so almost none was pumped outside them (ADWR 2020, Table 3-4; Maricopa–Stanfield Irrigation and Drainage District 2024, Table 2). In Maricopa–Stanfield in 2016–2021, CAP and the district's wells each supplied about 130,000 acre-feet a year, and Central Arizona's wells supply about half its water (Irrigation Leader, n.d.; CAIDD 2022).

In Harquahala and New Magma, wells belong to the farms that pump them: most Harquahala fields have one, few New Magma fields do, and New Magma runs no district wells. In the Upper Gila, wells supply more than half of the farm water (Gila Water Commissioner, n.d.). A farm's right to pump is a grandfathered right, set under Arizona's 1980 Groundwater Management Act (Bautista et al. 2000, 143). Access is uneven even inside one district, where the water table "could be 500 feet below the surface at one farm and 60 feet down at another" (InMaricopa 2021). The president of Maricopa–Stanfield said of CAP water, "The system was an equalizer to all farming across the district regardless of a cropland's groundwater capabilities. Now we have to sort out

this underground maze of unequal groundwater capacity" (Murphree 2021, 5).

2.3 What the Farmer Decides, and When

A farmer makes two decisions about water, one before the season and one within it. Before the season, the district tells each farm its limit, and the farmer then decides what to plant and what to leave fallow. Reclamation declared the shortage for 2022 in August 2021. Maricopa–Stanfield mailed its letters on the 2022 supply that October and its notice of turnout volumes in November (Maricopa–Stanfield Irrigation and Drainage District 2021b, 2021a). Growers sent the district their cropping plans for 2022 by December 31 (Table 1). They therefore knew of the cut before they planted any crop of 2022. Planting was set before the water fell short. Of the CAP fields fallow in 2022 and farmed in 2021, only 11.7 percent were green at some time from March through June (Appendix S12).

Table 1: Growers Knew the 2022 Cut Before They Planted: The Schedule in Maricopa–Stanfield

Date	Who	Step
March 29, 2021	District	Notice that the 2022 allocation "may be less than the 2020 allocation of 4.0 AF/ac"
August 2021	Reclamation	Declares the shortage for 2022
October 14, 2021	District	Letter to each grower with an estimated allotment per acre, based on the grower's 2021 turnouts and acreage
November 16, 2021	District	Notice of a volume for each turnout, by its service acreage, at $52 an acre-foot. "Growers are advised not to count on any additional supplies in excess of the per turnout allocation"
December 31, 2021	Grower	Submits the cropping plan for 2022
End of February 2022	Grower	Last day to combine the volumes of the grower's own turnouts
Through the season	Grower	Orders water, delivery by delivery
October 26, 2022	District	Letter for 2023: CAP "completely curtailed"; allocations as flow rates by turnout; the remaining CAP water for "zero well areas"

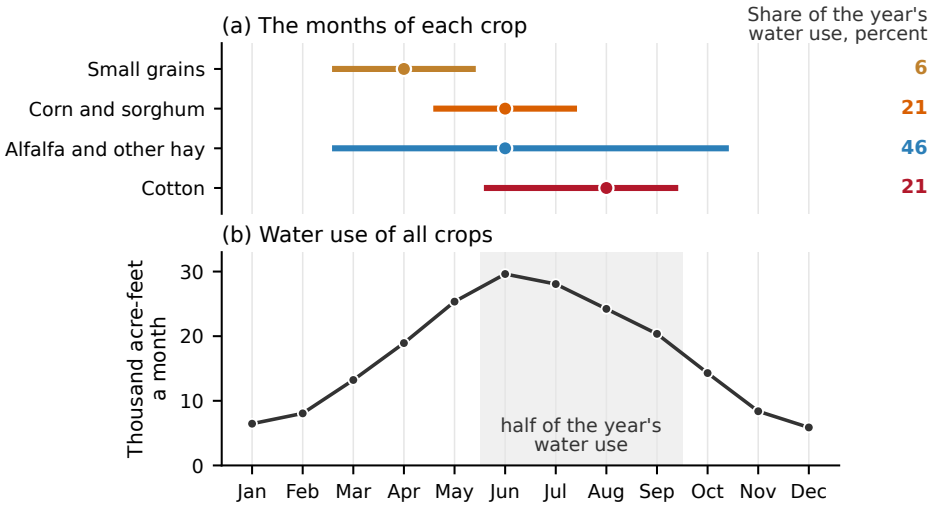
Notes: The district's notices and letters to growers (Maricopa–Stanfield Irrigation and Drainage District 2021b, 2021a, 2022a) and Reclamation's declaration (Reclamation 2021). AF/ac: acre-feet per acre.

The limit is an allotment for each acre with a water right, but the grower chooses where to use it. In July 2022 Pinal County's extension office reported that "the most common production change is to fallow more acres and focus all the irrigation water on the best producing acres" (Evancho 2022, 12). A grower who does so keeps close to the usual water on each planted acre. In the cut, water use per farmed acre stayed at 3.2 to 3.4 acre-feet (Appendix S13). Most of the land that left had grown cotton, corn, or sorghum the year before (Appendix S14). Fallowing is a choice the grower makes before any water is delivered, on the water the grower expects.

How much water a field needs in a month depends on its crop (Figure 2). The district's principal crops are cotton, grains, alfalfa, and feed for dairies (Maricopa–Stanfield Irrigation and Drainage District 2022c, 3). Small grains grow from November to May. Farmers plant corn in spring and cut much of it by the middle of July. They plant cotton in spring, and it stands into October. Alfalfa stays in the ground for years. Water use therefore peaks in June, and June through September hold half of the year's total.

Within the season the farmer decides when to order water and how much. Maricopa–Stanfield and Central Arizona describe in the same words when a shortage shows. "Shortage impacts usually occur during periods of above normal temperatures in the growing season when there is

Figure 2: Each Crop Has Its Months, and Summer Holds Half of the Year's Water Use: Maricopa–Stanfield



Notes: A typical year, the mean of 2017–2019. Panel (a): the line covers the months in which the crop's water use is at least half that of its peak month, and the dot is the peak month. Share: the crop's part of the year's water use; other crops hold the remaining 6 percent. Panel (b): the shaded months, June through September, hold 50 percent of the year's water use. Both panels: evapotranspiration (OpenET ensemble) of the 2,529 fields inside the district's boundary, by each field's crop of the year in the Cropland Data Layer. Fallow fields and land that is not cropland are left out. Small grains: barley, wheat, rye, and oats.

high demand, or at the end of the year when the mandated reduced allotment has been used" (Maricopa–Stanfield Irrigation and Drainage District 2022c, 7; CAIDD 2022).

Maricopa–Stanfield met such a peak in the hot summer of 1990. On many days the longer laterals could not carry the orders of the day. The district then lowered the flow at every farm turnout, from a design rate of about 15 cubic feet per second to about 9 (Bautista et al. 2000, 147–148). Of the farmers interviewed the next year, 85 percent called the service equitable. The daily service window still affected some farms more than others. It affected most the farms at the end of long laterals, where a change in flow arrives late, and the farms without wells. Farms with wells shut off the canal water within working hours and finished the irrigation with well water (148).

Once a crop is planted, the farmer rarely gives it up. Of the cotton fields green by the middle of July 2022, 2.2 percent were not green again that season (Appendix S12). A shortfall within the season therefore shows as less water on a standing crop. The two decisions give the paper its outcomes. The first shows in whether a field is left fallow. The second shows in the water a planted field uses in the months of its crop, and in its yield.

2.4 How Districts Divide Water

When a canal cannot fill every order at once, the district has to divide the water. A district that delivers on order can lower the flow at every farm turnout by the same share, as Maricopa–Stanfield did in 1990. It can also fill orders as the water passes down the canal, and then the fields the water reaches first are served first. I say that such a district delivers *in order*. A district that rotates gives each farm a turn on a schedule, and the turn comes whatever its place on the canal.

In Maricopa–Stanfield the rule for the cut was proportional on paper. The district says it handles shortfalls "by proportionally reducing the water delivery allocation for each farmer"

(Maricopa–Stanfield Irrigation and Drainage District 2022c, 7). What growers got depended on where their fields are. For 2022 the district's October letter gave each grower an estimated allotment "based on your 2021 turnouts and acreage" and "subject to change based on new well and pipeline infrastructure and well runtime" (Maricopa–Stanfield Irrigation and Drainage District 2021b). In November the district gave each turnout a volume based on its service acreage, and growers could combine the volumes of their own turnouts (Maricopa–Stanfield Irrigation and Drainage District 2021a). The usual 4 acre-feet per acre became 1.7 to 2.8 "depending on where the grower's fields are in the district" (Evancho 2022, 12). For 2023 it set allocations as flow rates by turnout, and it sent the little CAP that remained to "zero well areas" (Maricopa–Stanfield Irrigation and Drainage District 2022a). In the district's figures, CAP fell from about 131,700 acre-feet a year in 2016–2021 to 29,754 in 2022 and 4,000 in 2023. The district's wells rose from about 129,300 acre-feet a year to 169,764 and 183,246.

Districts divide water by different rules, which Table 2 sets side by side. The Upper Gila canals run on the Gila River's natural flow, which the Gila Water Commissioner divides by a 1935 court decree (Doyle 2022). Inside a canal, farms may take the water in rotation (Arizona Supreme Court 1955, 217–218). San Carlos allots its stored water by the decreed acre, set each January, and natural flow goes by each account's priority date.[1] Central Arizona runs its own wells and, by accounts of its operations, fills the remaining orders with CAP.[2] Hohokam's stated duty is to "equitably deliver" water,[3] and I find no document that gives it an order along its canals. Outside CAP, Appendix A11 documents lower-end losses and gate losses in the Gila Valley, capacity pressure in senior Yuma districts, and downstream storage operations in Roosevelt Irrigation District.

The rules and the records sort the districts into the three groups that Section 7.2.1 compares. The CAP districts with junior rights are Maricopa–Stanfield, Central Arizona, Harquahala, and Hohokam. The Upper Gila group holds the canals of the upper Gila Valley under the 1935 decree. The senior-rights districts, all on the Colorado River, are Wellton-Mohawk, Yuma County Water Users, Yuma Mesa, Yuma Irrigation, North Gila Valley, and Unit B. New Magma, whose rights my audit does not classify, and San Carlos, whose rights are mixed, are in none of the three and enter in Section 8.

[1] San Carlos Irrigation and Drainage District, Water Policy (undated), and the Globe Equity decree, Art. VII.

[2] The district's annual water user agreements of 2016 and 2022 reserve to it the choice of which wells to run, and its 2022 application for federal funds describes its supply (CAIDD 2022). The order, district wells first and CAP for the rest, comes from accounts of the district's operations; I have not found it in a district document.

[3] Hohokam Irrigation and Drainage District, "About Us" page, on its 1985 contract with Reclamation.

Table 2: How Arizona's Districts Divide Water

District	Water source	Priority	How water is divided	District wells into canals	Monthly record
CAP districts					
Maricopa–Stanfield	CAP and district wells	Junior; pool held by the district	Seasonal allotment per acre, ordered along canals; in the cut, turnout volumes and flow rates	Yes: 144 canal pumps, located; 106 rated	CAP by month; wells by year
Central Arizona	CAP and district wells, about half each	Junior; pool held by the district	District wells first and CAP for the rest; proportional cut for each farmer	Yes: 434 wells; records give capacity, not which ran	CAP by month
New Magma	CAP in-lieu water, 96 to 98 percent of farm deliveries	Pool and partner water held by the district; unclassified in my audit	By order along canals; farms barely replaced lost CAP with wells	None in the model	CAP by month
Harquahala	CAP and private wells	Junior; pool held by the district	By order along canals; 78 of 748 fields have no well	None in the model	CAP by month
Hohokam	CAP and private wells	Junior; pool held by the district	Duty to "equitably deliver"; no document gives an order along canals	None in the model	CAP by month; misses water
Gila River systems					
Upper Gila canals	Gila River natural flow and private wells	By decree; dates listed by parcel under each canal	Decree across canals; rotation inside them	None in the model	Each canal's diversion
San Carlos	Stored water and natural flow, some CAP	Mixed: decree classes inside the district	Stored water by decreed acre, set each January; natural flow by priority date	Project wells; not in the monthly record	The decree's split of the project's diversion
Senior rights on the Colorado River					
Wellton-Mohawk	Colorado River	Senior; one district-held contract	Metered turnouts; water 1.30 to 1.42 times demand	None in the model	Reclamation's decree accounting
Three Yuma districts	Colorado River	Senior; held at project or district level	Metered turnouts; water 1.4 to 2.5 times demand	None in the model	Reclamation's decree accounting

Notes: Priority: my audit of district, Reclamation, CAP, and decree records (Appendix S8). Pool: the Agricultural Settlement Pool. Three Yuma districts: Yuma County Water Users, Yuma Mesa, Yuma Irrigation. Water relative to demand: Appendix A15. Section 8.1 gives each district's water series and which wells the model uses.

3 A Model of Canal Delivery

Each month water enters a district's canals, and the crops on its planted fields need water. The model says how the district divides the month's water among its fields. It takes the planted fields and the water supplied as given. The model has three free parameters: how much a field with a well claims from the canal, and two weights that set how water splits along a canal and at its branches. I use it in two steps. Sections 6 and 7 test its predictions across the whole network, using only demand. Section 8 adds the water supplied, runs the model in the districts that record their water by month, and estimates the three parameters from fields' water use.

3.1 Supply and Claims

Let d_{it} be the *crop demand* of field i in month t, the irrigation water its crop needs after rain. A fallow field has none. Section 8.1 builds it from the field's acres, its crop calendar, and the weather. The district's *main supply* enters at the heads of its canals. I scale it by irrigation efficiency, the share of delivered water that crops consume, so that supply and crop demand are in the same units.

Water rights and contracts determine which districts lose water first when a river runs short (Section 2.1). The model starts at the heads of a district's canals and divides whatever water reaches the district. In the senior-rights districts the water recorded exceeds crop demand (Table 2). The districts with junior rights are cut first, and there a month's water can fall short of what the planted fields need.

A *local pump* serves its owner's fields, and a field *has a well* if a local pump serves it. A field without a well claims its whole crop demand from the canal. A field with a well claims only a part of it, the *take* τ, and its well serves the rest. The *claim* of field i in month t is

$$c_{it} \;=\; \begin{cases} d_{it} & \text{for a field without a well,} \\ \tau\, d_{it} & \text{for a field with a well.} \end{cases} \tag{1}$$

The take is the model's first free parameter. A claim is for one month of canal water. It is not the farm's allotment for the season.

3.2 The Division Rule

When the water that reaches a point on a canal covers every claim downstream of it, every claim is met. When a flow F falls short of two claims a and b, so that $F < a + b$, a rule divides it. The claim a receives

$$G_\theta(F;\, a,\, b) \;=\; \theta \min(a,\, F) \;+\; (1-\theta)\, F\, \frac{a}{a+b}, \qquad 0 \le \theta \le 1, \tag{2}$$

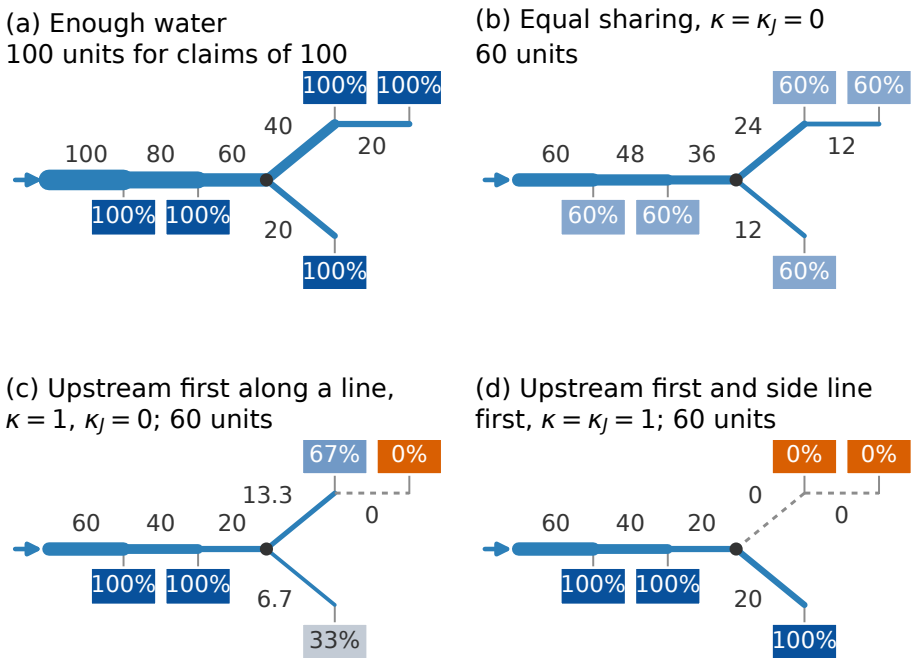
and the claim b receives the rest.

The model applies the rule in two places. At a point where fields take water, $\theta = \kappa$, a is the claim of the fields there, and b is the claim on the canal downstream of them. At $\kappa = 1$ they take all they need before water moves on. At $\kappa = 0$ every field on the line gets the same share of its claim. A rotation that gives each field its turn in proportion to its demand does the same over a month. At a *split*, where a side line leaves a canal, $\theta = \kappa_J$, a is the claim on the side line, and b is the claim on the line that continues. At $\kappa_J = 1$ the side line comes first, and at $\kappa_J = 0$ the two

share by claims. Elsewhere branches share by their claims. Each pair (κ, κ_J) is a *rule*. Figure 3 shows the corner rules on a small canal, and Appendix A1 writes out the recursion.

The weight κ does not say why upstream claims come first. A district may deliver water in order down the canal, or farms upstream may draw their seasonal allotments first in the peak months. Both give the same division. The model needs no over-diversion to produce a shortfall: in a month when the canal carries less than the crops need, upstream claims alone exhaust the water before it reaches the tail.

Figure 3: The Division Rule on a Small Canal



Notes: An illustration of the rule, not data; the shares come from the model's code. Five fields, each with a claim of 20 units, on a canal that divides once; the lower branch is the side line. Numbers on the canal: the water flowing in each reach, also shown by the width of the line; dotted: no flow. Squares: the fields, shaded by their delivered share (equation (3)); orange: no water. Panel (a): the water equals all claims, 100, and every field is served under any rule. In the other panels it is 60. Panel (b): every field gets the same share. Panel (c): the two fields above the junction take their claims first. The remaining 20 splits two to one between the branches, by the claims along each (40 and 20); the first field on the upper branch takes all that reaches it, and the field after it receives nothing. Panel (d): the side line comes first and takes all of the remaining 20.

3.3 Canal Pumps and the Shortfall

A pump is a canal pump or a local pump by how its water reaches fields. A *canal pump* is a district well that puts its water into a canal. Canal pumps serve the fields below them first, with no order among those fields. The canal's main supply then meets what is still claimed. A canal pump cannot send water upstream of where it enters. Its place on the canal therefore decides which claims it meets and which are left to the main supply.

A field's *delivered share* is the part of its claim that the canal meets:

$$r_{it} = \frac{w_{it}}{c_{it}}, \qquad 0 \le r_{it} \le 1, \tag{3}$$

where w_{it} is the water the model delivers to field i in month t, from canal pumps and from the

main supply, and c_{it} its claim. Fields at one point share one delivered share, which is 1 in a month when that point has no claim. The model gives each field a canal shortfall for each month, the share of its crop demand that the canal does not meet:

$$\ell_{it} \;=\; \begin{cases} 1 - r_{it} & \text{for a field without a well,} \\ 1 - \tau\, r_{it} & \text{for a field with a well,} \end{cases} \tag{4}$$

For a field with a well, a canal shortfall does not mean the crop lacks water, because the well can supply what the canal does not. Such a field has a shortfall of $1 - \tau$ even in a month when the canal meets its whole claim.

3.4 What the Model Predicts

The model's predictions follow, and Table 3 sets each beside its estimate.

Shortage and senior rights. When the water covers all claims, every rule meets every claim (Figure 3, panel a). When supply is cut, or in the months crops need the most water, the water a field gets depends on where it sits on the canal. Upstream demand should therefore lower a field's water use in drought in the districts with junior rights, where canal water falls short. It should not in the senior-rights districts, unless a canal is too small for its peak months.

Direction along the canal. Number the fields on one line from its head, and let the line carry F. When the district delivers in order ($\kappa = 1$), field i receives

$$w_i \;=\; \min\Big\{c_i,\; \Big[F - \sum_{j<i} c_j\Big]_+\Big\}, \tag{5}$$

so only the claims upstream of a field lower its water. When the district shares by claims ($\kappa = 0$), every field gets the delivered share $r_i = \min\{1,\, F/\sum_j c_j\}$, so upstream and downstream claims lower its water alike, through their sum. Sections 6 and 7 test the difference. They split the demand around a field into its position, which is upstream minus downstream demand, and the canal total, which is their sum (Section 6.3). Where the district delivers in order, a higher position should lower a field's water use. Where it shares or rotates, a larger canal total should lower it, whichever side the demand is on.

Sharing at splits. When the flow at a split falls short of the claims downstream of it and the branches share by claims, more claims on a field's branch send more water down that branch. A field that is short takes some of it as it passes. Demand downstream of a field can then raise its water.

Canal pumps. A district well that pumps into the canal between upstream land and a field, and runs below its capacity, replaces what that land diverts. A field with such a pump above it should lose less to upstream demand. When the main supply is cut and the canal pumps carry more of the water, distance from the head of the canal says less about who goes short.

Fields with a well. A local pump can replace water the canal does not deliver, and the model does not say how much a farmer pumps. If the farmer replaces the water, a canal shortfall should lower water use less on a field that has a well than on a field without one.

Monthly shortfalls. Maricopa–Stanfield and Central Arizona charge each farm's deliveries against a seasonal allotment (Section 2.2). A farm that takes more in one month takes less later. A field at the head and a field at the tail can then receive the same water over the season while

the field at the tail goes short in the peak months. The model divides water by the month, so it predicts a shortfall in the months a canal falls short, even where the season's totals are equal. A field without a well should use less water in those months.

Planting and fallowing. Farmers decide what to plant before the season (Section 2.3). Where farmers expect larger shortfalls, planting earns less, and fields should be left fallow more often. Across the network, the fields with larger expected shortfalls are those far down canals that deliver in order (Section 7.1). In the 2022–2023 cut, they are the fields the model says run short when each field's demand is held at its usual level (Section 8.2).

The model divides water by the month, not by the day. No loss in the model grows with distance along a canal. The model predicts who goes short, and the dollar losses of Section 8.8 and Appendix A9 also use crop budgets.

The irrigation network branches. Fields on sibling branches share the water of the trunk without lying upstream of each other. The design of Section 6 leaves such pairs out (Section 6.2), so upstream demand misses some competition, whose sign I leave open. The delivery model of Section 8 keeps them.

Table 3: Model Predictions and What the Data Show

Prediction	**Predicted sign**	**Estimate**	**Where**
Shortage in drought	Upstream demand lowers water use more in drought	Upstream demand × drought at a fixed canal total, water use relative to the crop's need: -0.022 ($p < 0.001$)	Sec. 7.1, App. Table A7
Senior rights	Position matters less where rights are senior	Position × drought, water use: CAP districts with junior rights -0.011 ($p < 0.001$), senior $+0.003$ ($p = 0.31$)	Sec. 7.2.1, Fig. 7
Direction	Downstream demand does not lower a field's water use	Downstream demand × drought: $+0.016$ ($p < 0.001$). Position × drought: -0.011 ($p < 0.001$)	Sec. 7.1, Table 5; App. Table A7
Sharing at splits	Downstream demand can raise a field's water	Downstream demand × drought, CAP districts with junior rights: $+0.016$ ($p < 0.001$). Equal sharing at splits and along lines rejected (score -19.3, $p = 0.005$)	Sec. 7.2.1, App. Table A7; Sec. 8.4, App. A12
Canal pumps	A field with a canal pump above it loses less	Maricopa–Stanfield, fields without a well, from 2016–2021 to the 2022–2023 cut: where the canal pumps could supply half to three quarters of the field's need, 11.6 points (3.9) more land farmed and 20 percent (18.5 log points, standard error 5.9) more water use than where they could supply under a quarter. CAP districts, 2021 against 2019–2020: below a canal pump, position does not lower water use (-0.001 and $+0.000$); with no backup groundwater it lowers it by 0.019	Sec. 8.5; App. Table A10
Fields with a well	A field with its own well loses less	Harquahala, where farmers pump their own wells: as the canal shortfall goes from none to all of the claim, water use falls 31.4 log points (14.5) on fields without a well and does not fall on fields with one (+0.4 (7.0)). New Magma: fields without a well were left fallow 23 points more often than fields with one in 2022 and 27 in 2023. CAP districts, position × drought: water use falls 0.023 in fields with no backup groundwater and 0.006 to 0.014 in the others	Sec. 8.6; App. A12; App. Table A10
Monthly shortfalls	A field loses water in the months its canal falls short; no fixed gradient over a season of allotments	Maricopa–Stanfield, fields without a well, months with a shortfall of 0.35 or more against months with a shortfall of 0.01 to 0.05: water use 27 to 31 percent lower (-31.6 (10.1) and -37.5 (10.0) log points). CAP districts with junior rights, fields that stayed planted, 2021 against 2019–2020: water use fell 5 to 11 mm in every third of usual position	Sec. 8.4; Sec. 7.1
Planting and fallowing	Fields far down the canal lose more in drought	Fallowing on usual position × drought: $+0.83$ percentage points ($p = 0.009$). Yield proxy on usual position × drought: -0.023 ($p = 0.024$)	Sec. 7.1, Table 5

Notes: Estimates of Sections 7.1 and 7.2: 2SLS, each irrigation district's distance cut, district drought, coefficients on drought terms; the CAP districts with junior rights unless stated. Water use relative to the crop's need, in the months of its crop, and the yield proxy in log points per log point of demand; fallowing in percentage points per log point of usual position. The CAP districts with junior rights and the senior-rights districts are estimated separately; I do not test the differences between groups. The estimates of Section 8 average over all rules at each district's best take, 0.66 in Maricopa–Stanfield, with standard errors in parentheses.

4 Data

4.1 Field Panel

I assemble a field-level panel from nine data blocks, and the delivery model of Section 8 adds two more. The overview below lists each block, its main source, and its role. The supplement documents each source, variable and construction step (Appendices S1–S10).

Data Inputs and Role in the Empirical Design

Data block	Main source	Role in the paper
Field panel	USDA Crop Sequence Boundaries	Defines 54,946 fields, 2016–2023.
Outcomes	OpenET and Sentinel-2	Measures monthly water use, fallowing, and the yield proxy (GCVI).
Crops	USDA Cropland Data Layer	Sets the crop-by-year effects and predicted demand.
Drought	SPEIbase	Measures drought (SPEI-24 and SPEI-3).
Canal infrastructure	NHDPlus and DEM	Builds the irrigation network (Section 5).
Water access	ADWR rights, groundwater rights, well registry, USGS withdrawals	Measures priority, groundwater access, wells, and water-source dependence.
Institutions	Irrigation-district records	Measures pricing, seniority, shortage protocols, rotation schedules, and district governance.
Soils	SSURGO	Describes field quality (salinity, clay, and other soil properties).
Geography	OpenStreetMap; protected-area, tribal, state-trust, and federal-land layers; community-water-system	Describes market access and land status.
Canal water	CAP delivery reports; Reclamation decree accounting; Gila Water Commissioner and San Carlos project records	Measures the water that enters each district's canals each month (Section 8.1).
Owners and wells	2025 CoreLogic tax roll; ADWR well registry; Maricopa–Stanfield well map; Pinal County ditch layer	Drops same-owner pairs; sets which fields have a well and where canal pumps stand (Section 8.1).

Note: A few further inputs feed controls within these blocks. District-institution variables draw on ADWR records and Central Arizona Project allocation documents alongside district records. Census and watershed (HUC12) boundaries enter only as base layers for mapping and spatial joins. The supplement gives the complete source list and construction steps.

The unit of observation is a field in a month for water use, and in a crop year for the yield proxy and fallowing. The fields come from the USDA Crop Sequence Boundaries, which define stable field boundaries from the satellite record. The same 54,946 Arizona fields are observed in every year of 2016–2023. The irrigation network links 28,588 of them to canals (Section 5). The estimation samples hold the fields with upstream or downstream fields beyond their irrigation district's distance cut (Section 6.2; Table 4).

The USDA Cropland Data Layer records each field's crop in each year. The crop sets the crop-by-year effects and each field's predicted demand, its acres times the typical water use of its crop (Section 6.3). The layer changed its method in 2019, and its labels shift between 2018 and 2019 (Appendix S1). The samples of Sections 6 and 7 start in 2019, after the change, and their usual

levels come from 2017 and 2018 (Appendix S1). About a fifth of the field-years in the fallowing sample are fallow (Table 4).

Section 5 describes the canal maps and how I join them into the irrigation network. Arizona's canal network saw no major construction or realignment during the sample period, so the network is fixed. What moves is the water its fields use, as fields change crops or go fallow and as the season and drought change their demand.

4.2 Outcomes and Drought

All three outcomes come from satellite data. Water use is the field's monthly evapotranspiration from the OpenET ensemble, in millimetres, from January 2016. The models use its log. It measures the water the crop uses, not the water delivered. The yield proxy is GCVI, a chlorophyll index from Sentinel-2 imagery. I measure it in the weeks that form each crop's yield. Alfalfa is cut seven to ten times a year, so I take its mean over the crop year. For cotton I take the mean from mid-July to late September, and for wheat and barley the mean from February to May. Other crops take their highest value in their own months. I call the measure crop-season GCVI and use its log (Appendix A6). Satellite vegetation indices track harvested yield in ground data (Lobell et al. 2020). The yield-proxy coefficients are log changes in GCVI, not percent changes in yield. A field is fallow in a crop year when the Cropland Data Layer records no crop or its monthly water use shows none. A crop year starts in November. Appendix S6 gives the formulas and the windows.

To measure drought, I use the 24-month Standardized Precipitation Evapotranspiration Index (SPEI-24), which counts both rainfall and evaporative demand. The 24-month index measures how dry the last two years were. A 3-month index would measure only the last three months. I average each field's SPEI-24 over May–August, the months of peak irrigation demand. Section 6.2 turns that average into one drought indicator for each irrigation district and year (Appendix S7).

Across the sample, drought covers 20.4 percent of field-months in the CAP districts with junior rights and 16.7 percent in senior-rights districts (Table 4). SPEI marks dry years, not cuts. In the CAP districts with junior rights, it marks mainly 2021, the dry year before the cut. The cut years, 2022 and 2023, are the subject of Section 8 (Appendix A20). Appendix A8 separates 2021 from the cut years in the models of Section 7.

4.3 Water Access, Rights, and Institutions

The three rights groups compared in Section 7.2.1 are the CAP districts with junior rights, the Upper Gila canals, and the senior-rights districts. They come from an audit of district, Reclamation, CAP, and court-decree records for the 30 districts that hold 95.6 percent of member fields (Section 2.4; Appendix S8). I classify each district's surface-water priority within its own allocation system as senior, junior, or mixed, and I code its physical supply as surface water, groundwater, or mixed. The CAP group holds only the fields inside four of the junior districts, and the senior-rights group only the fields inside the senior districts. Fields in mixed or unclassified districts, or outside district boundaries, most of them on reservations, enter the all-fields sample but neither group.

To measure a farm's access to other water during a surface shortage, I link each field to Arizona's Grandfathered Groundwater Rights database and count the registered wells (from the ADWR Wells55 registry) that serve the field. I also match fields to ADWR's point records of surface-water rights. Roughly 72 percent of fields match no recorded right, and priority usually stops at the gate

of the district (Section 2.1), so this variable is only a coarse control. None of these variables is a measured annual delivery entitlement for a given field. The water-right and well variables enter the yield and fallowing models interacted with drought (Section 6.4). Appendices S8 and S9 document the audit and the other controls.

4.4 Summary Statistics

Table 4 describes the three samples of Sections 7.1 and 7.2, for all fields and by how districts deliver water: the CAP districts with junior rights, the Upper Gila canals, and the senior-rights districts. The water sample has 570,116 field-months of 24,104 fields in 43 irrigation districts, in the months of each field's crop in crop years 2019–2023. The yield sample has 91,481 planted field-years of 21,571 fields in the same years, inside the irrigation-district polygons. The fallowing sample has 137,830 field-years of 27,566 fields. Fields in the CAP districts with junior rights are larger than fields in senior-rights districts, 31.5 against 14.0 acres in the yield sample. They are left fallow far more often, in 30.3 against 6.6 percent of field-years. In 11.7 percent of field-months a field has no upstream fields beyond the distance cut. It then enters with zero upstream demand and its own indicator (Section 6.2).

5 The Irrigation Network

The design compares fields by the order in which canal water reaches them. No public record gives that order. Irrigation districts do not publish maps that tie fields to turnouts, and the national canal maps say neither which way the water flows nor where it leaves a canal. I build the network that gives the order: Arizona's irrigation canals from each water source to every field they serve, the direction of flow along each canal, and the point where each field takes its water. The network covers 46 canal systems, with 28,588 fields on 627,800 acres and 6,988 km of canals (Figure 4a). A system is whoever delivers the water: an irrigation district, a reservation, or a private canal company. This section describes how the network is built, how it orders fields, and how I check it. Appendix S2 gives the details.

5.1 Canals and the Direction of Flow

The canal lines come from several maps. NHDPlus High Resolution, the national map of streams and canals, gives 63 percent of the canal length. The Salt River Project's map of its laterals, county and district GIS layers, district maps and reports, other national layers, and OpenStreetMap give 18 percent. I traced the remaining 20 percent from aerial imagery, where a canal or ditch is visible on the ground but drawn on no map (Appendix Table S1). Canals pass under roads and through siphons and pipes, so the maps break where the water does not. I join a break where the imagery shows the canal going on, however long the break. I do not join a canal to a wash or a drain, because neither delivers water.

Water enters the network at 109 heads. They are river diversions on the Colorado, Gila, Salt, Verde, and San Pedro rivers, intakes on the Gila Gravity Main Canal, the Yuma Main Canal, and the Salt River Project's canals, and 31 turnouts on the Central Arizona Project (CAP) aqueduct. From each head the water flows down a tree of canals. The direction of each line comes first from the maps. NHDPlus, the other national layers, and OpenStreetMap record it for 36 percent of the canal length. Another 28 percent is drawn in the direction of flow: the Salt River Project's

laterals, the district maps, and the lines traced in the review, whose direction the reviewer judged from imagery, structures, and relief. For the rest, I compare the mapped direction with the slope of the land along the line. The land confirms it for 27 percent of the length and reverses it for 8 percent (Appendix Table S2). Water also runs uphill where a pumping plant lifts it, as on the CAP aqueduct and the Wellton–Mohawk Canal, and these canals keep their mapped direction.

5.2 Fields on the Network

Each field takes its water at one point of the tree, its *intake*. Water reaches a field through a turnout on a canal, often by a farm ditch that runs along several fields. I place each field by the best evidence available (Appendix Table S3). Half the fields touch a turnout or lie on a mapped ditch with a known intake. Another 40 percent connect through a neighbouring field's turnout or a mapped ditch block, and the remaining 8 percent show no ditch and attach to the nearest point on their canal. A field with one intake has one route from its head.

Of the 31,131 fields inside the 46 systems, 2,543 are left off the network. Of these, 1,159 are built over or not farmland, or were taken off in the review, 664 are watered by wells, and 715 have no canal or ditch that reaches them. Of the other 5, 3 were left out when the network was built, and 2 take water from another district's canal. The network covers almost all of the farmland that Arizona's canals serve, about 90 percent of it by area inside irrigation districts. A few systems are not in it, mainly the canals around Gila Bend and four irrigation districts (Maricopa Water District, Roosevelt Water Conservation District, Queen Creek, and Mohave Valley). Appendix S2 lists them. The other fields of the panel lie outside canal systems, and where field surveys cover them, nearly all are watered by wells (Section 5.4).

5.3 Upstream and Downstream on the Network

A district does not deliver water field by field across its whole system. It divides its supply among the laterals that leave its main canals, and it schedules deliveries along each. I group the laterals into *branches*. Along each main canal, I take the laterals in the order in which they leave it, with the fields that take straight from the main at the points where they take. A lateral that serves at least 2,000 acres is a branch of its own, and smaller neighbouring laterals join until together they serve 2,000 acres. A system smaller than that is one branch. The 46 systems contain 154 branches, and 24 systems are a single branch (Appendix Table S4). In New Magma the CAP aqueduct is the district's main canal, so the district's turnouts along it take the place of laterals. Between branches, the district's schedule divides the water, so fields in different branches do not compete for it directly. I order fields only within a branch.

Inside a branch, water fills the canals from the head and reaches first the fields nearer the source along the canals. A field's *upstream fields* are the fields of its branch whose intake lies nearer the head, measured along the canals. Its *downstream fields* are those whose intake lies farther. Fields that take at one point keep the order of their turnouts. The rule does not let a lateral take all its water before the canal passes it on. A field near the head of a long lateral is upstream of fields farther down the main canal, but a field at the far end of that lateral is not upstream of every field past the lateral's junction. Figure 4b shows one field in Maricopa–Stanfield. Its upstream fields lie along its route and on the laterals that leave the main canal nearer the source. Its downstream fields lie farther along the canal.

The rule gives 4,618,052 ordered pairs of fields. In 146,956 of them, 3.2 percent, the two fields have the same owner in 2025 parcel records, and Section 6.2 drops these pairs. Owners are matched for 80 percent of the fields on the network. Most of the rest are on reservations, where land has no private owner. A second rule lets each lateral take its water in turn before the canal passes it on. The two rules agree on 3.96 million pairs and reverse 467,386. Appendix S3 defines both rules and reports the results under the second.

(a) Maricopa–Stanfield: its 19 branches, one color each

(b) One field in Maricopa–Stanfield

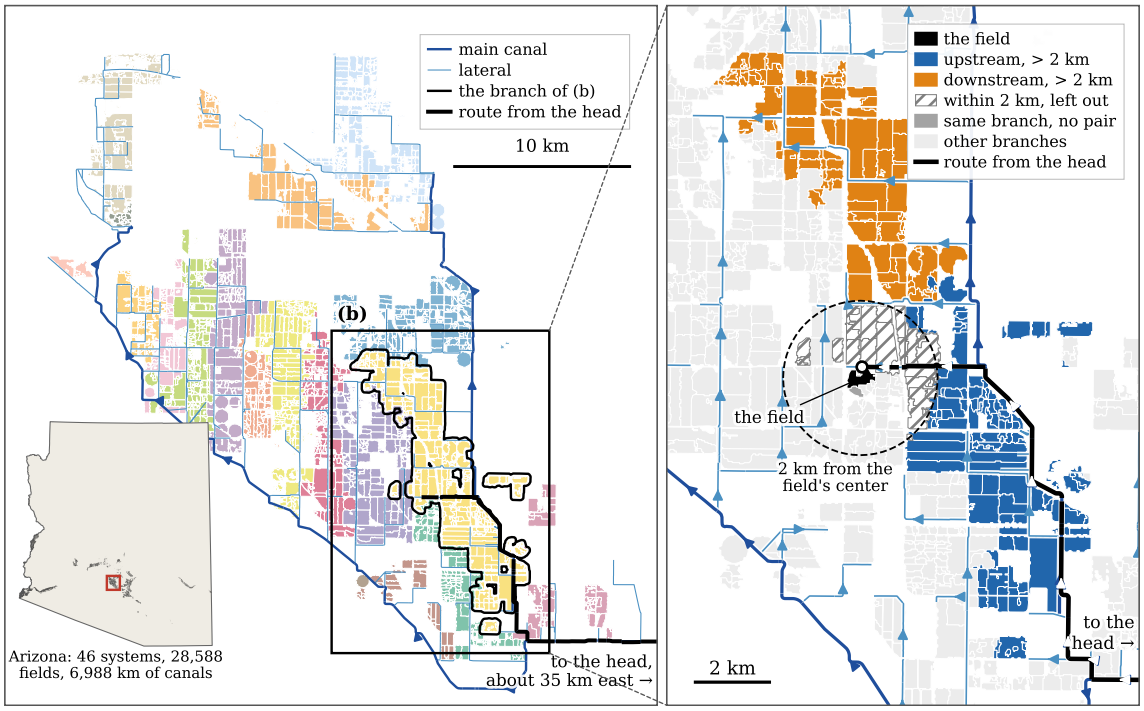


Figure 4: The Irrigation Network, and One Field's Upstream and Downstream Fields

Notes: Panel (a): Maricopa–Stanfield, one of the 46 systems of the network, with its 2,384 fields in 19 branches. Each branch has its own color; the colors only tell the branches apart, unlike the blue and orange of panel (b). Dark blue: main canals; light blue: laterals. The black outline is the branch of panel (b), the box is the extent of panel (b), and the thick line is the field's route from the head, which lies about 35 km east of the district. The inset shows the network in Arizona: 46 systems, 28,588 fields (grey), and 6,988 km of canals; the red square is the district. Panel (b): one field in Maricopa–Stanfield (black), in a branch of 280 fields. The thick line is the field's route from the head, which lies about 40 km east of the panel, to its intake (white dot). Arrows give the direction of flow. Blue: the field's 128 upstream fields beyond 2 km; 115 of them lie off its route, on other canal lines but nearer the head along the canals. Orange: its 114 downstream fields beyond 2 km. Hatched: the 36 upstream and downstream fields within 2 km, which the measures of Section 6.2 leave out. The dashed circle is 2 km from the field's center; a field counts as within 2 km when its center lies inside, so a large field can reach into the circle. Grey: fields of the same branch that form no pair with the field, because they have the same owner or take at the same point. Light grey: fields of other branches.

5.4 Checks

No district publishes its deliveries by turnout, so the network cannot be checked against delivery records. I check it in four other ways.

Imagery. I reviewed every system against aerial imagery, district by district, on maps that show each field, its intake, its branch, and the route of its water. Where a canal or ditch was missing or

misplaced, I drew it. Agents working from imagery and lidar checked doubtful places under rules I set, and I approved their changes. In a later round I checked every district again and drew 145 pieces of canal and ditch, which moved 454 fields onto the ditches that serve them and brought 126 more fields onto the network.

Reclamation's records. The Bureau of Reclamation maps the canals and pipelines of the projects it built, among them the main canals and laterals of twelve Arizona irrigation districts and the Gila Gravity Main Canal (Reclamation 2026a). The network was drawn without this map, except for 41 km of lines added from it afterwards. Of the 1,497 km of open canal it records there, 91 percent had a network line within 30 m before these were added, and 93 percent has one now. Most of the rest is laterals in Maricopa-Stanfield and the Yuma Valley, and Tonopah's canal, which serves none of the fields in the sample. Buried pipelines cannot be seen from the air and are left out of the comparison.

The land. Water runs downhill in an open canal unless a pumping plant lifts it. If the order is right, fields later in the order should lie lower. In 135 of the 141 branches with at least 20 fields, a field's number of upstream fields and its land height have a negative rank correlation (Appendix Figure A4). Each of the other six has a physical explanation. Four take their water through pumping plants that the imagery and lidar show, one hangs on a canal that runs along a hillside while the valley floor rises, and one does not climb at all (Appendix Table S5). The check is not fully independent of the network, because the land slope set the direction of 8 percent of the canal length. It does compare the two rules on the same lines, though: under the rule that lets laterals take in turn, only 126 of the 141 branches run downhill.

Field surveys. USGS field surveys record the water source of each field in fourteen groundwater basins. Of the 10,062 surveyed fields that the network leaves off, 89 percent use groundwater only. Almost all of the rest, 1,052 fields, lie in Gila Bend, where canals from the Gila River serve fields that the network does not include. Outside Gila Bend, 99.8 percent of the 8,168 surveyed fields left off use groundwater only. On the network, all 729 surveyed fields in Harquahala mix canal water with groundwater, and the surveys record the 30 in the St. David and Pomerene systems on the San Pedro River as using groundwater only.

The delivery model of Section 8.1 cuts each district's canals out of this network, below the district's documented intakes, and moves the district's recorded water down them month by month. It treats the fields that take at one point of the tree as one claimant. Its predictions of which fields run short are a further check on the network, and Section 8 reports them.

6 Identification Strategy

A field's place on the canal is itself an equilibrium outcome, the result of long-run choices and not an assigned treatment. Land development, infrastructure, rights, groundwater investment, crops, and exit can all adjust around a persistent order on the canal. Farms at the end often get less water every year and adjust to it. They may grow different crops or rely more on wells, and some stop farming. A fixed gradient in crop outcomes therefore combines delivery order with sorting and long-run adaptation. Which fields run short is not fixed from year to year. It changes as the fields upstream and downstream of a field change crops or are left fallow. Direct flow measurements

(Akram and Mendelsohn 2017; Jacoby and Mansuri 2020) do not follow one farm as the water used by a branching set of farms above it changes over time. I follow the same field in the same calendar month over the years, as the water used by the fields above and below it changes. The test is whether more demand above the field lowers its water use more in drought than in other years. Three parts of the design keep shared shocks out of this comparison. Predicted demand, fixed when the neighbours plant before the season, stands in for their water use. Only fields beyond a distance cut count. And fields below share the local shocks but cannot take water first, so they test the direction.

Unlike the neighbours' actual water use, predicted demand does not change with the month's deliveries. Farmers decide what to plant after the district tells them their water for the season (Section 2.3), and the district effects take out any limit shared across a district. The first CAP cut was announced in August 2021, for 2022, so it could not change what was planted in 2021. To keep the comparison clean, fields of the same owner do not count as each other's neighbours (Section 6.2), and neither does land inside the distance cut. A neighbour counts as having no demand only if it grew no crop all season. The Cropland Data Layer gives its crop, and the water-use rule marks it bare only if even its second-highest month looks like bare soil (Appendix S6). A hidden factor could bias the 2021 estimate only if it hit the land below a field harder than the land above it and spared the fields below a canal pump (Appendix Table A10, Panel C).

6.1 Neighbours Fallow Together

Fields near each other go fallow together. They share weather, pests, soils and markets. Figure 5 shows the pattern in the fallowing sample. Between a field and the fields within 500 m, the correlation of fallow status is 0.69, averaged over crop years 2019–2023. It falls with distance, to 0.36 at 3–5 km and 0.18 at 30–50 km, while shuffled fallow status gives a correlation near zero. The pattern is not one owner's decisions. With the field's own owner's fields left out, the correlation is 0.65 within 500 m and almost the same as before from 2 km on. When a nearby upstream field goes fallow, upstream demand falls, and the shock that made it go fallow may also hit the field itself. Demand from nearby fields would then mix competition for water with shared local shocks. The design answers in three ways. It counts only upstream and downstream fields beyond a distance cut set for each irrigation district from this co-movement (Section 6.2; Appendix A3 raises each district's cut to at least 2 to 10 km). The yield model controls for the fallow shares within 3 km. And it compares upstream with downstream demand (Section 6.3). A local shock reaches fields on both sides of a field, but water flows only one way. Beyond the cut the correlation falls but does not vanish, so the last comparison matters most.

6.2 Upstream and Downstream Demand on the Irrigation Network

Sections 7.1 and 7.2 ask whether, in drought, a field gets less water when the fields upstream of it use more. To answer, I need to know which fields lie upstream and downstream of each field and how much water they use. I also need a change in that use that the field's own conditions do not drive.

The irrigation network. Section 5 traces the canals from the water source to every field and defines each field's upstream and downstream fields. A field's *upstream fields* are the fields of its branch whose intake lies nearer the head, measured along the canals. Its *downstream fields* are

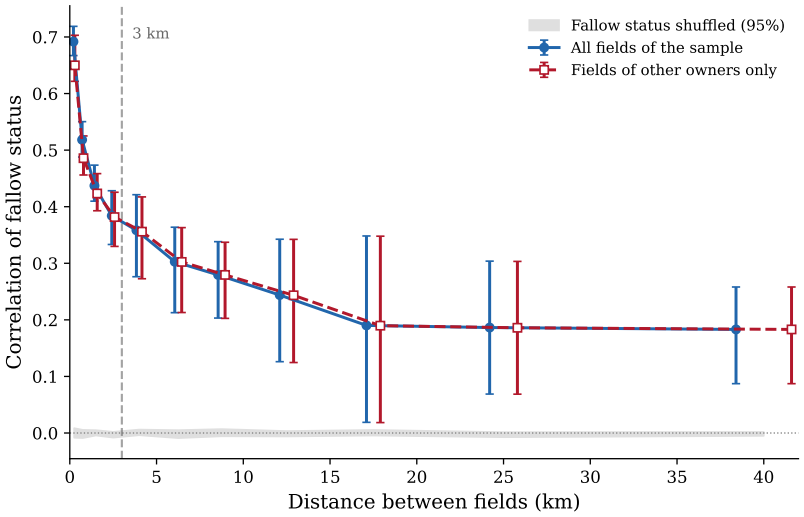


Figure 5: Fields Near Each Other Go Fallow Together

Notes: Correlation between a field's fallow status and the share of fallow fields at each distance from it, in the fallowing sample (Table 4, panel C: 137,830 field-years of 27,566 fields, crop years 2019–2023). A field-year is fallow when the crop maps record no crop or its monthly water use shows none. Solid: the neighbours are all fields of the sample in that crop year. Dashed: the same, with the field's own owner's fields left out, as the design leaves out same-owner pairs; a field without a matched owner is its own owner. Each point is the mean of the five crop years' correlations, and bars run from the lowest to the highest year; the two versions are set slightly apart. Distance bands: 0–0.5, 0.5–1, 1–2, 2–3, 3–5, 5–7.5, 7.5–10, 10–15, 15–20, 20–30 and 30–50 km, plotted at their midpoints; a field enters a band with at least three fields in it. Shaded: the 95 percent range of the same mean with fallow status shuffled across the year's fields, 20 draws. Vertical line: 3 km. The district distance cuts of Section 6.2 run from 0.75 to 6 km and are 2 km in most districts.

the fields of its branch whose intake lies farther. I leave out fields of other branches, because the district's schedule, not competition between fields, divides water between branches. I keep only fields of the same irrigation district, because I treat each irrigation district as a closed system. Arizona distributes water the same way (Section 2.2). An irrigation district here is whoever delivers the water, so a reservation or a private system counts as one. I also drop pairs of fields with the same owner in 2025 parcel records. An owner can move water between their own fields and makes their other decisions for all of them together. Upstream demand would then partly measure the owner's own choices. Same-owner pairs are 3.2 percent of all pairs. Owners are matched for 80 percent of fields, most of the rest on reservations, so some same-owner pairs remain.

Upstream and downstream demand. Upstream demand is the log of the water that a field's upstream fields use in the month. Each upstream field adds its acres times its water use per acre. Water use comes from the OpenET ensemble. Only fields farther away than the distance cut $r_{g(i)}$ of the field's irrigation district $g(i)$ count. For field i in month m of year t,

$$U_{itm} = \ln\Big(\sum_{j \in \mathrm{up}(i),\ d_{ij} > r_{g(i)}} \mathrm{acres}_j \, w_{jtm} \Big), \tag{6}$$

where w_{jtm} is field j's water use per acre and d_{ij} the distance between the two fields' centres. Downstream demand D_{itm} is the same log over downstream fields. A side with no use in the month, or no fields beyond the cut, enters as zero with its own indicator.

The distance cut. I leave out nearby fields because they share weather, pests, and markets, and their cropping moves together (Section 6.1). For each district with at least 400 fields, I set the cut at the distance where the correlation between fields' monthly water use in normal years levels off. The cuts run from 0.75 km in Yuma Mesa to 6 km on the Colorado River Indian Reservation, and the smaller districts share a cut of 2 km. Appendix S5 gives the rule and lists the cuts, and Appendix A3 raises each district's cut to at least 2 to 10 km.

Position and canal total. I write the two sides as the field's *position*, $P_{itm} = U_{itm} - D_{itm}$, and the *canal total*, $T_{itm} = U_{itm} + D_{itm}$. Position is high when upstream fields use much water and downstream fields use little, as at the tail of a busy canal. The canal total is high when the whole canal draws much water. A model written with U and D and one written with P and T give the same estimates (Appendix Table A7).

Drought. An irrigation district is in drought in a crop year when the mean of its fields' May–August SPEI-24 (Section 4.2) is below -0.6. The measure is the same for every field of an irrigation district in a year. Drought marks dry years, and in the CAP districts it marks mainly 2021, the year before the cut. Farmers learn the year's water supply before planting and decide then what to plant (Section 2.3).

How districts deliver water. Position along a canal should matter only where water moves along it in order. The districts' rules (Section 2.4) and the delivery model of Section 8 sort them. The CAP districts with junior rights, Maricopa–Stanfield, Central Arizona, Harquahala, and Hohokam, deliver on order and do not rotate, so position can matter there. In Maricopa–Stanfield the water records reject equal sharing. The Upper Gila canals rotate water, so position should not matter there. The senior-rights districts on the Colorado River do not run short. I estimate each group separately: the CAP districts with junior rights, the Upper Gila canals, and the senior-rights districts.

6.3 Downstream Demand as the Test of Direction

Downstream demand tests the direction. Water flows one way, so upstream fields can take water before a field and downstream fields cannot. If drought lowers a field's water use because upstream fields take the water first, upstream demand lowers it and downstream demand does not. If the shortage is instead shared across the canal, or the canal is too small for its peak, demand on either side lowers a field's water use through the canal total T_{itm}. Position P_{itm} then has no effect for a field with as much demand above it as below. Because demand enters in logs, its effect is negative for a field near the tail and positive for a field near the head (Section 3.4). Putting P_{itm} and T_{itm} in one regression separates rationing in order from a limit that the whole canal shares.

The instrument. The water use of upstream and downstream fields responds to the same month's heat and the same delivery cuts as the field's own. Ordinary least squares mixes "the fields upstream took the water" with "everyone got less." I instrument P, T, and their drought terms with the same terms built from *predicted demand*. A field's predicted demand is its acres times the typical water use of its crop in its county and month in other years. It is zero when the field is fallow that year. Predicted demand leaves out the current year's water use. It moves only

when fields change crops or go fallow. The instrument assumes that planting, decided before the season, does not respond to the shortage of a particular month.

6.4 Three Outcomes, Decided at Different Times

Each outcome is decided at a different time, so each model compares what can change then. Planting is decided before the season, so the fallowing model uses where a field usually sits on its canal, which a farmer knows then. A planted field draws canal water in the months its crop grows, so the water model compares those months. A crop grows over its whole season, so the yield model compares years. The fallowing and yield models compare fields by where they usually sit on their canal, and the water model by where they sit in the month, each in drought years and in other years.

Water use. A field draws on its canal when its crop needs water, and crops need different amounts. The water model therefore uses the months of the field's crop, when its typical water use in its county is at least half that of its peak month, and it measures water use relative to the crop's need: the log of the field's water use minus the log of the typical use of its crop in its county and month in other years. Position changes from month to month with the water use of the fields above and below a field, so the model uses it as it is. The model is

$$\begin{aligned} y_{itm} = b_P \left(P_{itm} \times \mathrm{Dry}_{g(i)t}\right) + b_T \left(T_{itm} \times \mathrm{Dry}_{g(i)t}\right) + a_P\, P_{itm} + a_T\, T_{itm} \\ + X'_{itm}\pi + \alpha_{im} + \gamma_{c(i)tm} + \delta_{k(i)tm} + \lambda_{g(i),\mathrm{Dry},m} + e_{itm}, \end{aligned} \tag{7}$$

on crop years 2019–2023. The term $\mathrm{Dry}_{g(i)t}$ marks drought in the field's irrigation district $g(i)$. The effects are field by calendar month, crop by year by month, county by year by month, and irrigation district by drought by month. Field by month effects absorb where a field usually sits in each calendar month, so b_P compares the same field and month across years.[4] The controls X_{itm} are the indicators for a side without fields, alone and with drought, the field's own SPEI-3 and SPEI-24, and the fallow shares within 3 km. Predicted demand instruments the two drought terms, position, and canal total. Standard errors are clustered by field and by crop by year by month.

Yield proxy. The yield model splits position into the usual position and this year's change in position. The yield proxy is crop-season GCVI, the satellite measure of Section 4.2. It is measured once per crop year, so the yield model is annual. The model uses its log, on planted field-years of crop years 2019–2023. The sample is the fields inside the irrigation-district polygons, because only those have the five-day image series that the measure needs (Appendix A6). I sum position and canal total over the crop season and split each in two. The *usual position* H_i^P is the field's mean position in crop years 2017 and 2018, before the sample.[5] *This year's change in position*

[4] Position is not fixed for a field. After the fixed effects and controls, about four-fifths of the variation left in position and canal total in the CAP districts is change from one year without drought to another, in the same field and month, as the fields above and below change crops or go fallow. About a fifth is the difference between drought years and other years. Position changes between years without drought in almost every field and month observed in two such years.

[5] Crop year 2016 has no crop-season position. A crop year starts in November, and the monthly water-use data start in January 2016.

is $W^P_{it} = P_{it} - H^P_i$. The terms H^T_i and W^T_{it} split the canal total the same way. A field far down its canal has a high usual position. This year's change in position is positive when the field's upstream neighbours planted more than in 2017–2018. It is also positive when the field's downstream neighbours left more land fallow. The model is

$$\begin{aligned} y_{it} = {} & \beta_W \big(W^P_{it} \times \mathrm{Dry}_{g(i)t}\big) + \beta_H \big(H^P_i \times \mathrm{Dry}_{g(i)t}\big) + \theta_W \big(W^T_{it} \times \mathrm{Dry}_{g(i)t}\big) + \theta_H \big(H^T_i \times \mathrm{Dry}_{g(i)t}\big) \\ & + c_P\, W^P_{it} + c_T\, W^T_{it} + X'_{it}\pi + \alpha_i + \gamma_{c(i)t} + \lambda_{g(i),\mathrm{Dry}} + e_{it}, \end{aligned} \tag{8}$$

with field, crop by year, and irrigation district by drought effects. The controls X_{it} hold the paper's control set and the fallow shares within 3 km. They also hold the water-right and well variables interacted with drought. Field effects absorb H itself. Predicted demand, split the same way, instruments the four drought terms and the two changes. Standard errors are clustered by field and by crop by year.

Fallowing. The fallowing model uses only the usual levels. A field is fallow in a crop year when the Cropland Data Layer records no crop or its monthly water use shows none. The model is a linear probability model on the usual position and the usual canal total, each interacted with drought. It has field, year, and irrigation district by drought effects and the same controls:

$$F_{it} = \psi_H \big(H^P_i \times \mathrm{Dry}_{g(i)t}\big) + \psi_T \big(H^T_i \times \mathrm{Dry}_{g(i)t}\big) + X'_{it}\pi + \alpha_i + \tau_t + \lambda_{g(i),\mathrm{Dry}} + e_{it}. \tag{9}$$

I leave out this year's changes in position and canal total, because neighbours decide the year's planting at the same time as the field. Year effects replace crop by year effects, since a fallow field has no crop. I also leave out the nearby fallow shares, since they measure fallowing too. Usual levels of predicted demand instrument the two terms. Standard errors are clustered by field and by irrigation district by year.

Every coefficient I report is on a drought term. It measures how much a slope shifts in drought years. The units are log points of the outcome per log point of demand. For fallowing, they are percentage points per log point of demand. Drought varies across irrigation districts, and the CAP districts with junior rights are four. Beside each estimate I report the p-value with standard errors clustered by branch (Section 5.3), the unit inside which position is defined. The sample's fields in those four districts lie on 41 branches. Appendix A10 adds a wild cluster bootstrap over branches.

7 Results

In a drought, the canals of a junior-rights district can carry less water than their fields order, and some fields run short. The results show which ones. In the CAP districts with junior rights, which lose surface water first, the fields that usually sit far down a canal run short. Before the season, they are left fallow more often. During the season, the planted fields far down a canal use less water than their crops need. Their yield proxy moves the same way, less precisely. In these districts, drought marks mainly 2021, the year before the cut. Where canals rotate water, as in the Upper Gila, fields along a canal share a shortage. There, and in senior-rights districts, fields far down a canal do not use less water in drought than fields near the head. Using the network measures and the 2SLS models of Section 6, I first test these patterns in the CAP districts (Section 7.1) and then compare them across rights groups (Section 7.2).

Table 4: Three Samples, All Fields and by Rights Group

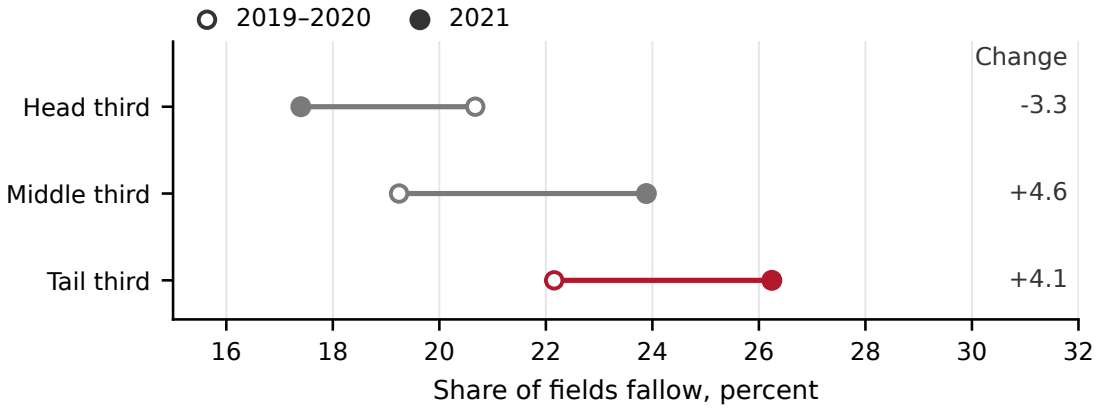
	All fields		CAP, junior rights		Upper Gila		Senior rights	
	Mean	(SD)	Mean	(SD)	Mean	(SD)	Mean	(SD)
A. Water use, field-months of the crop's months								
Field-months	570,116		102,791		16,788		248,960	
Fields	24,104		5,410		875		9,598	
Irrigation districts	43		4		10		7	
Branches	142		41		10		33	
Drought	0.179	(0.383)	0.204	(0.403)	0.361	(0.480)	0.167	(0.373)
ET observed (mm per month)	120.5	(50.8)	128.7	(48.8)	118.5	(43.5)	111.7	(53.1)
ET demand (mm per month)	120.6	(32.7)	129.3	(31.7)	118.6	(28.5)	111.5	(33.2)
ET observed / ET demand	1.002	(0.366)	0.995	(0.309)	0.999	(0.300)	1.008	(0.426)
Position	0.013	(3.693)	0.166	(3.951)	0.486	(3.630)	−0.060	(2.920)
Canal total	10.626	(3.122)	10.038	(3.133)	9.329	(2.639)	11.764	(2.540)
No upstream fields beyond the distance	0.117	(0.321)	0.141	(0.348)	0.086	(0.280)	0.050	(0.219)
B. Yield proxy, planted field-years								
Field-years	91,481		21,196		3,797		47,915	
Fields	21,571		5,626		1,000		10,157	
Irrigation districts	40		5		10		7	
Drought	0.179	(0.384)	0.220	(0.414)	0.367	(0.482)	0.163	(0.369)
ln of crop-season GCVI	1.463	(0.633)	1.471	(0.552)	1.241	(0.569)	1.516	(0.669)
Usual position	0.001	(4.328)	0.111	(5.105)	0.432	(4.374)	−0.082	(3.521)
This year's change in position	0.000	(0.636)	−0.012	(0.877)	−0.012	(0.864)	0.004	(0.494)
Usual canal total	14.629	(3.642)	13.851	(3.862)	12.862	(3.112)	15.666	(3.007)
This year's change in canal total	−0.050	(0.743)	−0.426	(1.010)	−0.045	(0.897)	0.148	(0.518)
Field acres	21.4	(31.9)	31.5	(40.0)	29.3	(55.8)	14.0	(14.5)
C. Fallowing, field-years								
Field-years	137,830		30,565		5,545		51,445	
Fields	27,566		6,113		1,109		10,289	
Irrigation districts	43		5		10		7	
Drought	0.191	(0.393)	0.200	(0.400)	0.400	(0.490)	0.160	(0.367)
Fallow	0.203	(0.402)	0.303	(0.460)	0.302	(0.459)	0.066	(0.249)
Usual position	0.014	(4.857)	0.117	(5.129)	0.835	(4.491)	−0.120	(3.578)
Usual canal total	14.171	(3.873)	13.825	(3.905)	12.643	(3.116)	15.611	(3.047)
Field acres	21.9	(34.6)	29.2	(38.2)	24.3	(47.5)	13.7	(14.4)

Notes: Samples of equations (7), (8) and (9): fields with upstream or downstream fields beyond their district's distance cut on the irrigation network (Section 6.2). Panel B keeps the fields inside the irrigation-district polygons, where crop-season GCVI is measured. CAP, junior rights: Maricopa–Stanfield, Central Arizona, Harquahala, Hohokam. Upper Gila: the canals of the Gila Valley. Senior rights: fields inside the boundaries of irrigation districts with senior rights. Irrigation districts: a reservation counts as its own district (Appendix S7). In Panels B and C the CAP group's fifth district is the Gila River Indian Reservation, with three fields inside Maricopa–Stanfield's boundary in Panel B. In all three panels the senior-rights group's seventh district is the Cocopah Reservation, with five fields in the yield sample of Panel B. Drought: share of field-months or field-years in irrigation districts in drought. Water use: monthly evapotranspiration, OpenET ensemble. Position and canal total: upstream minus downstream demand and their sum, each side the log of the water its fields use in the month (Section 6.2). In drought field-months of the CAP sample, position runs from −1.95 at the 25th percentile to +2.66 at the 75th. Usual position and canal total: the field's 2017–2018 mean, in log points. This year's change: the crop year's value minus the usual one. Fallow: no crop in the Cropland Data Layer or in the field's monthly water use.

7.1 In Drought, Fields Far Down CAP Canals Run Short

A first look. The raw data already show where the water ran short in 2021. If a canal that delivers in order runs short in drought, its tail should run short first. I start without a model, in the CAP districts with junior rights, which lose surface water first. In each of them, I rank fields by usual position and split them into thirds. Figure 6 compares 2019–2020 with 2021, when 86 percent of these fields were in irrigation districts in drought. The share left fallow fell 3.3 points in the head third and rose 4.1 points in the tail third. The gap of 7.4 points has a 95 percent interval of 5.3 to 9.6 points, from a bootstrap over fields. The water followed. Counting fallow fields, water use over the crop year rose 15 mm in the head third and fell 27 mm in the tail third, a gap of 42 mm (95 percent interval 27 to 55). Fields that stayed planted lost about the same water in every third (5 to 11 mm). The tail's water use fell mostly because more of its land was left fallow.

Figure 6: In the 2021 Drought, Fallowing Fell at the Head of CAP Canals and Rose Farther Down



Notes: Share of fields left fallow, by third of usual position within each CAP district with junior rights (Maricopa–Stanfield, Central Arizona, Harquahala, Hohokam): open circles 2019–2020, filled circles 2021. Usual position: the field's 2017–2018 mean of upstream minus downstream demand on the irrigation network, beyond the district's distance. Head third: least upstream demand relative to downstream; tail third: most. 6,273 fields with upstream or downstream fields beyond that distance and twelve months of water use in each crop year of 2019–2021, the sample of the water use in the text. Fallow: no month with a crop in the crop year. Raw shares, no controls.

Fallowing. Fields that usually sit far down CAP canals are left fallow in drought. A farmer decides before the season which fields to plant (Appendix S12). Take a field that usually sits far down a CAP canal. The farmer can expect it to run short when its irrigation district is in drought. If the canal will not finish a crop, the farmer can leave the field fallow. In equation (9), one log point more of usual position raises a CAP field's chance of fallowing in drought by 0.83 percentage points ($p = 0.009$; $p = 0.030$ with clusters by branch; 6,113 fields; Table 5, Panel C). Over all fields it is 0.44 ($p = 0.043$). The usual canal total does not predict fallowing in any group. The effect sits in 2021, the drought year of three of the four districts: relative to 2019, the CAP fallowing slope on usual position is 1.09 points steeper in 2021 ($p = 0.038$), against +0.52 in 2020. Of the fields left fallow in 2021 after two farmed years, only a third were farmed again in 2022, the first year of the cut, and most stayed fallow through 2023. More than half of those left fallow in 2019 or 2020 were farmed again the next year.

Water use. The fields that stay planted on CAP canals use less water than their crops need when they sit far down a canal. A short canal could share water in two ways. If it shared equally, a field's position on the canal would not matter. If it delivered in order, fields the water reaches later would run short. In the months a field's crop grows, I compare its water use with what the same crop uses in its county and month in other years (equation (7); Table 5, Panel A). Section 3 predicts where position matters. Delivery in order can cost a field water only if the field has no other water sources, so a field with its own well, or below a canal pump, loses less (Table 3). A canal pump is a district well that pumps into the canal. I therefore split the CAP fields into four groups, by whether the owner has a well in the district and whether a canal pump stands within 2 km above the field (Appendix Table A10). In the 539 fields with neither, one log point more of position lowers water use relative to the crop's need by 0.023 in drought ($p < 0.001$ with clusters by branch). The 2021 estimate is 0.019 against 2019–2020 alone and 0.017 against 2017–2018 ($p = 0.004$ and $p = 0.008$ with clusters by branch). Below a canal pump, position does not lower water use in 2021. The four groups differ ($p = 0.009$ with clusters by branch). This result does not depend on the 2 km reach of a canal pump. With a reach of 1, 3 or 5 km, position lowers water use in the no-backup fields by 0.019 to 0.023 in drought and by 0.014 to 0.019 in 2021 against 2019–2020 ($p \leq 0.010$ with clusters by branch; Appendix A8). Over all CAP fields, which mixes exposed and protected fields, the drought estimate is 0.011 ($p < 0.001$; $p = 0.006$ with clusters by branch, 41 branches; 102,791 field-months of 5,410 fields). A field at the 75th percentile of position then uses about 5 percent less water, relative to its crop's need, than one at the 25th, in a drought month of its crop's season. Against 2019–2020 alone, this average is about half as large (0.006). The drop comes from the fields with a backup source. In the no-backup fields, the estimate moves only from 0.023 to 0.019. Over all fields in the state, position does not lower water use (+0.001, $p = 0.46$), so the effect appears only in the CAP districts, where canals deliver water in order. Table 5's drought estimate compares drought years, mostly 2021, with all other years, including the 2022–2023 cut. Fields with no backup groundwater in senior-rights districts, where water does not run short, show no such effect, and the gap between fields without and with an owner's well differs between the CAP and senior districts ($p = 0.029$ with clusters by branch; Appendix Table A11). One district does not drive this effect. When I split the no-backup fields by district in a single regression, the estimate against 2019–2020 is 0.020 in Hohokam and Harquahala, which have no canal pumps ($p = 0.001$ with clusters by branch), and 0.021 in Central Arizona. No two districts differ ($p \geq 0.13$), and the estimate is smallest in Maricopa–Stanfield against 2017–2018. In the delivery model of Section 8, Maricopa–Stanfield's canals still met the planted fields' need in 2021 (Appendix A14). Over all CAP fields, position does not lower water use in 2022–2023 (+0.002, $p = 0.52$). The no-backup fields still lost water in the cut. One log point more of demand on their canal lowered their water use by 0.030 ($p = 0.005$ with clusters by branch), the most of the four groups. In Hohokam and Harquahala, where no district wells feed the canals, position from the head also lowered their water use, by 0.046 ($p < 0.001$). Where district wells fed the canals along their length, position from the head no longer marked which fields came last, for the reason Section 7.2.2 gives. The yield proxy follows the same split across the four groups. Fallowing does not, because the decision to leave land fallow is made before the season, for the whole farm, from the share of water the district announces (Section 2.3).

Yield proxy. The yield proxy of the planted CAP fields moves the same way as their water use, but less precisely. In drought, the usual position lowers the yield proxy by 0.023 log points per log

Table 5: Position on the Canal and Drought: Water Use, Yield Proxy, and Fallowing

	(1) All fields	(2) CAP, junior rights	(3) Upper Gila	(4) Senior rights
Panel A. Water use relative to the crop's need, months of the crop, ln				
Position × drought	0.0010	−0.0111***	0.0101**	0.0026
	(0.0014)	(0.0028)	(0.0039)	(0.0026)
	[0.583]	[0.006]	[0.050]	[0.290]
Canal total × drought	−0.0001	0.0052*	−0.0098	0.0011
	(0.0018)	(0.0029)	(0.0068)	(0.0034)
	[0.978]	[0.284]	[0.147]	[0.870]
Field-months	570,116	102,791	16,788	248,960
Fields	24,104	5,410	875	9,598
Smallest first-stage F	3,830	3,686	680	501
Panel B. Yield proxy, ln of crop-season GCVI				
This year's change in position × drought	−0.025	−0.046**	−0.022	0.056
	(0.027)	(0.022)	(0.030)	(0.068)
	[0.294]	[0.065]	[0.474]	[0.261]
Usual position × drought	−0.003	−0.023**	−0.004	0.006
	(0.005)	(0.010)	(0.007)	(0.004)
	[0.586]	[0.023]	[0.507]	[0.245]
This year's change in canal total × drought	0.010	0.014	−0.053*	0.070
	(0.020)	(0.022)	(0.029)	(0.076)
	[0.661]	[0.466]	[0.069]	[0.195]
Usual canal total × drought	0.002	0.007	0.020*	−0.007
	(0.004)	(0.006)	(0.012)	(0.005)
	[0.642]	[0.400]	[0.071]	[0.225]
Field-years	91,481	21,196	3,797	47,915
Fields	21,571	5,626	1,000	10,157
Smallest first-stage F	1,094	1,572	820	170
Panel C. Fallowed, percentage points				
Usual position × drought	0.44**	0.83***	0.19	0.01
	(0.22)	(0.29)	(0.66)	(0.16)
	[0.096]	[0.030]	[0.832]	[0.903]
Usual canal total × drought	−0.21	−0.55	−1.03	−0.09
	(0.28)	(0.61)	(1.00)	(0.27)
	[0.469]	[0.338]	[0.301]	[0.635]
Field-years	137,830	30,565	5,545	51,445
Fields	27,566	6,113	1,109	10,289
Smallest first-stage F	57,066	19,151	33,529	149,792

Notes: 2SLS; the drought terms of position and canal total are instrumented by the same terms of predicted demand. Upstream and downstream fields beyond each irrigation district's distance on the irrigation network, same-owner pairs removed; a side without such fields counts as zero demand. Drought: the irrigation district's May–August SPEI-24 below −0.6. In the CAP districts with junior rights, drought marks 2021 in three districts and 2022 in Harquahala. Appendix Table A10 separates 2021 and 2022–2023, each against 2019–2020. CAP districts with junior rights: Maricopa–Stanfield, Central Arizona, Harquahala, Hohokam. Upper Gila: the canals of the Gila Valley. Senior rights: fields inside the boundaries of irrigation districts with senior rights. Each column is estimated separately. Panel A: equation (7), the months of the field's crop, crop years 2019–2023, water use relative to the crop's typical use in its county and month; clustered by field and by crop by year by month. Panel B: equation (8), crop years 2019–2023, fields inside the irrigation-district polygons; crop-season GCVI reads each crop in the weeks that form its yield (Appendix A6); usual level: 2017–2018 mean; clustered by field and by crop by year. Panel C: equation (9), crop years 2019–2023, coefficients times 100; clustered by field and by irrigation district by year. Brackets: p-value with standard errors clustered by branch; Appendix Table A13 adds a wild cluster bootstrap, for Panel B on the peak of GCVI over the crop year. Smallest first-stage F: the smallest cluster-robust Wald F of the excluded instruments across the instrumented terms. Standard errors in parentheses. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

point ($p = 0.024$; $p = 0.023$ with clusters by branch), on 21,196 field-years of 5,626 fields (Table 5, Panel B). This year's change in position lowers it too, by 0.046 ($p = 0.039$; $p = 0.065$): a planted field has a lower yield proxy when its upstream neighbours planted more than in 2017–2018, or its downstream neighbours left more land fallow. The changes in canal total do not lower the yield proxy, and over all fields neither term is significant. The peak of GCVI over the crop year gives similar point estimates (Appendix Table A6). On that peak, a wild bootstrap over branches gives $p = 0.002$ for the usual position and $p = 0.19$ for this year's change in position (Appendix A10). Against 2019–2020 alone, both position terms are negative in 2021, as for water use, but neither is significant (-0.011, standard error 0.010, and -0.012, standard error 0.025; Appendix Table A10).

7.2 Position Matters Where Canals Deliver Water in Order

Water law decides which irrigation districts lose surface water first. How a district delivers its water then decides whether position inside it matters.

7.2.1 The CAP Districts, the Upper Gila, and Senior Rights

Section 2.4 lists the irrigation districts by rights and by how they deliver water. The delivery model of Section 8 tests those rules on the water records (Appendix Table A18). In Maricopa–Stanfield and New Magma the records reject equal sharing. In the Upper Gila, whose canals rotate (Section 2.4), no rule with an order along the canals beats equal sharing. Position along a canal should therefore matter in the first and not in the second. I estimate each group separately, with all the effects of the main models. Table 5 and Figure 7 report the estimates.

In the CAP districts, position lowers water relative to the crop's need in drought, and the usual position lowers the yield proxy and raises fallowing. In the Upper Gila, fields far down a canal do not lose more water and are not left fallow more often. In drought, position goes with more water use relative to the crop's need ($+0.010$, $p = 0.050$ with clusters by branch, 10 branches). The Upper Gila's drought years are 2021 and 2022, and the sign comes from its comparison years. Position went with less water in 2019 and 2023 and stayed near its 2017 level in 2021 and 2022. Against 2017–2018, its 2021 estimate is -0.002 ($p = 0.71$ with clusters by branch; Appendix A8). The usual position does not raise its fallowing ($+0.19$ points, $p = 0.78$; $p = 0.83$ with clusters by branch). The usual position does not lower its yield proxy (-0.004, $p = 0.56$). Nothing moves in senior-rights districts, where water does not run short: position gives $+0.003$ in water use ($p = 0.29$ with clusters by branch), and the usual position $+0.006$ in the yield proxy and 0.01 in fallowing.

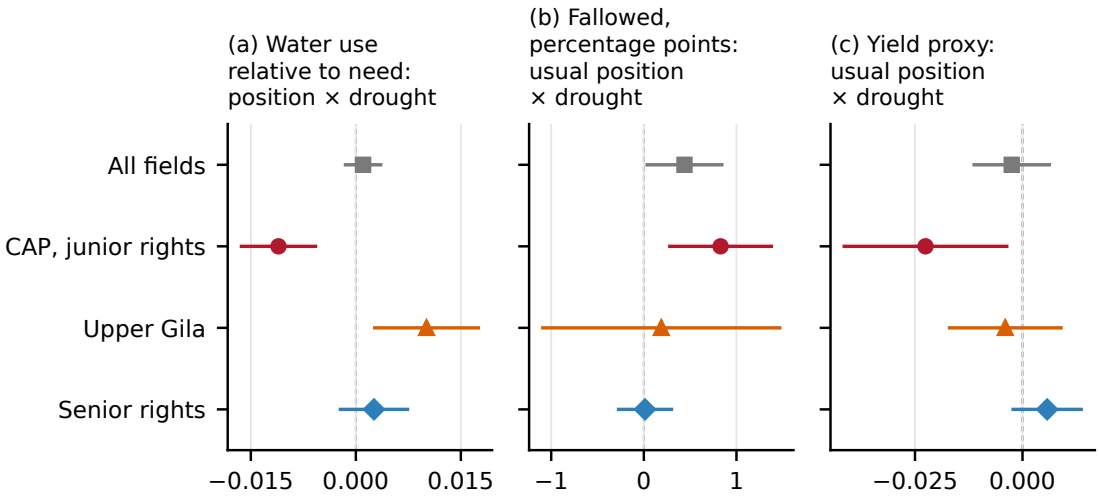
Earlier drought. The CAP districts with junior rights show the effect in 2019–2023 but not in the drier years of 2008–2015. In 2008–2015, position did not lower water use relative to the crop's need in drought ($+0.001$, $p = 0.57$); in 2019–2023 it does (-0.012, $p < 0.001$), and the difference is -0.013 ($p < 0.001$; $p = 0.008$ with clusters by branch; Appendix A7). CAP supply was full in 2008–2014 (Appendix Table S9). Position matters when CAP supply runs short, not in drought alone.

Appendix A9 puts the losses from fallowing and from the yield proxy in dollars.

7.2.2 Limits of the Demand Design and Why Supply Records Are Needed

The CAP result rests on few droughts, mostly 2021 in three districts and 2022 in Harquahala. The estimates hold when standard errors are clustered by the sample's 41 branches (Appendix A10).

Figure 7: Position in Drought, by Rights Group



Notes: 2SLS estimates of Table 5, each group estimated separately: (a) Panel A, (b) Panel C, (c) Panel B. Bars are 95 percent intervals with the paper's clusters.

The instrument rests on timing. Farmers choose their crops and the land they leave fallow before the season (Section 2.3), months before the canals run short. Planting can respond to the shortage they expect, but not to the shortage of a particular month. The yield proxy measures differences in yield within a crop, not harvested yield (Appendix A6 reports other measures). Well-registry coordinates can also place a well at a field's edge, on the neighbouring field.

The demand design cannot see three things. First, it does not see where water enters a canal. The design reads position from the head of the canal down. That fits its drought years in the CAP districts, mainly 2021, a dry year in which CAP water still entered at the head. The first CAP shortage came in 2022. In the 2022–2023 cut, Maricopa–Stanfield and Central Arizona lost CAP water. They relied on district wells that pump into the canals along their length (Section 2.2). Then the fields first in line were the fields below those pumps, not the fields near the head. So in the cut, the years of the deepest shortage, fields far down a canal no longer used less water than fields near the head in the CAP districts taken together (Appendix Table A10). Second, the design cannot see how much water arrived. Satellites measure the water a field uses, not the water delivered to it. So the design cannot say how much water a field lacked or what sharing rule divided the flow. Third, the design cannot separate the sharing rule from behaviour. It shows that shortage follows the direction of flow. It cannot tell a district that delivers in order from upstream farms that take more than the rules intend. Section 8 adds what is missing: monthly records of the water each district received, where its pumps stand, and sharing rules judged by how well they predict fields' water use in years left out of the fit. It follows which fields run short as the source of water changes, and it tests the rule against the behaviour.

8 Who Gets Canal Water When It Falls Short

Public records show how much water enters each district's canals each month, but not how much reaches each field. I carry that water down the canals and estimate each district's sharing rule. I judge each rule by how well it predicts fields' water use in years left out of the fit. The model

has three free parameters. It says which fields run short, in which months, and why: the district's sharing rule, where its canal pumps stand, and who runs the wells. Three tests check each part. Moving fields to other places on the canal tests who. Moving each month's water to other years tests when. Spreading the same pump water evenly over all fields, or changing the rule, tests why. The model covers the ten districts that hold 85 percent of the acres in Arizona's large surface-water districts, plus ten Upper Gila canals (Appendix A12 gives each estimate in full).

Three steps answer what the demand design could not see.

1. Which sharing rule divides the water, and does it predict who runs short (Sections 8.3, 8.4, 8.6, and 8.7)? The rule the data pick follows how each district delivers water. Where water moves in order along canals, the data reject equal sharing. Where canals rotate, no rule with an order along the canals beats equal sharing. In five of the seven districts that run short, fields without a well use less water where and when the model says their canal falls short, and they are left fallow more often. In the other two, Central Arizona and Hohokam, the records leave out too much to tell. Where the model predicts enough water, in the senior-rights districts, fields do not lose water.

2. What happens when the water enters somewhere else (Section 8.5)? In the 2022–2023 cut, Maricopa–Stanfield lost the CAP water entering at the head of its canals and relied on leased wells pumping along their length. Then the canal pumps upstream of a field decided whether it kept water and stayed planted.

3. Did fields near the water sources take extra water, and what did the cut cost (Sections 8.8 and 8.9)? In Maricopa–Stanfield, fields near the water sources used at most 8 percent more water than fields far from them with the same crops, so the losses do not come from them taking extra water. The cut hit in two waves: land left fallow before the season, and planted fields short of water in peak months. Leaving that land fallow cost $8.0–12.1 million a year in returns over operating costs, 24 to 40 percent of what the district's farmland would normally earn. Changing the sharing rule alone cannot solve the problem, because canal pumps cannot send water upstream to the fields above them.

8.1 Inputs to the Delivery Model

The delivery model of Section 3 combines each district's monthly canal water with each field's crop demand, the canal network, and the wells to predict monthly deliveries to each field. I built the model on Maricopa–Stanfield, which has the fullest records and maps, and I run the same recipe in the other districts. Appendix A1 gives the distances, thresholds, and counts behind each part.

Canal water. Each district's monthly canal water V_t comes from its own record (Table 2). In the CAP districts it comes from CAP's delivery reports, and in Wellton-Mohawk and the three Yuma districts from Reclamation's decree accounting. In San Carlos it is the district's share of the project's diversion under the Globe Equity decree, and in the Upper Gila it is each canal's monthly diversion in the Gila Water Commissioner's records (Gila Water Commissioner, n.d.). In the Upper Gila, reported diversions depend partly on what farmers ordered, so I also run the river's flow at the Solomon gage down the decree's list of rights (Appendix A2). The irrigation efficiency e is the share of turnout water that crops consume. A district's water balance over 2017–2019 sets e at 0.72 in Maricopa–Stanfield, 0.73 in Central Arizona, and 0.75 in Hohokam. Harquahala has

no measured pumping and takes the pooled value of those three, 0.73. The other districts take 0.70 by assumption (Appendix A1). Water lost along a canal enters only through e, so no loss in the model grows with distance.

Crop demand. A field's monthly demand depends on its acreage A_i, its crop and growth stage, reference evapotranspiration ETo_{it}, and effective rain P^e_{it}. A farmed field's irrigation demand in month t is

$$d_{it} \;=\; A_i \times \max\bigl(0,\; \widetilde{K}_{it}\,\mathrm{ETo}_{it} \;-\; P^e_{it}\bigr), \tag{10}$$

and a fallow field's demand is zero. The crop coefficient $\widetilde{K}_{it} = c_{gm}K_{it}$ takes each crop's timing from Sentinel-2 imagery. The factor c_{gm} scales its level to match OpenET water use in 2017–2019, by region, crop group g, and month m. Without the factor, the FAO-56 coefficients put crop need 30 to 50 percent above measured use in every year, the years of full supply included. Year-to-year changes in a field's demand come from whether it is farmed, its crop, and the weather.

The network. Each district's canals form a tree below its entry gates (Section 5), down which the main supply eV_t moves under the sharing rule of Section 3.2. The model places each field at its own mapped turnout or ditch if it has one, else at its neighbors' turnout, else at the nearest point of its canal line (Appendix Table A1). The mapped ditches exist only in Pinal County. Fields attached to the same point on the tree have no order among them, because the data cannot place them more finely.

Wells. Only Maricopa–Stanfield and Central Arizona have canal pumps in the model, because they lease wells from landowners and pump that water into their canals (Sections 2.2 and 3.3). In Maricopa–Stanfield, the canal pumps are the 144 district wells that pumped in 2019 and feed a canal, pipeline, or ditch. Each year they pump their share of the district's reported well water, or what the canals still need after CAP if that is less. Central Arizona records only each well's capacity, not which wells ran, and the other districts have no such wells or no record of their pumping (Appendix A15).

Well access goes by ownership. A field has a well if its owner holds a registered well rated at 100 gallons per minute or more. In Maricopa–Stanfield, where the ditches show what a well can reach, the well must also reach the field by ditch or lie close to it. District and federal wells are no field's private water, so in the other districts they do not give a field a well. Sections 7.1 and 7.2 use a narrower own well, a registered well inside the field (Appendix Table A8). A field with a well claims the take τ of its demand from the canal (equation (1)). Maricopa–Stanfield's water record puts an upper bound of 0.82 to 0.86 on the take in each year of 2016–2021 (Appendix A1), without using any data on water use.

8.2 Finding the Rule That Describes the System

I do not observe deliveries to individual fields. But each candidate rule (τ, κ, κ_J) in the delivery model gives a different distribution of water across the network. I summarize it by each field's monthly canal shortfall ℓ_{it}, the share of its crop demand that the canal does not meet (equation (4)). If a rule captures how the district divides its water, the shortfalls it predicts should explain which fields use less water in short months.

For any candidate rule, I link its predicted shortfalls to monthly water use within the season:

$$y_{it} \;=\; \beta_0\,\ell_{it}\,(1-W_i) \;+\; \beta_1\,\ell_{it}\,W_i \;+\; \phi\,S_t\,(1-W_i) \;+\; X_{it}'\gamma_m \;+\; \alpha_{ikm} \;+\; \alpha_{iy} \;+\; \alpha_{kym} \;+\; u_{it}, \quad (11)$$

where y_{it} is 100 times the log of the field's monthly ET from OpenET, its *water use*, and $W_i = 1$ if the field has a well. β_0 is the change in monthly water use, in log points, on a field without a well when its canal goes from meeting all of its claim ($\ell_{it} = 0$) to none of it ($\ell_{it} = 1$). A change of b log points is a proportional change of $e^{b/100} - 1$. β_1 is the same change on a field with a well. The model predicts $\beta_0 < 0$, and β_1 closer to zero if the field's own well replaces the water (Section 3). S_t is the district's monthly *shortage*, the share of the month's crop demand that its water cannot meet. The regression holds it constant for fields without a well, together with drought controls X_{it}. The fixed effects are by field, crop, and month (α_{ikm}), by field and year (α_{iy}), and by crop, year, and month (α_{kym}). With the district's shortage and each field's yearly level held constant, β_0 comes only from how the rule spreads water across fields within a season. I leave out owner effects, because an owner's fields sit together on the same canal. Standard errors are clustered by owner and by year-month.

Searching over rules. To see whether a sharing rule describes the system, I search over a grid of the take τ and the sharing weights (κ, κ_J), each from 0 to 1 in steps of 0.02. The grid has 132,651 combinations, or 2,601 sharing rules at each take. I score each combination by leaving out one year at a time. I fit equation (11) on the other years and measure how much the rule's shortfalls reduce the squared prediction error in the year left out. The *score* is that reduction in basis points, against a baseline with only the district's shortage and the controls.

A rule clears the *bar* if its score beats the 95th percentile of the best score in 200 draws. Each draw flips the sign of the baseline's residuals owner by owner and repeats the whole search. The same test shows which named rules the data reject, such as equal sharing ($\kappa = \kappa_J = 0$) or upstream first ($\kappa = 1$), and which they keep. To estimate the slope $\hat{\beta}_0$ without relying on one selected rule, I average ℓ_{it} over all 2,601 sharing rules at the district's best take.

I then check that the network and the timing of the water drive the result. I move each calendar month's water across years, which tests when. I move fields, or whole owners' fields, to other places on the canal tree, which tests who. Each test has 1,000 draws. Farmers choose their crops and the land they leave fallow before the season. The demand above and below a field in summer is therefore set before water runs short. CAP orders follow that demand. The district's monthly shortage and the crop-by-year-by-month effects hold the district's orders constant. The slope comes from how the rule spreads each month's water across fields. Appendix A1 gives the details of the equation, the search, and the tests.

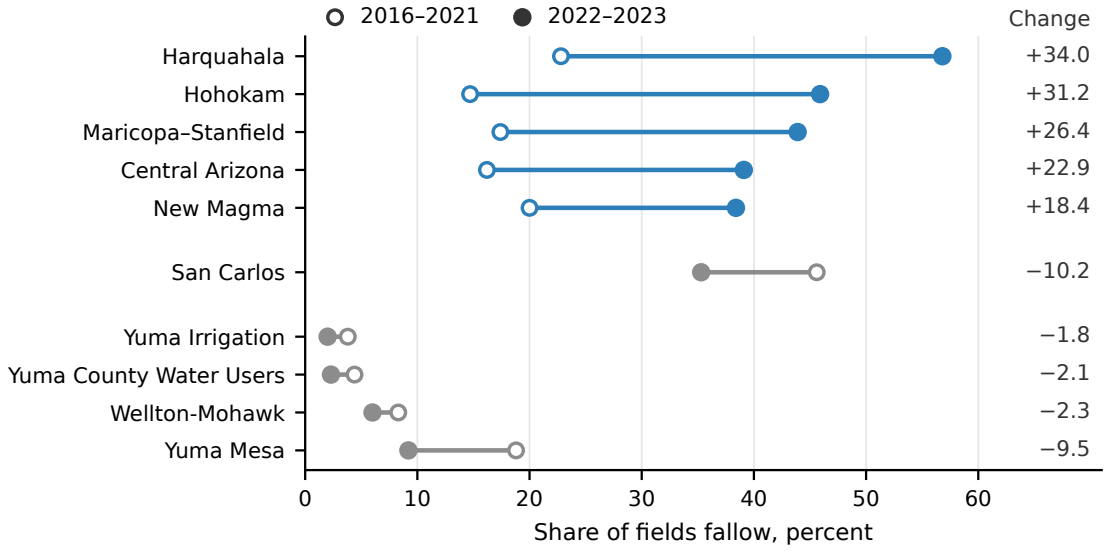
The 2022–2023 cut. I estimate equation (11) on 2016–2021 in Maricopa–Stanfield, Central Arizona, Harquahala, and Hohokam, and on 2016–2023 elsewhere. The years 2016–2021 are the years before the cut, and they are not all alike. In 2021 three of the four districts were in drought (Section 7.1), and in August Reclamation announced the cut. The cut began in 2022, and in 2023 the pool received no water. Farmers knew of the 2022–2023 cut before planting and left land fallow ahead of the season, so the field by year effects absorb the cut. To test whether the model also predicts who lost water and land in the cut, I hold each field's demand at its 2016–2021 monthly mean, so that only supply moves the shortfall. A field's *predicted rise* is its shortfall in 2022–2023

minus its shortfall in 2016–2021. I test whether a larger predicted rise lowers a field's water use and farmed share, net of the same contrast before the cut (2020–2021 against 2016–2019). A field's *total stress* is last year's shortfall plus this year's predicted shortfall. I test whether it predicts fallowing among fields farmed the year before. In this section a field is fallow when the Cropland Data Layer gives it no crop. I leave out the water-use rule of Appendix S6, which reads the same water use that this section's outcome measures; Table A26 reports the results on it. Appendix A1 gives the specifications.

8.3 Fields Went Fallow Where the Model Says Water Fell Short

From 2016–2021 to 2022–2023, the fallow share rose 18 to 34 points in the five CAP districts with a predicted shortage (the four of Section 2.4 and New Magma). It fell 2 to 10 points in San Carlos and the four senior-rights districts (Figure 8). Fallowing also rose in two districts with no predicted shortage, so a rise alone does not show a shortage (Appendix A16). The divide across districts follows water law (Section 2.1). The model's test therefore lies inside each district, where water rights are the same and fields differ in their place on the canal and in their wells.

Figure 8: Fallowing Rose in the Districts the Model Says Ran Short

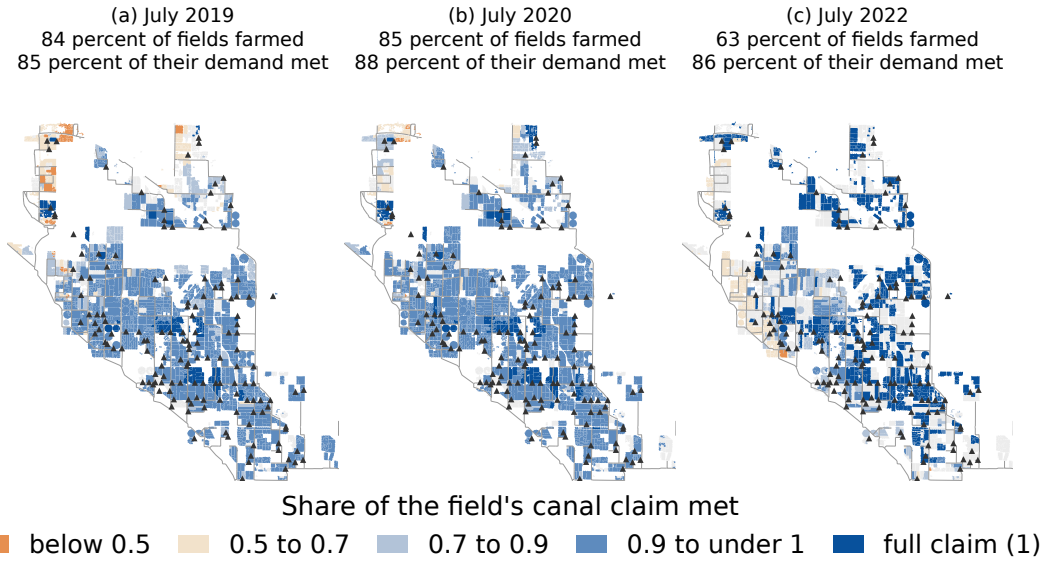


Notes: Share of a district's fields left fallow. Blue: the five CAP districts. Grey: San Carlos and the four senior-rights districts of at least 10,000 acres. These districts hold 390,143 of the 460,999 acres in surface-water districts of at least 10,000 acres; the Upper Gila's canals, each smaller than that, come in Section 8.6. Left out: Roosevelt and Buckeye, with no monthly supply record; Salt River Valley, whose farms kept full allocations; Cortaro–Marana, where wells are the main source (Appendix A16). Yuma Mesa's level may reflect crop labels.

8.4 Inside a District, Water Use Follows the Shortfall

In Maricopa–Stanfield in 2016–2021, CAP and the district's wells (Section 2.2) came close to crop demand over a year, but not in every month. Central Arizona wrote that shortages "usually occur during periods of above normal temperatures in the growing season when there is high demand" (CAIDD 2022). Figure 9 shows who gets water in the model in July of 2019, 2020, and 2022. In July 2019, the fields that receive less than half of their claim gather in the northwest of the district, where a tenth of fields are that short.

Figure 9: In Short Months the Canal Stops Meeting Some Fields' Claims, Maricopa–Stanfield



Notes: The share of each farmed field's claim delivered, averaged over all 2,601 rules at a take of 0.66, in July of 2019, 2020, and 2022. July 2022 lies in the cut, after the 2016–2021 sample of the monthly estimates. The colors group the share into five classes, and the darkest blue is a field whose full claim is met. The titles give the percent of the map's fields farmed that month, and the delivered water as a percent of the farmed fields' crop demand. Light grey: fields not farmed that month. Triangles: the 144 canal pumps. Grey lines: the canal tree.

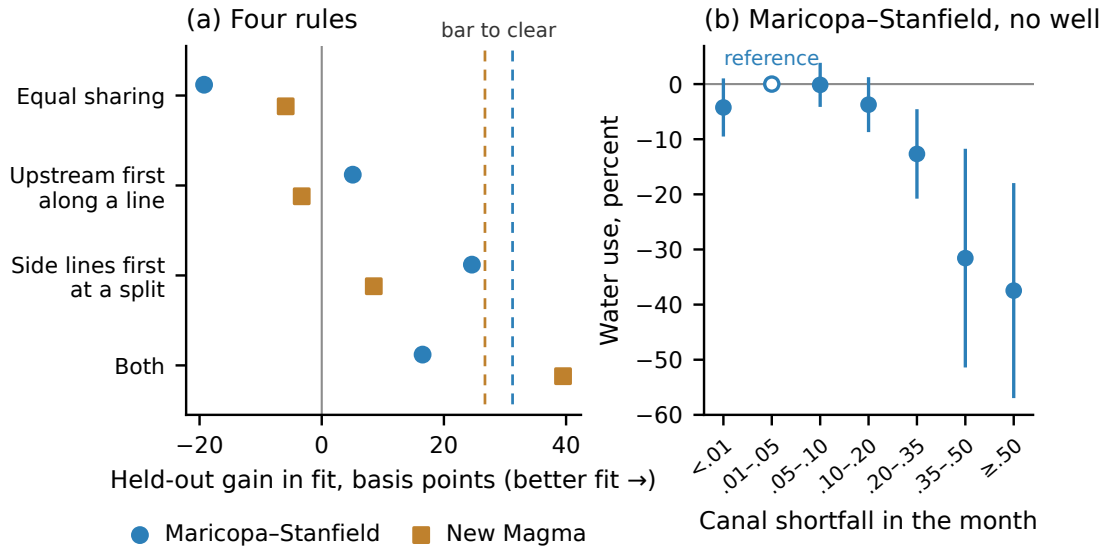
Fields without a well in Maricopa–Stanfield use less water in the months the model says their canal is short (equation (11)). With the shortfall averaged over all rules at the best take, raising it from 0 to 1 lowers the monthly water use of a field without a well by 61.5 log points, about 46 percent. The loss sits in the fields the model says are short, in and around the months it says are short. Measured from months with a shortfall of 0.01 to 0.05, water use falls by less than 4 percent while the shortfall stays below 0.20. Where the shortfall is 0.35 or more, it falls by 27 to 31 percent (Figure 10, panel b; Appendix Table A22).

With the dates of the water shuffled, or the fields moved to other places on the canal, the model does not reproduce the result. Reassigning each calendar month's water across the years reaches the real slope in none of 1,000 draws. Moving fields, or whole owners' fields, to other places on the canal reaches neither the slope nor the best score.

The data in Maricopa–Stanfield reject equal sharing and show that the canal serves side lines first at splits, without fixing the order along a line (Figure 10, panel a). The best rule clears the bar of 31.2 with a score of 36.8. It serves side lines first at the splits and upstream fields first in part along a line. The test rejects equal sharing and upstream first only along a line, and no pure rule clears the bar.

Fields with a well in Maricopa–Stanfield also use less water when their shortfall rises. That is what the district's wells predict. The district runs wells leased from landowners, and its canal pumps gave 92.4 percent of its 2019 well water. A well on a farmer's land is therefore not water the farmer controls (Appendix Table A24; Appendix A14). What marks which fields keep water is how much of their need the district's canal pumps can supply (Section 8.5). For the same shortfall, fields whose pumps could supply half or more of their need lose at most half as much water as the others (Appendix Table A23).

Figure 10: Equal Sharing Fits Neither CAP District, and Water Use Falls Where the Shortfall Is Large



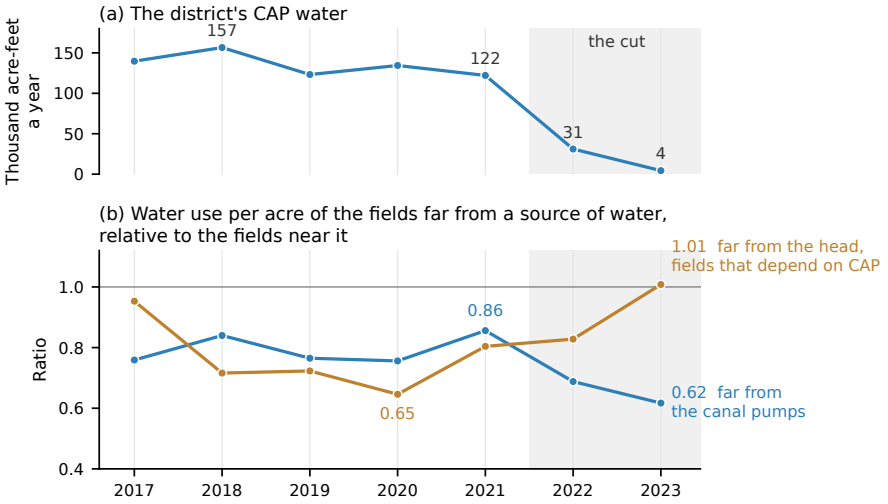
Notes: Panel (a): each rule's score, Maricopa–Stanfield 2016–2021 at a take of 0.66 and New Magma 2016–2023 at 0.70. The best take is 0.66 in Maricopa–Stanfield and 0.72 in New Magma. Dashed lines: each district's bar. Equal sharing: $\kappa = \kappa_J = 0$. Upstream first along a line: $\kappa = 1$, $\kappa_J = 0$. Side lines first at a split: $\kappa = 0$, $\kappa_J = 1$. Both: $\kappa = \kappa_J = 1$. Panel (b): water use by size of the shortfall in the month, fields without a well, all rules at a take of 0.66, against months with a shortfall of 0.01 to 0.05; bars are 95 percent confidence intervals.

8.5 Losses in the Announced Cut Followed the Model, and Canal Pumps Mark Which Fields Kept Water

When the cut took away Maricopa–Stanfield's CAP water at the head of the canals, the fields that the canal pumps could supply least lost the most water (Figure 11). CAP deliveries fell from 122 thousand acre-feet in 2021 to 4 thousand in 2023, and the district's wells, which pump into the canals, became its main supply. Counting fallow land, water use per acre fell further behind on the fields where those pumps could supply under a quarter of their 2016–2021 need. Among the fields that depend most on CAP water, those farther from the head used less water per acre while CAP flowed, and as much as the nearer ones in 2023 (the second line of panel b). In the cut, distance from the head alone even points the other way. Fields far from the head lost less water (Appendix A14).

The rise in shortfall that the model predicts marks which fields without a well lost water use and farmed land in the cut. Farmers knew the cut before planting, and the districts rationed water by rule (Section 2.2), so the cut shows in annual outcomes. I hold each field's demand at its 2016–2021 level, so that only water moves the shortfall. On fields without a well, a predicted rise one standard deviation larger lowers 2022–2023 water use by 5.6 percent. It also lowers the farmed share by 4.9 points, though the contrast before the cut accounts for part of that fall. Before the cut, when the canal fell short in one month, a planted field offset it with more water in the season's other months. Its water use in a month rose 7.8 percent for each 10 percent of its claim left unmet in the other months (Table 6). The season's water use therefore did not always fall, and the yield proxy did not fall. In the cut, there was no water to offset a short month. A field's water use in a month then fell 3.1 percent for each 10 percent left unmet in the other months. A short month

Figure 11: Which Fields Used Less Water Followed the Source of the Water, Maricopa–Stanfield



Notes: Panel (a): the district's CAP water by year, from CAP's delivery reports. Panel (b), blue line: water use per acre of land, fallow land included, on fields whose pumps could supply under a quarter of their need, relative to the rest. Ochre line: among the 541 fields whose pumps could supply under a quarter of their need and with no large district pump on the canal above them, the half farther from the head relative to the nearer half (Appendix Table A29). The share is the water the district's pumps alone could deliver to a field in the delivery model, up to its need in each month, over its need in 2016–2021. Under a quarter: 16,438 acres; a quarter or more: 45,023 acres. Appendix Table A28 gives each class. Water use is OpenET evapotranspiration above the year's mean on fallow fields. All fields farmed at least once in 2017–2021, with and without a well.

became a real deficit over the season. A predicted loss of 10 percent of the season's water lowered the season's water use by 9.3 percent. It lowered the yield proxy by 10.3 percent, less precisely (Appendix A17).

Table 6: Before the Cut, Other Months Offset a Short Month; in the Cut They Did Not, Maricopa–Stanfield

Change in a planted field's water use in a month (percent)	Before the cut 2017–2021	Change in 2022–2023	In the cut 2022–2023
The canal leaves 10 percent more of the field's claim unmet in that month	−7.0 (1.7)	4.7 (2.0)	−2.3 (1.0)
The canal leaves 10 percent more of the field's claim unmet in the season's other months	7.8 (1.9)	−10.9 (2.4)	−3.1 (1.3)

Notes: Percent (log points times 100); standard errors in parentheses, clustered by owner. One regression on 2017–2023 with the change in 2022–2023; the last column is the sum. Monthly OpenET water use in the crop's months from March to October, on the field's canal shortfall in that month and the demand-weighted mean shortfall of the season's other months. All rules at a take of 0.66, all fields with and without a well; field by crop by month and crop by year by month effects; 51,353 field-months. Panel B of Appendix Table A36, which also gives the season's totals.

Total stress predicts which fields without a well are left fallow. A field's total stress adds last year's shortfall to this year's predicted shortfall. With field and year effects, one unit of total stress raises the chance of fallowing by 18.7 points on fields without a well farmed the year before. This response comes from the cut years.

While CAP flowed, distance from the head decided who ran short, and in the cut the canal pumps above a field decided who kept water (Figure 12). Before the cut, the delivered share fell with distance from the head (Appendix A14). Take the fields that depend most on CAP water, with no large pump above them. In each year from 2018 to 2021, the farther half of them used 20

to 35 percent less water per acre than the nearer half (Appendix Table A29). Where the pumps stand produces nearly three times the spread in the predicted rise in shortfall that the same pump water pooled across all fields does (standard deviations 0.173 and 0.062). With canal pumps where they stand, the model predicts monthly water use, losses in the cut, and fallowing. With the same pump water pooled across all fields, it predicts none of them once both are in one regression, and with field and year effects its coefficient on fallowing has the opposite sign. Entered alone, it predicts monthly water use as well as the pumps do (Appendix Table A23).

Fields that the canal pumps could supply kept more farmed land and water during the cut (Appendix Figure A2). Fields without a well whose pumps could supply half to three quarters of their need kept 11.6 points more land farmed in the cut than fields under a quarter. They also used 20 percent more water (18.5 log points). The district chose where its pumps stand, and every sharing rule keeps them in place. The cut therefore shows what pump locations predict. It cannot separate sharing rules or show what moving a pump would do. Among fields at a similar distance from the head, losing CAP water equal to 10 percent of need raised the chance of fallowing by 2.2 points (Appendix Table A17). In the cut, the canal pumps mattered mostly through which fields stayed farmed.

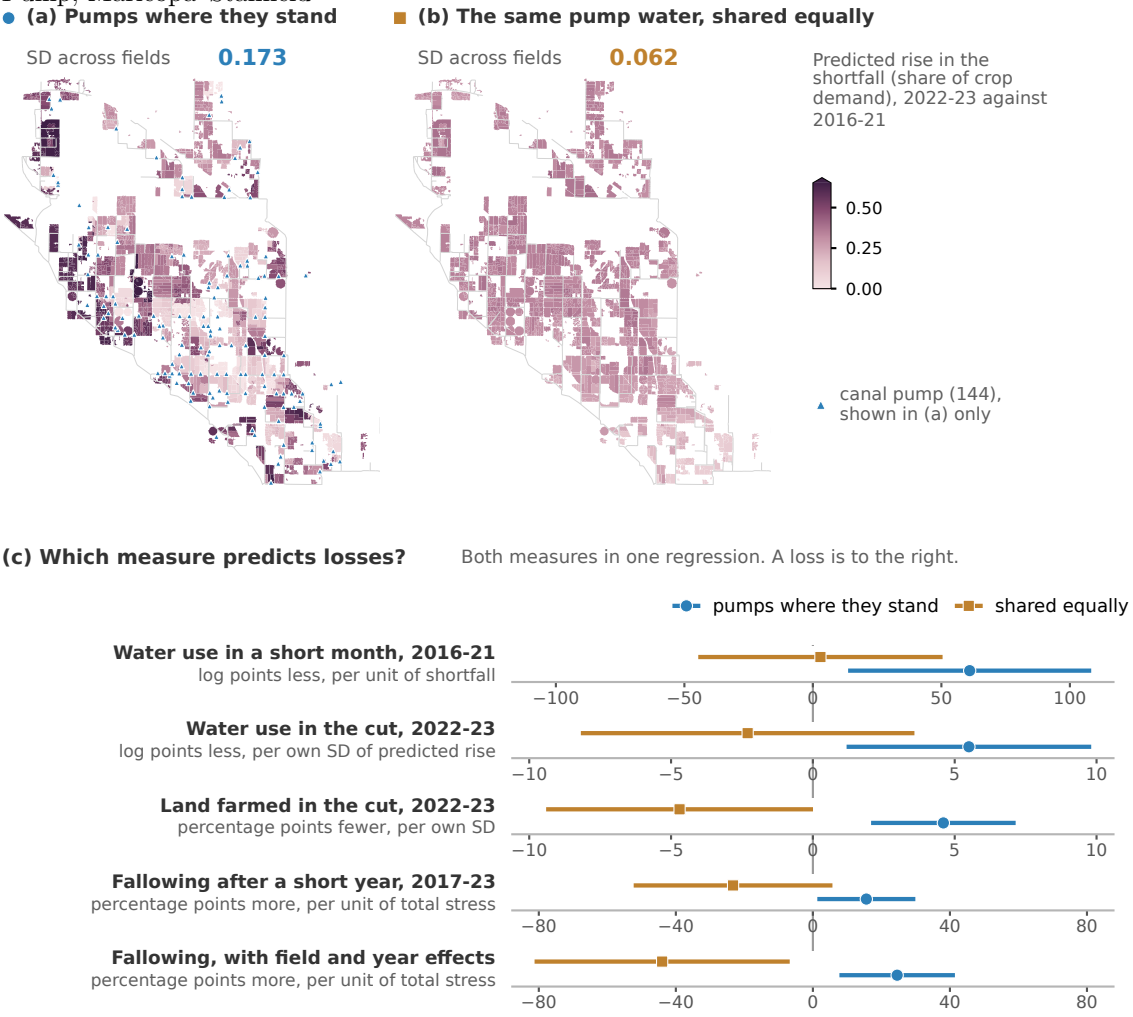
8.6 The Results Follow Each District's Rules, Wells, and Records

Appendix Table A18 sets what each district's rules and records predict beside what I find. Among the districts that deliver in order, Maricopa–Stanfield has the fullest records and the clearest result. In New Magma the rule clears its bar, but the monthly slope is less precise (-6.6, standard error 4.1).

Three patterns hold across the districts in Appendix Table A18. First, in Maricopa–Stanfield, New Magma, Harquahala, the Upper Gila, and San Carlos, fields without a well use less water where and when the model says their canal falls short. Moving fields or owners to other places on the canal rarely reaches those slopes. Where water does not fall short, in Wellton-Mohawk and the three Yuma districts, no field uses less water when the model marks its canal as short. Second, the sharing rule follows how the district delivers water. Equal sharing is rejected where water moves by order along canals, in Maricopa–Stanfield and New Magma. In the Upper Gila, where canals rotate, no rule with an order along the canals beats equal sharing. A rule near equal sharing fits San Carlos. Third, who keeps water depends on who runs the wells. Where farmers pump their own wells, losses fall on fields without a well in Harquahala and New Magma. In the Upper Gila, fields without a well lose about as much water in a short month as fields with one. Fields without a well are left fallow more often there when the river gives less water. Where the district runs leased wells that pump into its canals, in Maricopa–Stanfield, the canal pumps mark which fields keep water. Where such wells are dense and run first, in Central Arizona, every field loses with the district's total.

Rotation on a river: the Upper Gila. The Upper Gila rotates water inside its canals (Section 2.4). A rotation gives each field its turn in proportion to its demand, so no order inside a canal should beat equal sharing. On each canal's reported diversions, equal sharing is the best rule, with a score of 61.0 against a bar of 9.7. Under equal sharing, almost all the variation in a field's delivered share is between canals. This result therefore says which canals got less water, not how water moves inside a canal.

Figure 12: Who Lost Water Follows Where the Canal Pumps Stand, Not Only How Much They Pump, Maricopa–Stanfield



Notes: Panels (a) and (b) map each field's predicted rise in shortfall from 2016–2021 to 2022–2023. The shortfall is the share of a field's usual crop demand that the canal does not meet. The maps show the 1,979 fields without a well of their own. Fields with a well are blank. In (a), each of the 144 canal pumps (triangles) serves the fields below it first. In (b), the same total pump water is shared equally by all fields. The mean rise is about the same in both, 0.339 in (a) and 0.308 in (b). SD is the standard deviation across fields. The darkest shade also holds the 1 percent of fields in (a) with a rise of 0.65 or more. In panel (c), each row is one regression on fields without a well, with both versions of the shortfall entered together. Blue is the estimate with the pumps where they stand, and ochre is with the pump water shared equally. A mark to the right of zero is a loss on the fields that version marks as short. Bars are 95 percent confidence intervals. Water use in a short month is 2016–2021 monthly use as the shortfall goes from none to all of the claim. A fall of 61 log points is about 46 percent. The cut rows compare 2022–2023 with 2020–2021, per standard deviation of each version's predicted rise, at fixed demand. Fallowing is the chance that a field farmed the year before is left fallow in 2017–2023, per unit of total stress. Total stress is last year's shortfall plus this year's predicted shortfall. The last row adds field and year effects. Each version's shortfall averages the model's sharing rules at a take of 0.66. Appendix Table A23 gives each version's estimates alone and together, and their correlation.

In the dry summers of 2019, 2020, and 2023, the canals ran lowest and the Gila Valley district pumped most. Fields without a well were then left fallow more often than fields with one, by 9.6 points against 3.3, a descriptive difference (Appendix A2).

Mixed rules: San Carlos. In San Carlos, which allots stored water by the decreed acre and natural flow by priority date (Section 2.4), a rule close to equal sharing clears the bar.

District wells first: Central Arizona. In Central Arizona I cannot tell whether the monthly model fits, because the district's records give the capacity of its leased wells and not which of them ran (Sections 2.2 and 2.4). Its wells are dense and run first, and CAP water is the remainder. When CAP fell, every field lost in proportion to the district's total shortfall.

Records that miss water: Hohokam. Hohokam is the one district the model does not fit.

Hohokam's records miss water that reached its fields, so a predicted shortfall here need not mean a shortage (Appendix A15). The district's rules set no order along its canals (Section 2.4), and the flat cut along the canals is what those rules predict.

8.7 A Shortage on Paper Does Not Produce the Result

In the senior-rights districts, where water is not short, the same satellite data and the same code find no loss from shortfalls. In Wellton-Mohawk, water covers crop demand in every March–October month but two. No sharing rule clears the bar. The slope has the opposite sign from the short districts (23.8), and it rests on those two months. Fallowing does not follow total stress.

A shortage created on paper does not produce the result in three of the four senior-rights districts. I lower the share of diverted water reaching crops from 0.7 to as low as 0.3, while the fields' real water stays the same. A model that found a slope in any shortage it is given would find one here. In Wellton-Mohawk, Yuma Mesa, and Yuma County Water Users, no sharing rule clears the bar in any run, and fallowing does not rise.

Yuma Irrigation is the exception. It clears the bar when the share of diverted water reaching crops is set to 0.6 or 0.5. Because Yuma Mesa clears no bar, I read the Yuma Irrigation result as a possible real shortage, not a finding.

8.8 What Shortfalls Cost

The 2022–2023 cut hit Maricopa–Stanfield in two waves. Before the season, farmers left land fallow. During the season, fields that stayed planted ran short of water in particular months. Water use per farmed acre over the year hides both waves, because farmers left enough land fallow to keep it at 3.2 to 3.4 acre-feet (Appendix S13).

Planted fields near the water sources used about as much water over the season as fields far from them. In every year of 2017–2023, planted fields in the third nearest the head used at most 8 percent more water, for their crops' need, than fields in the farthest third (Appendix Table A30). Planted fields within 1 km below a canal pump used at most 6 percent more than fields more than 3 km below one. The losses in the cut do not come from fields near the sources taking extra water. Table 7 sets the two waves side by side on the three outcomes, with what each cost.

Most of the loss came in the first wave, when land was left unplanted. Leaving that land fallow cost $8.0–12.1 million a year in returns over operating costs, 24 to 40 percent of what the district's

Table 7: The Two Waves of the 2022–2023 Cut on Three Outcomes, Maricopa–Stanfield

Outcome	Before the cut, 2017–2021	In the cut, 2022–2023	What the cut cost a year
Land left fallow (first wave)	No clear response to total stress: −6.6 percentage points (15.5) per unit	18.0 percentage points more likely per unit of total stress (7.8)	$8.0–12.1 million in returns over operating costs; about three times as much had every field stayed planted
Water use on planted fields (second wave)	A short month was offset in the season's other months; on average the season's water use did not fall: 0.5 percent (2.9)	Short months were not offset; the season's water use fell 9.3 percent (2.9)	Lost yield, priced from the fall in monthly water use: 1.2 percent of gross revenue in 2022 and 3.1 percent in 2023, planted fields without a well
Yield proxy on planted fields (second wave)	Did not fall (Appendix Table A36)	Fell 10.3 percent (5.8), less precise	Counted in the row above

Notes: Standard errors in parentheses. All rules at a take of 0.66. Land left fallow: linear probability that a field without a well, farmed the year before, is left fallow, per unit of total stress (last year's shortfall plus this year's predicted shortfall at usual demand), with year effects, estimated within 2017–2021 and within 2022–2023 (Appendix Table A22, Panel C); with field and year effects over 2017–2023 the estimate is the 18.7 of Section 8.5. Water use and yield proxy: percent change (log points times 100) in the season's water use relative to demand and in crop-season GCVI per 10 percent of the season's water lost in the model; field by crop group and crop group by year effects; all planted fields with and without a well; standard errors clustered by owner (Appendix Table A36, Panel A). Costs: Section 8.8 and Appendix Table A38.

farmland would have earned with its normal rotation (Appendix Table A38, Panel C). The model's shortfalls account for about 18 percent of the land left fallow. The rest differs mostly by crop, and cotton and corn fields were left fallow first (Appendix S14). Fallowing was the cheaper answer. Had farmers planted every field and spread the water thin, crop budgets imply a loss about three times as large.

The second wave hit the fields that stayed planted. Their average water use over the year looked normal. But their canals fell short in particular months, most of all in June and July. The season's water use fell with the shortfall (Table 7). On planted fields without a well, these shortfalls cost $0.7 million of gross revenue in 2022 and $1.1 million in 2023, 1.2 and 3.1 percent of their gross revenue (Appendix Table A38, Panel B; Appendix A18).

Would an even division of the district's water have made these losses smaller, or would it have moved them to other fields? That depends on whether an acre-foot of water is worth more on a short field than on a well-supplied one (Table 8).

Dividing the same water differently would not have reduced the first wave's loss. In these calculations, the unequal delivery caused no efficiency loss in that wave, because farmers knew their cut before planting (Section 8.5). Each farmer left land fallow to match the water coming and watered the rest as before. Sharing the canal water equally, or pooling the canal pumps, would have changed which fields went fallow, but total fallowing would have moved by fewer than 100 acres. Moving water from low-value to high-value crops, as in Rafey (2026), would raise the district's returns by 8 percent in 2022 and 13 percent in 2023. Almost all of that gain comes from moving water between crops, and little from moving water along the canals (Appendix Table A40).

In the second wave, crops were already in the ground, so how yield responds to water decides whether an even delivery helps. If yield follows a straight line in water, as FAO's response coefficients assume (Doorenbos and Kassam 1979), moving water from one field to another leaves total output unchanged. In my monthly estimates, a field's water use falls by less than 4 percent while its monthly shortfall stays below 20 percent, and it falls steeply above that (Section 8.4). The district's mean shortfall on planted fields stayed below 14 percent in every month. An even delivery of

Table 8: The Efficiency Loss Is Zero When Owners Know Their Water and Depends on the Response in the Second Wave, Maricopa–Stanfield

	Loss		Efficiency loss, percent of the loss	
	2022	2023	2022	2023
A. First wave, land left fallow: returns, $ million				
Owners knew their water before planting, as happened: any response	8.0–11.7	9.1–12.1	−3 to 2	−1 to 0
Had owners set land before knowing their water: straight line			0 to 1	0 to 12
Had owners set land before knowing their water: field-trial responses			2 to 13	7 to 31
B. Second wave, planted fields without a well: gross revenue, $ million				
Straight line	1.0	1.3	−14	−5
Field-trial responses, shortfall over the season	0.8 to 2.1	0.9 to 2.7	3 to 14	4 to 19
The district's monthly response	0.7	1.1	91	70
A second monthly response: two straight lines meeting at a shortfall of 0.20	0.8	1.2	36	51

Notes: The efficiency loss is the part of a loss that an even delivery of the same water would have saved, in percent of that loss: the same cut for every owner in the first wave, and the same shortfall on every planted field in the second wave. In Panel A, the loss is the returns over operating costs lost on land left fallow. The range of that loss spans four ways of counting and valuing the fallowed land (Appendix Table A38, Panel C). In the top row of Panel A, owners know their water before planting, land follows the water, and the efficiency loss does not depend on the response. That top row is calculated under a straight line and compares the district's division with the divisions that the canals allow. The efficiency loss there and under the straight line in Panel B differs from zero only because fields differ in crop and revenue. In the next two rows, every owner plants for the district's cut and then receives the water that reaches that owner's fields. Those two rows have no entry under Loss, because their efficiency loss is measured against the same case with the same cut for every owner. Their percent is of the first wave's loss as it happened, the top row's Loss. Their range takes the lowest efficiency loss over the highest loss and the highest over the lowest. In the top row, each percent is of the loss under the same division and the same valuation. In Panel B, each row gives the second wave's loss under that row's response and the percent of that loss that an even shortfall would have saved. I price the second wave with three responses besides the straight line. First, I use the seasonal responses from field trials of maize (Trout and DeJonge 2017) and alfalfa (Li et al. 2023), each in water consumed and in water applied. Second, my main method groups the monthly data of 2016–2021 by the size of the shortfall and joins the group averages with straight lines (the bins of Table A22, Panel A). Months with any shortfall sit about 4 percent above months with none, so I measure each group against months with a small shortfall (0.01 to 0.05). Third, I use a response in which the loss grows slowly below a shortfall of 0.20 and much faster above it (estimates in Appendix A19). I evaluate the straight lines and the field-trial responses on every crop at the water level of the district's fields before the cut, and the ranges span the functions (Appendix A19).

the same water would therefore have kept every field out of the steep part. It would have saved 91 percent of the loss on fields without a well in 2022 and 70 percent in 2023. Under responses from field trials, an even delivery would have saved 3 to 19 percent. In those trials, yield falls almost in proportion to water. What an even delivery saves therefore runs from nothing to most of the loss, depending on how yield responds to water. Appendix A19 compares the responses. Under every response, the second wave cost fields without a well $0.7 to 2.7 million a year (Table 8). The first wave's fallowing cost more in total, at $8.0 to 12.1 million a year. In the model, in July 2022 more than half of the planted fields received their full claim (Figure 9, Appendix A12), so the shortfall fell on the rest. The even delivery is a benchmark. The district could not reach it by changing its rule alone, because canal pumps cannot send water upstream (Section 8.9).

8.9 What a Remedy Would Need

Whether a remedy pays depends on the year. In the years before the cut, 2016–2021, CAP water and the district's canal pumps met nearly all demand. Filling every shortfall on fields without a well would have added $137,000 a year, 0.7 percent of their returns over operating costs (Appendix Table A37). This figure gives no credit for any extra water a field used in other months of the season, so it is an upper bound (Appendix A17). Investments do not repay their capital in such years. The gain is 3 percent of the yearly cost of a new well with pipeline (Maricopa–Stanfield Irrigation and Drainage District 2024), and lining the Upper Gila canals does not repay its capital either.

A remedy has to be judged on years like the cut, because the next cuts are already set. Interior's rules for 2027–2028 cut deliveries to the lower Colorado River states (Interior 2026; Reclamation 2026b). If Maricopa–Stanfield's CAP water stays near its 2023 level, the next cuts continue the conditions of 2023 for this district. In 2023, a new well returned 32 percent of its yearly capital cost across all fields without a well, and 58 percent in the third of fields with the largest shortfall.

A change of the district's sharing rule does not solve the problem alone. In Maricopa–Stanfield, serving fields without a well first would have moved fallowing and lost revenue onto fields with a well. It would not have reduced them, because the district pumps those fields' wells into its canals. Their water use falls at least as much for the same shortfall (Appendix A12). With CAP water gone, the district depends on its canal pumps, and a canal pump cannot send water upstream of where it enters. A remedy must bring water to the canal reaches above the pumps. Covering the model's shortfalls in the cut would have kept land farmed worth $1.3–1.5 million a year in returns, and added $1.0 to $1.4 million a year in gross revenue on planted fields. These sums are benefits only, and I do not set them against the cost of a well.

9 Conclusion

This paper asks whether farms with the same water rights share the shortage from a long drought equally. Arizona is a hard case for finding a gap, because its water rules are well developed. Water rights and contracts decide which users lose water first, and the 2022 cut in Colorado River water was carried out as the rules required. To answer the question, I trace Arizona's canals from their sources to every field and measure, for each field and month, how much water the fields upstream and downstream of it use.

Farms with the same rights do not share a shortage equally, even when the rights work as

written. Position on a canal matters where canals run short and do not rotate water, as in the CAP districts with junior rights. In the 2021 drought, fields that usually sit far down a canal were left fallow more often and used less water. Their yield proxy points the same way, but the evidence is only suggestive. The drop in water use was concentrated in fields with no backup source of groundwater: the owner has no well, and no canal pump stands within 2 kilometers above the field. Fields below a canal pump were protected by a large groundwater source, and there position did not lower water use. Where canals rotate water, and in senior-rights districts, position does not leave fields fallow or lower water use. In the CAP districts, position did not lower water use in the droughts of 2008–2015, when CAP supply was full.

Districts with monthly water records show how the gap arises. Where farmers run their own wells, the loss falls on fields without a well. Where the district pumps leased wells into its canals, the canal pumps mark which fields keep water. The fields farthest from the source of the water lost, and when the source moved, the losers moved with it. Across the CAP districts, position from the head no longer lowered water use in the cut. Maricopa–Stanfield has records of its canal pumps and wells, so I test the pumps there. In Central Arizona and Hohokam, the records leave out too much to tell: which wells ran in Central Arizona, and water that reached fields in Hohokam. In Maricopa–Stanfield, while CAP water entered at the head, among the fields that depend most on CAP water, those farther from the head used less water. By 2023, with almost no CAP water left, they no longer did. Fields without a well that the canal pumps could not supply were left fallow more often and used less water. In the cut, the canal pumps mattered mostly through which fields stayed farmed (Appendix Table A17, Panel C).

Farmers knew the cut before planting and answered first by leaving land fallow, which kept the season's water on the fields they planted near normal. This first wave caused most of the loss, \$8.0–12.1 million a year in returns over operating costs, or 24 to 40 percent of what the district's farmland would normally earn. Had every field stayed planted and shared the water, the loss would have been about three times as large. Before the cut, a planted field offset a short month with more water in the season's other months. In the cut it could not. In this second wave, the season's water use and, less precisely, the yield proxy fell with the shortfall (Table 7). Equal sharing of the same water would have changed which fields were left fallow, not how much land. The first wave cost more in total, while the second wave's loss fell on the planted fields without a well that the district's canal pumps could not reach. An even delivery would have saved most of it under my estimated monthly response, less than a fifth under field-trial responses, and nothing under a straight line. Changing the sharing rule alone cannot solve the problem in the next cuts, because canal pumps cannot send water upstream to the fields above them.

What we learn is what well-defined water rights leave open. Water rights and seasonal allotments set how much water each farm may use, and fields near water sources do not take extra water. In Maricopa–Stanfield, planted fields near the sources use at most 8 percent more water over the season than fields far from them with the same crops (Appendix Table A30). What the right does not set is when and where the canals can deliver the water. The gap comes from delivery: canals that cannot carry every field's need at peak demand, and canal pumps that reach only the fields below them. In 2022 Maricopa–Stanfield itself set each grower's allotment from their turnouts and acreage, at 1.7 to 2.8 acre-feet per acre depending on where their fields were. The district said the allotment would change with new wells, pipelines, and well runtime (Section 2).

The study also has limits. The crop measures come from satellites and are proxies for yield. I do not observe the water delivered to each field, so I cannot separate delivery schedules, losses

along the canal, and gate operations. District maps stand in for the areas each district serves. Most fields in the sample sit in the largest canal systems of one state and are observed over one main drought. The revenue figures assume a link between the satellite index and revenue, and they measure lost revenue, not lost profit or welfare.

These results matter for how shortage rules are judged. In 2022 Arizona's rules worked as written at the source. Inside the canals, farms with the same claims did not lose the same amount. Programs that pay farms to leave land fallow might consider where along the canal the fallowed land lies. In Maricopa–Stanfield, serving fields that cannot pump first would pay only if fields with wells replace the water they give up, which my estimates do not show. New wells and lined canals do not repay their cost in years without a cut. The method in this paper makes such questions possible to study. With its own water records, a district facing the 2027–2028 cuts could use it to see which fields will go short, in which months, and why. It uses only public data on canals, land elevation, and field boundaries, so it can be applied to other irrigated regions. It can also be applied to other networks that deliver a resource to users one after another, such as natural gas pipelines and electricity grids that cut supply during shortages.

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Appendix A. Supplementary Results and Model Details

Appendices A1 and A2 give the details of the delivery model of Sections 3 and 8.1. Appendices A3–A11 support Sections 7.1 and 7.2, and Appendices A12–A19 support Section 8. Appendix A20 reports the CAP curtailment schedule and the outcomes in the districts it cut.

A1 The Delivery Model: Details

The canal trees. Each tree holds the lines of the rebuilt canal network below a district's documented intakes and above its fields, with joins across roads, siphons, and pipes. Water leaves only at laterals, so a field linked to a main canal takes its water from the nearest lateral within 2 km. A field may lie at most 1 m above the canal where it takes water, at every level of evidence. Table A1 gives Maricopa–Stanfield's fields by level. Maricopa–Stanfield surrounds the Ak-Chin Indian Reservation, which is not part of the District (Maricopa–Stanfield Irrigation and Drainage District 2022c): the 38 fields on the reservation are left out of the District, and its tree does not run through the reservation's farm ditches (two links cut). Elsewhere the trees place 2,324 fields in Central Arizona, 819 of 840 in Hohokam (98 percent of demand), 851 of 865 in Harquahala (97 percent of demand), 579 in New Magma, 1,380 in San Carlos (one more than Table S4, which counts a field that two systems list once), 4,264 of 4,332 in Wellton-Mohawk, and 1,064 on the ten Upper Gila canals. Only Maricopa–Stanfield's tree has had my marks on imagery and the checks against decoys. In those checks, on images shown blind, a takeoff is visible at 11 of 29 clear turnouts (38 percent) and at 2 of 28 decoys (7 percent), points on the same laterals away from any ditch ($p = 0.006$). For the inferred intakes it is 6 of 19 against 0 of 20 ($p = 0.008$).

Table A1: Where Maricopa–Stanfield's Fields Take Water

Level of evidence	Fields	Share of demand, %
Evidence of the field's own connection		
Lateral within 30 m	442	30.5
Lateral added from Reclamation's or the district's map, within 60 m	106	6.5
Mapped ditch followed upstream for at most 3 km to a lateral, or an intake I marked	792	32.5
Ditch with no detected turnout: intake inferred within 1 km of a lateral	565	18.7
Evidence from the fields around it		
Turnout of its ditch system	91	2.7
Turnout of a touching neighbor	218	3.0
No canal evidence		
Projection onto its line, in blocks	170	2.8
Ditches reach a registered well: off the canal	17	1.2
Line off the tree: not reachable	64	2.1

Notes: 2,465 district fields; a field takes the first rule that applies, with a marked intake first, and the first seven levels place 2,384. The inferred link is the weakest: 42 percent of inferred gaps exceed 300 m. Share of 2016–2021 demand. Ditches: Pinal County's water-management layer, concrete ditches of 2 to 5 feet, read for direction from the local terrain. The canal search runs before any well label, so a well never cancels a visible canal.

Water. The placed fields receive the district's water in the month times their share of its demand, and that water, times e, enters at the head of the tree. In the CAP districts the water is Agricultural Settlement Pool and agricultural in-lieu water from CAP's delivery reports. New Magma's is in-lieu water, 96 to 98 percent of its farm deliveries in 2016–2022 and 86 percent in 2023. In Wellton-Mohawk and the Yuma districts it is the diversion in Table 4 of Reclamation's decree accounting, and every year's months sum to the printed totals. In San Carlos it is the decree's split of the project's gravity diversion at Ashurst-Hayden: stored water equally per decreed acre,

natural flow by Article VI(3) on the month's mean flow, and Agricultural Settlement Pool water at the root. The split comes to 0.43 to 0.48 of the project. The project's wells and private wells are not in that series. The Upper Gila's water comes in Appendix A2.

The allocation. Let a point v of the tree receive a flow F_v, with claims c_v from its own fields and claims b_v on the branches below. Its fields take $o_v = G_\kappa(F_v;\, c_v,\, b_v)$ (equation (2)), and their delivered share is $\min(1, o_v/c_v)$, or 1 when $c_v = 0$. A field with no demand of its own keeps its point's share. The rest, $R_v = F_v - o_v$, goes to the branches. At a side line with claims N_s and a continuing line with claims N_c, the side line takes $R_v N_s/(N_s + N_c)$ when $R_v \geq N_s + N_c$ and $G_{\kappa_J}(R_v;\, N_s,\, N_c)$ (equation (2)) otherwise; the continuing line takes what remains. At other branch points each branch takes a share by its claims. A claim on a branch is net of any pumped water that enters inside the branch. Where a district has canal pumps, the model runs in two steps. In the first, only pumped water flows, at $\kappa = \kappa_J = 0$, and a point's claims are met by a share s_v. In the second, the main supply flows under the rule over the claims still unmet, $c_v(1-s_v)$, and meets a share m_v of them. The delivered share is $r_v = s_v + (1 - s_v)\, m_v$. In districts with a separate water record for each canal, each canal's water enters at its own root.

Canal pumps. The 144 canal pumps of Maricopa–Stanfield are the district wells that pumped in 2019 and feed the district's network: 87 have a feed point on a canal or pipeline (74 of these also reach fields by ditch), and 57 reach placed fields only by ditch. They pumped 115,848 acre-feet in 2019, 92.4 percent of the district wells' 2019 water, and have a capacity of 502.6 cubic feet per second; the 38 unrated pumps take a capacity from their 2019 volume at the median use of rated canal pumps. Each pump stands at a wellhead seen on NAIP imagery (127) or at the district map's symbol (17) and feeds every canal, pipeline, or ditch within 100 m of that point. A canal or pipeline feed enters the tree at the first point at or below it on the line; where lines meet within 50 m of a pump, the pump is moved to the meeting point, and a point below another point of the same pump is dropped. A ditch feed reaches the placed fields its ditches reach that lie no higher than the pump's ground, plus a small allowance; pumps whose ditches overlap reach the fields of the pumps that stand no higher. A pump's capacity and its 2019 volume are split over its points by the 2016–2021 need below each point. In each year the canal pumps pump their share of the district's reported well water. The months follow the canal claims at the head, net of CAP, up to a share α_y of capacity, set so that the year sums to that share; a year whose need falls below it pumps the need. Within a month the pumps fill the claims below them from the bottom of the tree up. Each pumps the least of its capacity, λ times its 2019 volume, and the claims below it that pumps further down do not cover, with λ set so that the month's total is pumped. Water that no claim below a pump can take is not pumped. As local pumps, 10 district wells that pumped in 2019 but feed no canal, pipeline, or ditch, and 139 private wells, serve their owners' fields; the map's 174 inventory wells, which did not pump in 2019, stay out. Monthly pumping by pump is not observed.

Local pumps. Maricopa–Stanfield has 149 local pumps: 10 district wells that pumped in 2019 but feed no canal, pipeline, or ditch, and 139 private wells rated at 100 gallons per minute or more. A local pump serves the field it sits on, or the nearest within 200 m, and the owner's fields it can physically reach: on its ditch system and not above the well by more than 1 m, or within 400 m if the well is not on a ditch. Local pumps serve 369 of the 2,384 placed fields. In the other districts a well rated at 100 gallons per minute or more serves all its owner's fields, at any distance: 720 of 1,064 placed fields in the Upper Gila, 417 of 1,380 in San Carlos, 100 of 579 in New Magma, and 1,207 of 4,264 in Wellton-Mohawk. The water record bounds the take. The district wells that

feed no canal pump $1 - 0.924$ of the district's reported well water; that water, times e and times the placed fields' share of the district's demand, covers part of the need of the fields with a local pump, which claim the rest from the canal. So $\tau \leq 1 - e \times$ (that water)/(their need), which is 0.82 to 0.86 in the years 2016–2021 and 0.84 over the six years. Private wells have no record, so this is an upper bound.

Demand. A field's monthly irrigation demand is its acres times $\max(0, \widetilde{K}_{it}\,\mathrm{ETo}_{it} - P^e_{it})$, with the locally calibrated crop coefficient $\widetilde{K}_{it} = c_{gm}K_{it}$ (equation (10)). K_{it} is the FAO-56 crop coefficient on the field's crop calendar: the timing of its crop in the 2017–2019 Sentinel-2 imagery, with the FAO-56 stage lengths between onset and harvest and alfalfa's summer dormancy. Crops without a calendar, about 5 percent of field-years, take the mean coefficient of the district's calendar crops in that month. ETo_{it} is gridMET reference evapotranspiration in the field's 4 km cell, scaled each month to the Penman–Monteith value at the AZMET station nearest the district. P^e_{it} is effective rain, $0.6P - 10$ millimeters for monthly rain P up to 70 and $0.8P - 24$ above, and zero when negative. The calibration factor is

$$c_{gm} \;=\; \frac{\sum A_i\,\mathrm{ET}_{it}}{\sum A_i\,K_{it}\,\mathrm{ETo}_{it}},$$

where ET_{it} is the field's OpenET consumption and the sums run over the farmed field-months of crop group g in calendar month m of 2017–2019, the years of the Sentinel-2 calendars, within the region (Maricopa–Stanfield, Central Arizona, Hohokam, and Harquahala together, or five Upper Gila canals). In those CAP districts each factor rests on 201 (sorghum) to 6,639 (alfalfa) field-years; Upper Gila crop groups with fewer than 50 field-years (corn, other hay, small grains) take the factor of both regions together. A fallow field demands nothing. New Magma, San Carlos, Wellton-Mohawk, and the Yuma districts take the CAP region's factors, and the Upper Gila's added canals those of the first five, with no estimation on their own fields. Demand over OpenET less rain comes to 0.93–1.03 by year in Wellton-Mohawk, 0.79–1.02 in Yuma County Water Users, 1.02–1.31 in Yuma Mesa, 0.84–1.05 in Yuma Irrigation, 0.91–1.15 in New Magma, and 0.95–1.13 in San Carlos.

Irrigation efficiency. Demand is crop consumption, so a field must receive $1/e$ acre-feet at its turnout for each acre-foot its crops consume. I take each district's e from its water balance: the ET of its farmed fields net of the ET met by effective rain (OpenET, all twelve months), over all the water applied, surface water at the turnouts plus groundwater as the district or the state reports it, over 2017–2019, the years of the crop-coefficient calibration, rounded to two decimals. The ratio is 0.72 in Maricopa–Stanfield (0.71 to 0.75 by year; district wells only, so private pumping is missing and the ratio is an upper bound), 0.73 in Central Arizona (2017, the only year with its district-well total), and 0.75 in Hohokam (private wells, from the state's annual water-use reports). Harquahala has no measured pumping in those years (its modeled pumping gives 0.60 in 2020), so it takes the pooled value of the other three, 0.73. Little of the rest is canal loss: CAP's recorded deliveries to Maricopa–Stanfield exceed the district's own delivery figures by 3.5 to 5.5 percent a year (Maricopa–Stanfield Irrigation and Drainage District 2024). The districts added later take 0.70. In New Magma, OpenET less rain is about 0.85 of the water in 2016–2021, so 0.70 likely overstates its shortage in those years. In Yuma Mesa and Yuma Irrigation, consumptive use over diversions in Reclamation's accounting is 0.52–0.70 and 0.53–0.56 (Appendix A15).

Owners. Owners come from the 2025 CoreLogic tax roll. A field takes the owner of the largest parcel whose point lies inside it, or else of the nearest parcel point within 800 m. I keep only integer

identifiers. The owner of record in 2025 stands in for the operator in 2016–2023.

The estimating equation. In equation (11), k, m, and y are the field's crop, the calendar month, and the year of month t. The shortfall is a prediction of the model, not a regression estimate: the model computes it from deliveries, demand, and the network before the ET regression is run, and that regression takes it as data. The shortfall, not the share, enters so that a larger value means less water, as a larger upstream demand does in Sections 7.1 and 7.2. The district's shortage is $S_t = 1 - \min\big(1,\, e \times \text{water}_t / D_t\big)$, where D_t is the month's crop demand. It counts the main supply and any district well water, and it takes one value a month for a district, or for the whole valley in the Upper Gila. It holds what fields without a well share in a month, so that β_0 rests on how shortfalls differ among fields. The controls X_{it} are the 3- and 24-month drought indices (SPEI), each with its own coefficient in each calendar month. The sample is the farmed field-months of March to October on the tree. β_1 should be closer to zero than β_0 if a field's own well replaces the water, since groundwater caps the crop cost of a shortfall. Field by crop by month effects remove each field's usual water use in each month of its crop's season. Field by year effects remove what changes for the field from year to year: its planting, its allotment, and its pumping. Crop by year by month effects remove what a crop's fields share in a month, such as heat and prices. What remains is how a field's shortfall moves against its own usual months as the month's water and the demand upstream change. I leave out owner effects. An owner's fields sit together on a canal, so their position differs little, and comparing them removes the variation the design uses. A zero within owners would say nothing about delivery. The shortfall moves with demand as well as with supply: with the month's water, and with the crops grown upstream and at the field. Weather moves demand, but weather that raises demand raises the shortfall and raises water use at the same time, so it biases β_0 toward zero.

The search. The bar allows for the size of the search. For each year in turn I fit the fixed effects and coefficients on the other years. The prediction for the year left out carries the field by crop by month effects of those years; its own field by year and crop by year-month effects are then removed. The search uses a compressed version of the score, and I score the best 200 cells exactly. The score is blind to sign, so a cell can clear the bar with a slope of the wrong sign, and I report each with its slope. The score covers all fields of a district, so it tests prediction across the district and not the slope of one group. The test of a named rule uses a coarser grid, with rules in steps of 0.1 and takes from 0.50 to 0.90. A rule stays in the set when the gain of that grid's best cell over it is below the 95th percentile of that gain in sign-flip draws around the rule's own fit. The best cell can rest on chance, so the main estimate picks no single rule. It averages the shortfall over all 2,601 rules at the district's best take, so no rule is picked on water use.

Shuffles. Each draw reruns all 2,601 rules at the district's take, with 1,000 draws of each kind. The one-sided p-value is $(1+\#\{b : \hat{\beta}_0^{(b)} \le \hat{\beta}_0\})/(1+B)$ over $B = 1{,}000$ draws. *Dates:* each calendar month's water moves across the sample's years, and S_t and pumping follow. *Fields:* placed fields move to other fields' points on the tree, each with its own demand and well status; pumps are redispatched and S_t stays real. *Owners:* the tree's attachment points are listed in order along the tree, owners are put in random order and laid end to end along that list, and each keeps its fields' real order from upstream to downstream. Everything else is as for fields. Moving fields one by one scatters an owner's fields, so the draws are too narrow (their standard deviation is 0.33 of the clustered standard error in Maricopa–Stanfield); moving owners gives 0.52. A faster version of the code reproduces the live code's scores and coefficients on the real data and on draws recomputed afterwards. The shuffles hold the take fixed, so they allow for the search over rules but not over

takes; the sign-flip bar allows for both. Randomization asks whether the model's inputs could produce $\hat{\beta}_0$ on their own. I prefer the owner shuffle to the field shuffle, because moving fields one by one makes the draws too narrow. The CAP districts deliver on order. Within a calendar month, Maricopa–Stanfield's CAP moves with the demand the model computes (correlation 0.63 over the 48 month-years), so a month's shortfall can fall because growers irrigated, not only because CAP arrived. The randomizations do not separate a shortage of supply from a pattern of orders.

The cut and fallowing. Farmers decide before the season which fields to plant (Appendix S12), so the 2022–2023 cut gets an annual design. I hold each field's demand at its 2016–2021 calendar-month mean, so that only water moves the shortfall. A field's predicted rise is its demand-weighted mean shortfall in 2022–2023 minus that in 2016–2021, averaged over all rules at the take. I regress the change in a field's outcome, 2022–2023 against 2016–2021, on its predicted rise, its alfalfa share in 2016–2021, its log acres, and its kilometers from the head. The outcomes are water use and the farmed share. The same regression of 2020–2021 against 2016–2019 gives the earlier contrast. I stack the two and report the difference, per standard deviation of the predicted rise, with standard errors clustered by owner. The Upper Gila had no 2022 cut, so there I report 2022–2023 against 2016–2021. Growers know the year's delivery before they decide what to fallow, and they can read this year against last year. A field's total stress therefore adds two shares of its own year's demand: the share left short last year, at the demand it had, and the share predicted short this year, at its usual demand. A month with no demand of its own adds nothing, and the sum runs from 0 to 2. I regress fallowing, times 100, on total stress among fields farmed the year before, 2017–2023. One version has year effects and the controls above, and one has field and year effects. Standard errors are clustered by owner.

A2 The Upper Gila Model

Rules. The Globe Equity Decree of 1935 lets a canal pool its rights and rotate deliveries among its fields, at 1 cubic foot per second per 80 acres. The decree does not regulate pumping. The later settlement meters the wells and lets decreed land take at most 6 acre-feet per acre a year of river and well water combined. The Gila Valley Irrigation District's wells give 53 to 66 percent of its farm water, 69,000 to 86,000 acre-feet a year. Some pumps feed the canals, but no record says which. The registry's owner field matches 125 live wells near the canals to a canal company or the district, about 182 cubic feet per second, and they stay local in the model.

Canals and water. The model has ten canals: San Jose, Montezuma, Union, Graham, Fort Thomas, Brown, Fourness, Smithville, Dodge-Nevada, and Curtis. Colvin-Jones took no water in any month of 2016–2023. Monthly diversions come from the Gila Water Commissioner's annual plates, read from scans and checked against the plates' own totals. The canals match the valley total within 1 acre-foot in 80 of 96 months. Brown and Smithville have one split each, so κ_J has an effect only there. The river version takes the flow at the Solomon gage (USGS 09448500) and passes it down the decree's list of rights by canal and priority year. Over March–October the list gives 54,859 to 84,006 acre-feet a year, against 36,415 to 62,588 reported. An upstream-first version beside it lets each diversion, in river order, take its fields' need at the head. Table A2 compares the versions with reported diversions before any data on water use. The decree on the river comes closest, and equal water per acre next; upstream first is furthest, though it omits return flows from the upper canals.

Search and slopes. Table A3 gives the search on each supply. On reported diversions the best

Table A2: Dividing the River Among the Upper Gila Canals, Against Reported Diversions

	All months		Short months	
Rule across canals	Error, AF	Correlation	Error, AF	Correlation
Decree on the river	149.7	0.949	113.7	0.933
Equal per acre	169.9	0.937	147.5	0.896
Upstream first, up to need	202.0	0.891	152.2	0.884
Upstream first, up to the full right	227.7	0.895	199.9	0.856

Notes: Each rule gives a canal's share of the month's reported valley water. Error: mean absolute error per canal-month. 572 canal-months in 52 months, March–October 2016–2023. Short months: valley water below the same calendar month's 2016–2023 mean (275 canal-months).

cell clears the bar and has the right sign, and it is equal sharing, at 60.98 against 28.18 for upstream first along a line at a take of 1.00 (41.34 and 20.18 at 0.70). Almost all the variation in a field's delivered share is between canals: only 0.01 percent of its variance lies inside a canal and month under equal sharing, so a field's canal carries the result. On the river no cell clears the bar. At equal sharing and a take of 1.00 the decree on the river gives −6.04 without a well (standard error 4.70) and −5.01 with one (3.49), the right sign at about half the size of reported diversions, and I cannot tell.

Table A3: The Upper Gila: Search and Slopes by Supply, March–October 2016–2023

Supply	Best	Bar	Take, κ, κ_J	All rules, no well	All rules, with a well
Reported diversions, ten canals	60.98	9.68	1.00, 0, 0	−6.86 (2.19)	−6.39 (1.52)
Decree on the river, ten canals	−3.95	11.71	0.64, 1.00, 0.92	−1.57 (2.54)	−0.94 (2.14)
Upstream first on the river, ten canals	−1.16	8.10	0, 0.72, 1.00	1.86 (2.73)	−0.11 (2.66)

Notes: Best and bar: held-out gain in fit, in basis points, over 200 sign-flip draws. Slopes at a take of 1.00: 100 times log monthly ET per unit of the shortfall; standard errors clustered by owner and by year-month. 45,224 field-months of 980 fields of 320 owners on ten canals; 310 fields without a well. At the best rule on reported diversions the slopes are −11.44 (3.01) and −10.18 (2.01). S_t times no well alone: −3.52 (1.95) on reported diversions.

The annual design and pumping. The Upper Gila had no 2022 cut: reported water averages 45,085 acre-feet in 2022–2023 and 46,245 in 2016–2021, and on the river 2022 is the wettest of the eight years. So the design asks which canals gained or lost against their own 2016–2021. Table A4 gives the estimates. On the river, fields without a well lose water and farmed land where the river gives least, and fields with a well do not move; no orders enter these numbers. Reported diversions show nothing in this design. The Gila's dry time is July–September of 2019, 2020, and 2023. In those three summers the canals ran lowest and the Gila Valley district pumped most, 47,000 to 56,000 acre-feet against 18,000 to 31,000 in the others. Fields without a well then fallowed more than fields with one, by 9.6 points against 3.3. Those are eight points, descriptive, and owners with wells may differ in other ways. Fallowing on total stress has the right sign on reported diversions, 10.9 (standard error 6.4) without a well and 13.8 (3.6) with one, and most of it comes from this year's water, where a canal that fallows also diverts less. On the river it is 1.5 (5.4) and 2.1 (4.8), and I cannot tell.

A3 Larger Distance Cuts

I repeat equations (7) and (8) with each irrigation district's distance cut raised to at least 2, 4, 5, 6, 8, and 10 km: a field counts upstream or downstream only beyond both its district's cut and that distance. Tables A5 and A6 report the estimates. Each cut changes which fields count on each side and which fields enter the sample. The water sample falls from 24,104 fields at the district's

Table A4: The Upper Gila: 2022–2023 Against 2016–2021, Per Standard Deviation of the Predicted Rise

	No well		With a well		No well minus well	
Supply	Water use	Farmed	Water use	Farmed	Water use	Farmed
River, decree	−1.9 (1.8)	−6.6 (1.5)	−0.7 (1.4)	−1.3 (1.5)	−2.0 (2.2)	−5.8 (2.1)
River, upstream first	−3.8 (1.7)	−4.5 (1.6)	−0.3 (1.3)	−0.2 (1.5)	−3.2 (2.0)	−4.2 (2.1)
Reported diversions	4.3 (2.4)	0.5 (1.9)	1.5 (1.6)	0.5 (1.1)	4.6 (2.4)	1.7 (2.0)

Notes: All rules at a take of 1.00; fixed 2016–2021 demand; each canal's actual water at its root; owner clusters. 1,064 fields, 344 without a well; 339 and 710 in the design. Before, 2020–2021 against 2016–2019, no well: decree water use 1.8 (1.8), farmed −1.2 (2.1); upstream first 0.3 (1.9), −1.7 (2.0).

cut to 10,739 at 10 km, and in the CAP districts with junior rights from 5,410 to 1,761.

In water use, position lowers water relative to the crop's need in drought at every cut in the CAP districts with junior rights. The estimate lies between −0.009 and −0.015, with $p < 0.02$, up to 6 km. It is −0.006 ($p = 0.13$) at 8 km and −0.007 ($p = 0.24$) at 10 km. In the Upper Gila, position is positive up to 6 km and near zero beyond. Over all fields it is near zero at every cut. In senior-rights districts it has $p < 0.10$ at two cuts, with opposite signs: −0.005 at 5 km and +0.017 at 10 km.

Table A6 uses the peak of GCVI over the crop year and adds the fields outside the irrigation-district polygons. On that peak, the usual position lowers the proxy in drought in the CAP districts with junior rights at the district's cut and at 4 km (−0.018 and −0.013, $p < 0.05$). Beyond, it moves toward zero: −0.010 ($p = 0.15$) at 6 km and +0.001 at 10 km. This year's change in position is −0.060 ($p = 0.005$) at the district's cut, near zero at 4 and 5 km, and positive from 6 km on (+0.034, +0.034, and +0.085, on 4,640 to 1,857 fields). At 4 km, 5,443 of 5,629 fields remain and the usual position holds (−0.013, $p < 0.01$), so a change of sample is not why this year's change fades. Held on the same 1,857 fields at every cut, this year's change stays negative to 5 km (−0.046 to −0.071) and turns positive from 6 km. On those fields the usual position holds to 6 km (−0.017 to −0.025, $p \leq 0.04$) and is near zero at 8 and 10 km. So the turn at wider cuts comes from counting only farther fields, not from the smaller sample. On crop-season GCVI, the proxy of Table 5, the usual position also holds to 6 km (−0.021, standard error 0.006) and turns positive only at 10 km (+0.030, $p = 0.08$). This year's change fades by 4 km (−0.006), as on the peak. Table A6 adds both sets of rows. In senior-rights districts from 6 km on, this year's change in position and this year's change in canal total take large estimates of opposite sign. Few senior fields have fields more than 6 km downstream of them. The two changes move almost together there, so the model cannot separate them. At 10 km the first-stage F falls to 14, and the table does not report the estimates.

Table A5: Water Use at Larger Distance Cuts, by Group

Cut, km	Fields	First-stage F	Position × drought	Canal total × drought
All fields				
District's cut	24,104	3,830	0.0010 (0.0014)	−0.0001 (0.0018)
2	24,093	4,006	−0.0014 (0.0014)	−0.0001 (0.0018)
4	22,374	4,296	0.0007 (0.0015)	−0.0004 (0.0017)
5	20,215	3,625	−0.0002 (0.0015)	0.0019 (0.0019)
6	18,079	3,744	−0.0010 (0.0015)	−0.0036* (0.0020)
8	14,468	2,667	0.0002 (0.0018)	−0.0064*** (0.0022)
10	10,739	1,696	0.0029 (0.0025)	−0.0054** (0.0027)
CAP, junior rights				
District's cut	5,410	3,686	−0.0111*** (0.0028)	0.0052* (0.0029)
2	5,410	3,686	−0.0111*** (0.0028)	0.0052* (0.0029)
4	5,240	3,097	−0.0091*** (0.0031)	−0.0021 (0.0028)
5	4,977	3,275	−0.0087** (0.0035)	−0.0046 (0.0029)
6	4,456	3,876	−0.0152*** (0.0033)	−0.0078** (0.0035)
8	3,234	2,154	−0.0064 (0.0042)	−0.0000 (0.0040)
10	1,761	1,604	−0.0066 (0.0056)	0.0022 (0.0065)
Upper Gila				
District's cut	875	680	0.0101** (0.0039)	−0.0098 (0.0068)
2	875	680	0.0101** (0.0039)	−0.0098 (0.0068)
4	873	732	0.0082** (0.0035)	−0.0071 (0.0065)
5	859	596	0.0155*** (0.0045)	−0.0087 (0.0068)
6	799	469	0.0126*** (0.0047)	0.0001 (0.0071)
8	702	548	0.0033 (0.0046)	−0.0029 (0.0057)
10	572	503	0.0015 (0.0054)	−0.0083 (0.0066)
Senior rights				
District's cut	9,598	501	0.0026 (0.0026)	0.0011 (0.0034)
2	9,587	553	−0.0037 (0.0028)	0.0008 (0.0031)
4	8,742	441	0.0004 (0.0027)	0.0041 (0.0027)
5	7,442	294	−0.0051* (0.0030)	0.0150*** (0.0035)
6	6,336	179	−0.0015 (0.0030)	0.0075* (0.0039)
8	4,837	162	−0.0014 (0.0048)	0.0014 (0.0058)
10	3,698	186	0.0169** (0.0072)	−0.0178*** (0.0066)

Notes: Equation (7) as in Table 5, Panel A: water use relative to the crop's need, the months of the field's crop, crop years 2019–2023, 2SLS. Cut: each irrigation district's distance cut, or the stated distance where it is larger. Fields: fields with upstream or downstream fields beyond the cut. First-stage F: the smallest cluster-robust Wald F of the excluded instruments across the instrumented terms. Standard errors in parentheses, two-way clustering by field and by crop by year by month. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

Table A6: Yield Proxy at Larger Distance Cuts, by Group

			Position × drought		Canal total × drought	
Cut, km	Fields	First-stage F	Change	Usual	Change	Usual
All fields						
District's cut	26,005	1,166	−0.016 (0.020)	−0.003 (0.003)	−0.010 (0.018)	0.002 (0.004)
2	25,994	875	−0.019 (0.017)	−0.007** (0.003)	−0.013 (0.016)	0.004 (0.004)
4	24,153	1,372	0.008 (0.009)	−0.004 (0.003)	0.008 (0.009)	−0.001 (0.003)
5	21,877	1,882	0.010 (0.012)	−0.001 (0.003)	0.002 (0.012)	0.005* (0.003)
6	19,637	2,213	0.014 (0.012)	−0.004 (0.002)	−0.003 (0.012)	0.000 (0.003)
8	15,748	1,257	0.011 (0.014)	0.004 (0.003)	0.009 (0.014)	0.002 (0.003)
10	11,896	1,099	0.015 (0.019)	0.009** (0.004)	0.011 (0.019)	−0.001 (0.004)
CAP, junior rights						
District's cut	5,629	1,391	−0.060*** (0.021)	−0.018** (0.007)	−0.017 (0.021)	0.002 (0.008)
2	5,629	1,393	−0.059*** (0.021)	−0.018** (0.007)	−0.018 (0.021)	0.003 (0.008)
4	5,443	832	−0.006 (0.014)	−0.013*** (0.005)	0.032** (0.015)	−0.001 (0.007)
5	5,170	4,316	0.001 (0.019)	−0.005 (0.006)	0.014 (0.018)	0.003 (0.006)
6	4,640	809	0.034* (0.017)	−0.010 (0.007)	0.040** (0.016)	−0.000 (0.007)
8	3,332	1,532	0.034 (0.026)	−0.004 (0.010)	0.049** (0.022)	0.013* (0.007)
10	1,857	1,256	0.085** (0.036)	0.001 (0.009)	0.034 (0.029)	0.016* (0.008)
CAP, junior rights: crop-season GCVI (Table 5's proxy), fields inside the polygons						
District's cut	5,626	1,572	−0.046** (0.022)	−0.023** (0.010)	0.014 (0.022)	0.007 (0.006)
2	5,626	1,577	−0.046** (0.022)	−0.022** (0.010)	0.015 (0.022)	0.007 (0.006)
4	5,440	833	−0.006 (0.018)	−0.017*** (0.006)	0.046** (0.023)	−0.005 (0.006)
5	5,167	4,210	0.000 (0.023)	−0.010 (0.006)	0.025 (0.031)	0.001 (0.007)
6	4,638	785	0.034 (0.024)	−0.021*** (0.006)	0.054** (0.025)	−0.007 (0.007)
8	3,330	1,533	−0.002 (0.027)	−0.013 (0.009)	0.050 (0.039)	0.001 (0.006)
10	1,855	1,242	0.150*** (0.048)	0.030* (0.017)	0.046 (0.033)	0.023* (0.014)
CAP, junior rights: the 1,857 fields of the 10 km sample, held at every cut						
District's cut	1,857	826	−0.071** (0.028)	−0.018** (0.008)	0.120*** (0.037)	0.005 (0.009)
2	1,857	851	−0.068** (0.028)	−0.017** (0.008)	0.116*** (0.037)	0.006 (0.009)
4	1,857	986	−0.046 (0.029)	−0.023*** (0.007)	0.059* (0.030)	0.002 (0.008)
5	1,857	1,106	−0.060* (0.034)	−0.021*** (0.007)	−0.056* (0.029)	0.005 (0.008)
6	1,857	570	0.016 (0.029)	−0.025** (0.010)	0.006 (0.026)	−0.001 (0.009)
8	1,857	409	0.045 (0.091)	−0.002 (0.014)	0.007 (0.065)	0.022* (0.011)
10	1,857	1,256	0.085** (0.036)	0.001 (0.009)	0.034 (0.029)	0.016* (0.008)
Upper Gila						
District's cut	1,000	866	0.024 (0.054)	−0.017 (0.011)	−0.024 (0.049)	0.053*** (0.014)
2	1,000	853	0.026 (0.053)	−0.018 (0.011)	−0.019 (0.047)	0.051*** (0.015)
4	1,000	1,278	0.056 (0.035)	−0.002 (0.008)	0.023 (0.041)	0.044*** (0.016)
5	988	1,542	0.084* (0.043)	−0.007 (0.007)	0.029 (0.049)	0.050*** (0.016)
6	920	700	0.122*** (0.041)	−0.012 (0.009)	0.067 (0.051)	0.037*** (0.013)
8	816	2,150	0.125*** (0.039)	−0.028** (0.013)	0.086* (0.050)	0.040*** (0.012)
10	665	1,689	0.078 (0.057)	−0.008 (0.012)	0.100* (0.053)	0.033** (0.015)
Senior rights						
District's cut	10,157	161	0.070 (0.057)	0.002 (0.003)	0.081 (0.065)	−0.003 (0.005)
2	10,146	251	0.027 (0.033)	−0.003 (0.004)	0.053 (0.037)	0.003 (0.004)
4	9,243	215	0.001 (0.024)	0.003 (0.004)	0.026 (0.021)	0.001 (0.004)
5	7,879	137	0.034 (0.031)	0.001 (0.007)	0.020 (0.029)	0.007 (0.005)
6	6,711	53	0.086 (0.053)	−0.001 (0.005)	−0.025 (0.053)	−0.001 (0.006)
8	5,141	32	0.065 (0.071)	0.004 (0.008)	−0.043 (0.084)	−0.001 (0.009)
10	3,960	14	*first-stage F below 20; not reported*			

Notes: Equation (8) on the peak of GCVI over the crop year, with the fields outside the irrigation-district polygons (Appendix A6), crop years 2019–2023. The two added CAP panels: crop-season GCVI on the fields inside the polygons, the sample and proxy of Table 5, Panel B, at each cut. Then the peak of GCVI on the 1,857 fields of the 10 km sample, held at every cut. Change: this year's value minus the field's 2017–2018 mean; usual: the 2017–2018 mean. 2SLS: instrumented by predicted demand, split the same way. Cut and first-stage F as in Table A5; a row whose first-stage F is below 20 is not reported. In the rows of 2 to 10 km, the nearby fallow shares are those within that distance. Standard errors in parentheses, two-way clustering by field and by crop by year. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

A4 One Model, Written Three Ways

Any two of upstream demand U, downstream demand D, the canal total $U + D$, and position $U - D$ hold the same information. 2SLS does not change when I rewrite the regressors and the instruments the same way. Let the drought coefficients be a on U and b on D. The coefficient on U at a fixed total is $a - b$. The position coefficient is $(a - b)/2$, and the canal-total coefficient is $(a + b)/2$. Table A7 reports the fit with U and D and the fit with position and canal total, at each district's cut. The position and canal-total columns equal $(a - b)/2$ and $(a + b)/2$ of the first fit to 10^{-10}.

Table A7: Water Use: One Model Written Three Ways

	U and D		U at a fixed total	Position and total	
	U	D	U (with $U + D$)	$U - D$	$U + D$
All fields	0.0009 (0.0023)	−0.0011 (0.0023)	0.0021 (0.0028)	0.0010 (0.0014)	−0.0001 (0.0018)
CAP, junior rights	−0.0059 (0.0043)	0.0162*** (0.0038)	−0.0221*** (0.0056)	−0.0111*** (0.0028)	0.0052* (0.0029)
Upper Gila	0.0003 (0.0071)	−0.0199** (0.0085)	0.0202*** (0.0078)	0.0101** (0.0039)	−0.0098 (0.0068)
Senior rights	0.0036 (0.0041)	−0.0015 (0.0045)	0.0052 (0.0051)	0.0026 (0.0026)	0.0011 (0.0034)

Notes: Equation (7) as in Table 5, Panel A, 2SLS, drought terms. U and D: upstream and downstream demand in one model. U at a fixed total: $a - b$ from that model, the coefficient on U when the model is written with U and $U + D$; its standard error from the model's covariance. Standard errors in parentheses, two-way clustering by field and by crop by year by month. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

A5 Fields With and Without Their Own Well

A field with an irrigation well of its own can pump when the canal falls short. I estimate equation (8) separately for fields with and without one, on the peak of GCVI over the crop year (Table A8). A field has its own well when a registered well of the Arizona Department of Water Resources lies inside the field. The well must be non-exempt and not cancelled. It must have a casing of at least 8 inches. Six percent of fields have their own well. Appendix A8 splits these estimates into 2021 and 2022–2023.

Table A8: Yield Proxy on Fields With and Without Their Own Well

			Change in position × drought		Change in total	Usual position
	Fields	First-stage F	2SLS	OLS	× drought	× drought
All fields						
All	26,005	1,166	−0.016	−0.019	−0.010	−0.003
No irrigation well on the field	24,523	1,120	−0.015	−0.018	−0.010	−0.002
Irrigation well on the field	1,482	1,086	−0.014	−0.016	−0.012	−0.017***
CAP, junior rights						
All	5,629	1,391	−0.060***	−0.063***	−0.017	−0.018**
No irrigation well on the field	4,956	1,242	−0.061***	−0.065***	−0.017	−0.017**
Irrigation well on the field	673	822	−0.041	−0.041	−0.020	−0.023***
Senior rights						
All	10,157	161	0.070	0.027	0.081	0.002
No irrigation well on the field	9,924	158	0.071	0.029	0.080	0.002
Irrigation well on the field	233	9	−0.312	−0.397*	0.203	0.006

Notes: Equation (8), each district's distance cut, 2SLS except the OLS column; each row is estimated separately, and no test of the difference between rows is reported. For senior fields with a well (233 fields), the first-stage F is only 9. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

A6 The Yield Proxy Under Other Measures

The main text pools all crops with one measure, crop-season GCVI on Sentinel-2, with demand summed over November–September. Table A9 reports the estimate under other measures. The

main text's estimate is column (3) in the first row of Panels B and C. Panel A adds the fields outside the irrigation-district polygons, which have only peak GCVI. Panels B and C use fields inside the irrigation-district polygons, because only those have the five-day curves that crop-season GCVI needs. Reservation fields lie outside every polygon. Columns (1) and (2) use peak GCVI, on Sentinel-2 and on Landsat 7. Columns (3) and (4) use crop-season GCVI, on Sentinel-2 and on Landsat 7, from curves with clouds and spikes removed.

The proxies are set by what forms each crop's yield. Alfalfa is cut seven to ten times a year here, and the number of peaks on a five-day curve does not count the cuts, so I use its mean over the crop year. Cotton's index tracks lint at peak bloom and not at cut-out (Gutierrez et al. 2012), so I use its mean from July 14 to September 27. Barley and the wheats head in March and April and take their last water in late April and May, so I use their mean from February 1 to May 20; in Graham and Greenlee counties, February 15 to June 5. Rye, oats, and triticale use the maximum from February 1 to May 15. Corn and sorghum use the April–October maximum. Double crops use the sum of the peak in each crop's months. Other crops use their maximum over their own months.

Demand is summed over November–September, as in the main text, or over the crop's months, from planting to the end of its proxy's window: hay all year, cotton April–September, corn March–July, sorghum May–October, and small grains November–May (December–June in Graham and Greenlee). The usual level uses the same months in 2017–2018.

In the CAP districts with junior rights (Panel C, inside the polygons), every measure falls with this year's change in position. Peak GCVI over November–September gives -0.060 ($p = 0.004$) on Sentinel-2 and -0.036 ($p = 0.002$) on Landsat 7. On the crop's months it gives -0.058 ($p = 0.002$) and -0.030 ($p = 0.006$). Crop-season GCVI gives -0.046 and -0.045 on Sentinel-2 ($p = 0.039$ and $p = 0.033$) and -0.028 and -0.026 on Landsat 7 ($p = 0.14$ and $p = 0.12$). Without the 1 percent of fields with the most variation in this term, the estimates keep their sign, from -0.029 to -0.008, and lose precision. Appendix A8 splits these estimates into 2021 and 2022–2023.

Over all fields (Panels A and B), no measure falls with this year's change in position in drought. With the fields outside the polygons (Panel A), peak GCVI gives -0.016 ($p = 0.43$) on Sentinel-2 and $+0.006$ ($p = 0.68$) on Landsat 7, and every row of Panel B lies between -0.025 and $+0.097$. Comparing a field with itself within a crop group, or keeping only fields that stay in one crop group, gives positive estimates. The loss in the yield proxy is a loss in the CAP districts, as in Table 5.

Table A9: The Yield Proxy Under Other Measures

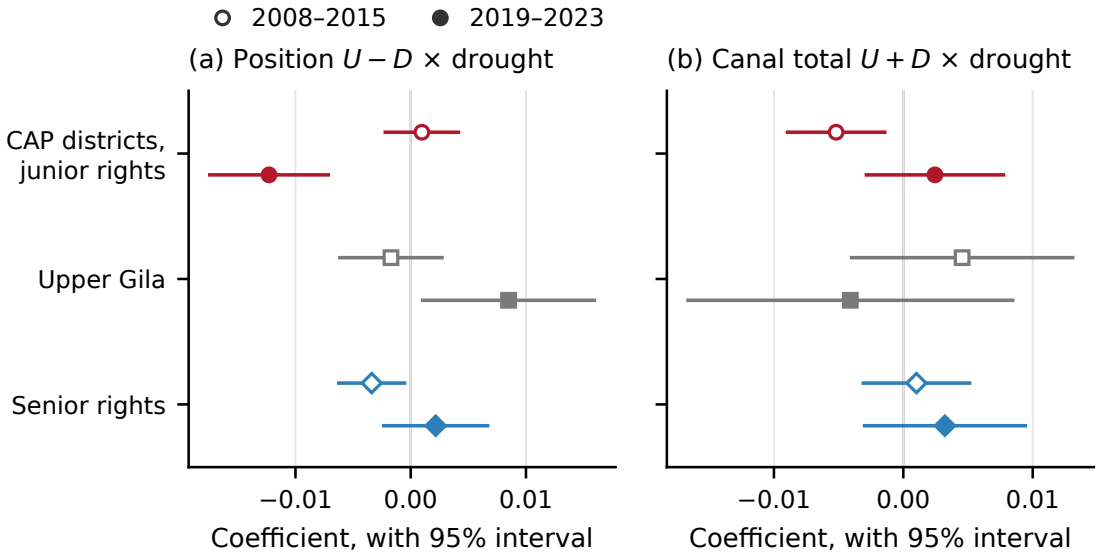
	Field-years		Peak GCVI		Crop-season GCVI	
	(1)–(3)	(4)	Sentinel-2 (1)	Landsat 7 (2)	Sentinel-2 (3)	Landsat 7 (4)
Panel A. With the fields outside the district polygons						
Demand over November–September	109,828		−0.016	0.006	—	—
			(0.020) [0.471]	(0.015) [0.695]		
Without the 1% of fields with the most variation	108,686		−0.006	0.009	—	—
			(0.018) [0.779]	(0.016) [0.643]		
Panel B. Inside the district polygons						
Demand over November–September	91,481	79,166	−0.023	−0.002	−0.025	−0.015
			(0.023) [0.313]	(0.017) [0.909]	(0.027) [0.285]	(0.023) [0.536]
Demand over the crop's months	91,481	79,166	−0.021	0.000	−0.019	−0.009
			(0.021) [0.324]	(0.015) [0.981]	(0.023) [0.340]	(0.020) [0.587]
On the crop's months, comparing:						
The same crop, district and year	91,481	79,166	−0.008	0.007	0.002	0.008
			(0.019) [0.673]	(0.016) [0.660]	(0.019) [0.923]	(0.019) [0.661]
A field with itself within a crop group	91,481	79,166	0.010	0.024	0.016	0.035
			(0.025) [0.687]	(0.021) [0.264]	(0.025) [0.544]	(0.025) [0.171]
Each crop group alone, averaged	90,352	78,037	−0.013	0.010	0.001	0.027**
			(0.012) [0.307]	(0.007) [0.252]	(0.010) [0.916]	(0.011) [<0.001]
Fields that stay in one crop group	40,340	34,485	0.066	0.070*	0.073	0.097**
			(0.046) [0.172]	(0.038) [0.089]	(0.045) [0.120]	(0.043) [0.032]
Without the 1% of fields with the most variation	90,531	78,318	−0.005	0.000	−0.015	−0.002
			(0.020) [0.818]	(0.016) [0.975]	(0.023) [0.377]	(0.022) [0.933]
Highest value, spikes removed	91,481		−0.010	−0.003	—	—
			(0.019) [0.635]	(0.015) [0.835]		
Range, leaving out any one district			−0.034 to 0.001	−0.009 to 0.014	−0.034 to −0.001	−0.023 to 0.007
p, wild cluster bootstrap by district			0.478	0.981	0.447	0.655
Panel C. CAP districts with junior rights						
Demand over November–September	21,196	18,734	−0.060***	−0.036***	−0.046**	−0.028
			(0.021) [0.016]	(0.012) [0.023]	(0.022) [0.011]	(0.019) [0.007]
Demand over the crop's months	21,196	18,734	−0.058***	−0.030***	−0.045**	−0.026
			(0.019) [0.024]	(0.011) [0.029]	(0.021) [0.031]	(0.017) [0.011]
Without the 1% of fields with the most variation	20,982	18,534	−0.029	−0.024*	−0.021	−0.008
			(0.021) [0.134]	(0.015) [0.226]	(0.024) [0.165]	(0.023) [0.544]

Notes: This year's change in position × drought, equation (8), each district's distance cut, 2SLS, crop years 2019–2023. Standard errors in parentheses, two-way clustering by field and by crop by year; stars use these clusters. Brackets give the p-value clustering by canal system (Section 5): 42 groups in Panel A, 38 in Panel B and 4 in Panel C. Column (4) has fewer field-years because it needs a Landsat 7 crop-season value. Each crop group alone: one regression for each crop group, averaged with weights set by each regression's precision. Highest value, spikes removed: the highest value of each field's curve over the crop year. Without the 1% of fields: fields are ranked by the variation in this term, on predicted demand, left after the fixed effects and the other terms. Range: the model is estimated again without each district. CAP districts with junior rights: Maricopa–Stanfield, Central Arizona, Harquahala, Hohokam.

A7 The Earlier Drought

Figure A1 estimates the water model of equation (7) on 2008–2015 and on 2019–2023 in one regression, with every term and every effect specific to the period. In the CAP districts with junior rights, the canal total lowered water use in drought in 2008–2015 and position did not. In 2019–2023 it is the other way round.

Figure A1: Position in Drought, 2008–2015 and 2019–2023



Notes: 2SLS estimates of equation (7) on 2008–2015 (open) and 2019–2023 (filled) in one regression, every term and every effect specific to the period; groups as in Table 5. Water use relative to the crop's need, in the months of the field's crop; the crop's typical use is taken within each period. Drought, position and distance cuts as in Section 6.2, on the same network. A field-year is active by the monthly water-use rule of the main runs, calibrated on 2016–2018 and 2020, applied to every year. The controls are SPEI-3 and SPEI-24; the nearby-fallowing shares exist from 2016 only and are left out of both periods. With them, 2019–2023 gives −0.011 for the CAP districts, as in Table 5, Panel A. In the CAP districts, the irrigation districts were in drought in 2010–2013 and in part of the group in 2009 and 2014 (52 and 33 percent of the sample's field-months), against 84 percent in 2021 and 14 percent in 2022. Position: +0.001 ($p = 0.57$) in 2008–2015 and −0.012 ($p < 0.001$) in 2019–2023; canal total: −0.005 ($p = 0.009$; $p = 0.046$ with clusters by branch) and +0.002 ($p = 0.38$). Against all of 2016–2023, the difference in position is −0.007 ($p = 0.013$; $p = 0.13$ with clusters by branch), because these districts had little drought in 2016–2018. Bars are 95 percent intervals, clusters by field and by crop by year by month. Samples: 336,394 field-months of 6,101 CAP fields, 45,081 of 1,067 Upper Gila fields, 652,649 of 10,220 senior-rights fields.

A8 Drought Years and Cut Years

In the CAP districts with junior rights, 86 percent of the fields were in drought in 2021, in Maricopa–Stanfield, Central Arizona, and Hohokam. In 2022 only Harquahala was, with 14 percent of the fields. No CAP district was in drought in 2019, 2020, or 2023. Table A10 replaces the drought indicator of Table 5 with indicators for 2021 and for 2022–2023, in every term and effect that uses drought, so each is measured against 2019–2020. For water use, position lowers the ratio by 0.006 in 2021 ($p = 0.036$; $p = 0.12$ with clusters by branch), about half the drought estimate. In 2022–2023 it does not (+0.002), and the canal total lowers it by 0.013 ($p < 0.001$; $p = 0.032$ with clusters by branch). Besides the comparison years, the two designs differ in Harquahala's 2022, which Table 5 counts as drought, and in the district effects, which here follow the periods. For the yield proxy, neither position term is significant in 2021. In 2022–2023 both are positive,

and the two canal-total terms are negative (-0.010 and -0.046, $p = 0.046$ and $p = 0.028$; $p = 0.25$ and $p = 0.057$ with clusters by branch). The drought estimate of Table 5 therefore rests partly on the cut years. In the fallowing model, against 2019, the slope on usual position is $+1.09$ points in 2021 ($p = 0.038$), against $+0.52$ in 2020, $+0.74$ in 2022, and $+0.22$ in 2023. In the other groups and over all fields, no period term of position in water use has $p < 0.10$ with clusters by branch.

Panel C of Table A10 shows where the 2021 effect sits. It is one regression on crop years 2017–2023, with 2019–2020, 2021 and 2022–2023 each measured against 2017–2018. Over all fields, position lowers water use in 2021 by 0.005 ($p = 0.23$ with clusters by branch). The fields are split into four groups by two backup sources of groundwater: a well of the field's owner in the district, and a canal pump (a district well whose water enters the canal, directly or through a pipeline) on the field's route within 2 km above the field. Canal pumps stand in Maricopa–Stanfield and Central Arizona; Hohokam and Harquahala have none. With clusters by branch, the 2021 estimate is $+0.001$ ($p = 0.84$) with both sources, -0.007 ($p = 0.038$) with only the owner's well, and $+0.006$ ($p = 0.33$) with only a canal pump. In the 581 fields with neither, it is -0.017 ($p = 0.008$), more than three times the estimate over all fields. That group minus the field-weighted mean of the other three is -0.016 ($p = 0.004$), and the test that the four groups are equal rejects ($p = 0.001$). The group has fields in all four districts: 218 in Maricopa–Stanfield, 210 in Central Arizona, 73 in Hohokam and 80 in Harquahala. Leaving one district out at a time, its 2021 estimate stays negative, from -0.009 to -0.024. Central Arizona contributes most: without it, the estimate is -0.009 ($p = 0.18$) and the difference from the other groups -0.008 ($p = 0.26$). Maricopa–Stanfield contributes least: without it, the estimate is -0.024 ($p = 0.014$). There the delivery model of Section 8 finds that the canals still met the planted fields' need in 2021 (Appendix A14). In 2022–2023, position does not separate the group from the others (-0.004, $p = 0.52$). For fields with no well below a canal pump, position goes with more water in 2022–2023 ($+0.017$, $p = 0.016$), as in the delivery model's cut design, where fields far from the head lost less (Appendix A14).

Panel D repeats the four groups in the designs of Panel A, on the 5,280 fields with an owner record and crop years 2019–2023: column (1) is Table 5's drought comparison, and columns (2) and (3) are measured against 2019–2020. In the 539 fields with no backup source of groundwater, position lowers water use by 0.023 in drought ($p < 0.001$ with clusters by branch) and by 0.019 in 2021 ($p = 0.004$). In the other groups the 2021 estimate runs from $+0.000$ to -0.007. The no-backup group minus the field-weighted mean of the other three is -0.014 in drought and -0.015 in 2021 ($p = 0.005$ and $p = 0.004$), and the four groups differ ($p = 0.009$ and $p = 0.025$). Fields with an owner's well and no canal pump also lose water in drought (-0.014, $p = 0.002$), less than the no-backup fields. On the same fields without the groups, the estimates are -0.011 in drought and -0.006 in 2021, as in Panel A.

Section 8 uses a 2 km reach for canal pumps. With 1, 3 and 5 km, the no-backup group of Panel D holds 863, 458 and 284 fields. Its estimate is -0.019, -0.022 and -0.022 in drought and -0.014, -0.018 and -0.015 against 2019–2020 ($p \leq 0.010$ with clusters by branch), and it differs from the other three groups at every radius ($p \leq 0.05$). Against 2017–2018 the estimates are -0.008 ($p = 0.26$), -0.016 ($p = 0.007$) and -0.010 ($p = 0.044$). Split by district in one regression, the no-backup fields of Central Arizona, Maricopa–Stanfield, and Hohokam with Harquahala give -0.023, -0.023 and -0.017 in drought, -0.021, -0.014 and -0.020 against 2019–2020, and -0.022, -0.006 and -0.020 against 2017–2018. No two parts differ ($p \geq 0.13$), and the weak estimate without Central Arizona in Panel C reflects Maricopa–Stanfield against 2017–2018. Estimated alone, Hohokam and Harquahala give a gap of -0.013 between fields without and with an owner's

well in 2021, against both 2019–2020 and 2017–2018 ($p = 0.007$ and $p = 0.036$ with clusters by branch, but only 8 branches; $p = 0.14$ and $p = 0.10$ with two-way clusters), and −0.002 in drought ($p = 0.88$).

In 2022–2023 against 2019–2020, position lowers the no-backup fields' water use by 0.046 in Hohokam and Harquahala ($p < 0.001$) and by 0.008 in Central Arizona ($p = 0.18$). In Maricopa–Stanfield, where district wells fed the canals, it raises it by 0.024 ($p = 0.096$). The yield proxy splits like water use. Usual position × 2021 against 2019–2020 is −0.024 in the no-backup fields ($p = 0.040$) and −0.002 to −0.007 in the others (gap −0.020, $p = 0.039$). In drought it is −0.032 ($p = 0.016$) against −0.014 to −0.021 (gap −0.014, $p = 0.16$). Fallowing does not split this way. Usual position × drought raises the fallow share by 0.007 in the no-backup fields and by 0.006 to 0.010 in the others, and the four groups do not differ ($p = 0.56$).

In the Upper Gila, drought marks 2021 and 2022. Against 2017, position goes with less water in 2019 (−0.018, $p = 0.011$ with clusters by branch) and in 2023 (−0.015, $p = 0.13$), and stays near its 2017 level in 2021 (−0.003) and 2022 (+0.005). The positive drought estimate of Table 5 comes from these comparison years. Few Upper Gila fields lie near a canal pump, so in 2021 the split is between fields with and without an owner's well. Fields with no well lean negative (−0.007, $p = 0.34$) and fields whose owner has a well lean positive (+0.006, $p = 0.47$). The gap between them is −0.012 ($p = 0.076$ with clusters by branch, 10 branches), the same order as in the CAP districts.

In the senior-rights districts, where water does not run short, the same split shows nothing in 2021. Position gives −0.004 with an owner's well ($p = 0.42$ with clusters by branch) and +0.003 without one ($p = 0.69$). Almost no senior field lies below a canal pump (57 of 9,620). The gap between fields without and with an owner's well is −0.010 in the CAP districts and +0.006 in the senior districts, and the two differ (−0.016, $p = 0.029$ with clusters by branch). The CAP gap does not differ from the Upper Gila's ($p = 0.79$). Table A11 sets the three rights groups side by side.

Position from the head fits 2021 and not the cut. In the 2022–2023 cut, Maricopa–Stanfield and Central Arizona lost CAP water and relied on wells that pump into the canals along their length (Section 2.2). Position from the head then no longer marks which fields are served last. In the delivery model's cut design, fields far from the head lost less (Appendix A14), and fields near the head stopped farming more often in 2022 (Appendix S14).

The yield results of the other appendices split the same way. On the peak of GCVI, this year's change in position gives −0.032 (standard error 0.026) in 2021, against −0.060 in drought (Appendix Table A6). Across that peak and the fields with and without a well (Appendix A5), each in 2SLS and OLS, and the four measures of Appendix A6 over both demand windows, all fourteen 2021 estimates are negative. They run from −0.041 to −0.001, and none is significant. In 2022–2023 all fourteen are positive, and none is significant. On the peak of GCVI, the usual position holds better. It gives −0.013 in 2021 ($p = 0.094$; $p = 0.016$ with clusters by branch), against −0.018 in drought. It is −0.025 on fields with their own well ($p = 0.013$; $p = 0.001$ with clusters by branch) and −0.011 on fields without one ($p = 0.17$; $p = 0.057$ with clusters by branch).

Table A10: Position in Drought Years and in Cut Years, CAP Districts with Junior Rights

	(1) Drought, as in Table 5	(2) 2021	(3) 2022–2023
Panel A. Water use relative to the crop's need, months of the crop, ln			
Position × year type	−0.0111***	−0.0059**	0.0018
	(0.0028)	(0.0028)	(0.0029)
	[0.006]	[0.119]	[0.630]
Canal total × year type	0.0052*	−0.0012	−0.0129***
	(0.0029)	(0.0033)	(0.0038)
	[0.284]	[0.809]	[0.032]
Field-months	102,791	102,791	
Fields	5,410	5,410	
Smallest first-stage F	3,686	2,542	
Panel B. Yield proxy, ln of crop-season GCVI			
This year's change in position × year type	−0.046**	−0.012	0.033*
	(0.022)	(0.025)	(0.019)
	[0.065]	[0.705]	[0.195]
Usual position × year type	−0.023**	−0.011	0.013
	(0.010)	(0.010)	(0.009)
	[0.023]	[0.202]	[0.098]
This year's change in canal total × year type	0.014	−0.028	−0.046**
	(0.022)	(0.023)	(0.021)
	[0.466]	[0.292]	[0.057]
Usual canal total × year type	0.007	0.009	−0.010**
	(0.006)	(0.005)	(0.005)
	[0.400]	[0.346]	[0.251]
Field-years	21,196	21,196	
Fields	5,626	5,626	
Smallest first-stage F	1,572	1,195	
Panel C. Water use, position × year type, against 2017–2018			
All fields		−0.0047	0.0039
		(0.0029)	(0.0026)
		[0.229]	[0.341]
Owner's well, canal pump within 2 km (1,404)		0.0007	0.0067*
		(0.0036)	(0.0036)
		[0.838]	[0.188]
Owner's well, no canal pump within 2 km (2,009)		−0.0069**	−0.0008
		(0.0030)	(0.0031)
		[0.038]	[0.891]
No well, canal pump within 2 km (1,539)		0.0057	0.0166***
		(0.0036)	(0.0040)
		[0.333]	[0.016]
No well, no canal pump within 2 km (581)		−0.0168***	0.0028
		(0.0047)	(0.0047)
		[0.008]	[0.679]
No well and no canal pump, minus the other three		−0.0160***	−0.0039
		(0.0038)	(0.0045)
		[0.004]	[0.522]
Four groups equal, p with clusters by branch		[0.001]	
Field-months, all fields / four groups		159,576 / 155,477	
Fields, all fields / four groups		5,669 / 5,533	
Smallest first-stage F, all fields / four groups		2,464 / 545	
Panel D. Water use, position × year type by group, as Panel A			
Owner's well, canal pump within 2 km (1,357)	−0.0056*	−0.0012	0.0028
	(0.0033)	(0.0034)	(0.0039)
	[0.208]	[0.784]	[0.565]
Owner's well, no canal pump within 2 km (1,903)	−0.0136***	−0.0068**	−0.0012
	(0.0029)	(0.0030)	(0.0034)
	[0.002]	[0.087]	[0.781]
No well, canal pump within 2 km (1,481)	−0.0072**	0.0001	0.0117***
	(0.0035)	(0.0036)	(0.0042)
	[0.195]	[0.988]	[0.092]
No well, no canal pump within 2 km (539)	−0.0230***	−0.0185***	0.0003
	(0.0039)	(0.0043)	(0.0050)
	[0.000]	[0.004]	[0.967]
No well and no canal pump, minus the other three	−0.0137***	−0.0155***	
	(0.0033)	(0.0038)	
	[0.005]	[0.004]	
Four groups equal, p with clusters by branch	[0.009]	[0.025]	
Field-months	100,244	100,244	
Fields	5,280	5,280	
Smallest first-stage F	1,014	709	

Notes: 2SLS. Column (1) repeats the CAP column of Table 5. In Panels A and B, columns (2) and (3) come from one regression per panel, in which indicators for 2021 and for 2022–2023 replace drought in every term and effect that uses it, so each is measured against 2019–2020. Panel C adds crop years 2017–2018 and measures 2019–2020, 2021 and 2022–2023 against them, in every term and in the district effects. Its first row is that model

Table A11: Position in 2021 by Backup Source of Groundwater, Three Rights Groups

	CAP, junior rights	Upper Gila	Senior rights
Position × 2021, water use relative to the crop's need, against 2017–2018			
All fields	−0.0047	−0.0023	0.0007
	(0.0029)	(0.0048)	(0.0033)
	[0.229]	[0.709]	[0.888]
Owner's well, canal pump within 2 km	0.0007	–	–
	(0.0036)		
	[0.838]		
	1,404 fields	*55 fields*	*38 fields*
Owner's well, no canal pump within 2 km	−0.0069**	0.0055	−0.0036
	(0.0030)	(0.0057)	(0.0035)
	[0.038]	[0.474]	[0.424]
	2,009 fields	*636 fields*	*3,659 fields*
No well, canal pump within 2 km	0.0057	–	–
	(0.0036)		
	[0.333]		
	1,539 fields	*18 fields*	*19 fields*
No well, no canal pump within 2 km	−0.0168***	−0.0066	0.0025
	(0.0047)	(0.0067)	(0.0038)
	[0.008]	[0.342]	[0.692]
	581 fields	*228 fields*	*5,904 fields*
No well minus owner's well, no canal pump	−0.0099***	−0.0121*	0.0062**
	(0.0038)	(0.0069)	(0.0030)
	[0.072]	[0.076]	[0.183]
CAP's difference minus this group's		0.0022	−0.0160***
		(0.0079)	(0.0049)
		[0.790]	[0.029]
Fields, all fields / four groups	5,669 / 5,533	937 / 937	9,626 / 9,620
Branches, all fields / four groups	42 / 41	10 / 10	33 / 33
Smallest first-stage F, groups shown	545	276	185

Notes: 2SLS, as Panel C of Table A10: crop years 2017–2023, with 2019–2020, 2021 and 2022–2023 each measured against 2017–2018. One regression per rights group, with position, canal total and the district effects by group of fields; only position × 2021 is shown. All fields: the same model without the groups. Owner's well and canal pump as in Table A10. A group with fewer than 100 fields shows no estimate: in the Upper Gila and the senior districts almost no field lies within 2 km below a canal pump. Difference row: no well and no canal pump minus owner's well and no canal pump. Last row: the CAP districts' difference minus the group's. The groups share no field and no branch, so the two estimates are treated as independent; the branch p uses t with the smaller group's branches less one. Standard errors in parentheses. Brackets: p-value with standard errors clustered by branch. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

A9 Dollar Losses from Position in Drought

I put the two margins in dollars. Table A12 reports both losses over the drought years of 2019–2023. I apply the yield-proxy estimate $\hat{\beta}_W$ to planted drought field-years whose change in position this year, W_{it}^P, is positive. Each such field-year loses its crop revenue times $0.8\,(1 - e^{\hat{\beta}_W W_{it}^P})$. I assume that revenue falls by 0.8 times the proportional fall in the yield proxy. I apply the fallowing estimate to fields lower on their canals than a field at the 25th percentile of usual position. A fallowed acre saves its variable costs, so I value it at its net return, \$192, the mean of the cotton and alfalfa budgets. I also value it at \$1,886, the mean crop revenue, an upper bound. A planted field has already spent its costs, so both totals count its yield loss at revenue.

Position costs the CAP districts' fields \$2.6 million at net return over the drought years (95 percent range \$0.9–4.1 million). It costs them up to \$10.4 million at revenue (\$4.3–16.5 million). Fallowing is 35 to 84 percent of the total. The fallowing loss comes from 4,637 extra fallowed acres. The yield loss is \$1.7 million. The \$2.6 million is 8.7 percent of what these fields would have earned at net return in their drought years, \$29.5 million on the planted acres and the extra fallowed acres at \$192 an acre. Of the \$1.7 million yield loss, \$1.3 million falls in 2021 and \$0.4 million in Harquahala's drought year, 2022. Applied to the 2021 field-years only, the 2021 estimate against 2019–2020 (−0.012; Appendix A8) gives a yield loss of \$0.3 million (−\$1.1 to \$1.6 million). With fallowing unchanged, the total is then \$1.2 million at net return (−\$0.3 to \$2.7 million) and \$9.1 million at revenue (\$3.1–15.2 million). In the Upper Gila, position costs \$0.3 million at net return (−\$0.5 to \$1.1 million). Senior fields show no clear loss in either margin.

The dollar figures count what fields lower on their canals lose, so they measure who carries the shortage.

Table A12: Losses from Position in Drought: Yield and Fallowing Together

	Yield	Extra	Fallowed acre at net return (\$192)		Fallowed acre at revenue (\$1,886)	
	loss	fallowed acres	Fallowing	Total	Fallowing	Total
All fields	2.1	7,984	1.5	3.7	15.1	17.2
	[−2.6, 6.5]	[95, 15,795]	[0.0, 3.0]	[−1.2, 8.4]	[0.2, 29.8]	[1.8, 32.8]
CAP, junior rights	1.7	4,637	0.9	2.6	8.7	10.4
	[0.1, 3.1]	[1,541, 7,735]	[0.3, 1.5]	[0.9, 4.1]	[2.9, 14.6]	[4.3, 16.5]
Upper Gila	0.3	272	0.1	0.3	0.5	0.8
	[−0.5, 1.0]	[−1,556, 2,101]	[−0.3, 0.4]	[−0.5, 1.1]	[−2.9, 4.0]	[−2.7, 4.2]
Senior rights	−2.6	32	0.0	−2.6	0.1	−2.6
	[−9.5, 3.4]	[−711, 790]	[−0.1, 0.2]	[−9.5, 3.4]	[−1.3, 1.5]	[−9.7, 3.6]

Notes: Million dollars over all drought field-years of 2019–2023, except the acres column. Yield loss: planted drought field-years whose position this year was worse than their 2017–2018 average; revenue is acres times the NASS revenue per acre of the crop and year; revenue falls by 0.8 times the proportional fall in the yield proxy. Extra fallowed acres: the fallowing coefficient times the usual position above its 25th percentile, times acres. A fallowed acre is valued at the mean net return of the cotton and alfalfa budgets (returns over total costs) or at mean crop revenue (an upper bound). Totals add yield and fallowing; the yield loss falls on planted field-years and the fallowing loss on fallowed ones, so the two do not overlap. Brackets: 95 percent of joint draws of the two coefficients, drawn independently. Gains of fields whose position improved and of fields that received the water are not netted out.

A10 Standard Errors Clustered by Branch

Drought and the delivery cuts it brings are set for each irrigation district and year. The effect I estimate works inside the irrigation district and year. Two fields of the same irrigation district face the same drought and the same cut in a year, but one draws on its canal before the other. The models include irrigation district by drought effects, so the drought terms compare fields within their own irrigation district.

Position is defined inside a branch: fields on different branches have no order (Section 6.2). I therefore also cluster by branch. This lets the errors of all fields of a branch be correlated over all years. In the sample, the CAP districts with junior rights have fields on 41 branches, the Upper Gila on 10, and the senior-rights districts on 33. The paper's tables cluster by field and by crop and time. With few clusters, I also compute the branch p-values with a wild cluster bootstrap that imposes the null (Cameron, Gelbach, and Miller 2008; Webb 2023).

Table A13 reports the three sets of p-values for the estimates of Table 5 and Figure 7. Its Panel B uses the peak of GCVI over the crop year. For crop-season GCVI, the brackets of Table 5 give the branch p-values. In the CAP districts, position in water use and the usual position in the yield proxy and fallowing hold with branch clusters. In water use relative to the crop's need, p is 0.006 with branch clusters and 0.016 with the wild bootstrap. In the yield proxy at its peak, it is 0.002 and 0.002. On crop-season GCVI it is 0.023 with branch clusters. In fallowing, it is 0.030 and 0.040. This year's change in position at the peak goes from $p = 0.005$ to 0.037, and to 0.19 with the wild bootstrap. On crop-season GCVI it goes from 0.039 to 0.065. In the Upper Gila, with 10 branches, position does not lower water use (+0.010; 0.050 and 0.075), and the usual position does not raise fallowing (0.83 and 0.83). The usual position lowers the yield proxy at its peak (−0.017; 0.044 and 0.025). On crop-season GCVI it does not (−0.004; 0.507 with branch clusters). In senior-rights districts, position gives +0.003 in water use (0.290 and 0.287); no other position term has p below 0.10.

Table A13: Water Use, Yield Proxy, and Fallowing, With Standard Errors Clustered by Branch

Term	Fields	Estimate	p			Branches
			Field and crop × time	Branch	Branch, wild bootstrap	
A. Water use relative to the crop's need, months of the crop						
Position × drought	All fields	0.0010	0.463	0.583	0.591	142
	CAP, junior rights	−0.0111	<0.001	0.006	0.016	41
	Upper Gila	0.0101	0.010	0.050	0.075	10
	Senior rights	0.0026	0.314	0.290	0.287	33
Canal total × drought	All fields	−0.0001	0.961	0.978	0.966	142
	CAP, junior rights	0.0052	0.079	0.284	0.311	41
	Upper Gila	−0.0098	0.150	0.147	0.178	10
	Senior rights	0.0011	0.760	0.870	0.865	33
B. Yield proxy						
This year's change in position × drought	All fields	−0.016	0.430	0.512	0.607	143
	CAP, junior rights	−0.060	0.005	0.037	0.194	41
	Upper Gila	0.024	0.657	0.653	0.637	10
	Senior rights	0.070	0.225	0.116	0.397	33
Usual position × drought	All fields	−0.003	0.295	0.259	0.273	143
	CAP, junior rights	−0.018	0.012	0.002	0.002	41
	Upper Gila	−0.017	0.106	0.044	0.025	10
	Senior rights	0.002	0.434	0.533	0.434	33
This year's change in canal total × drought	All fields	−0.010	0.588	0.663	0.725	143
	CAP, junior rights	−0.017	0.422	0.480	0.738	41
	Upper Gila	−0.024	0.634	0.592	0.598	10
	Senior rights	0.081	0.214	0.092	0.169	33
Usual canal total × drought	All fields	0.002	0.581	0.488	0.515	143
	CAP, junior rights	0.002	0.799	0.755	0.819	41
	Upper Gila	0.053	<0.001	0.002	0.015	10
	Senior rights	−0.003	0.524	0.513	0.882	33
C. Fallowed, percentage points						
Usual position × drought	All fields	0.44	0.043	0.096	0.112	144
	CAP, junior rights	0.83	0.009	0.030	0.040	42
	Upper Gila	0.19	0.777	0.832	0.826	10
	Senior rights	0.01	0.934	0.903	0.906	33
Usual canal total × drought	All fields	−0.21	0.459	0.469	0.473	144
	CAP, junior rights	−0.55	0.376	0.338	0.398	42
	Upper Gila	−1.03	0.307	0.301	0.356	10
	Senior rights	−0.09	0.740	0.635	0.726	33

Notes: Panel A: equation (7), the months of the field's crop; Panel B: equation (8) on the peak of GCVI over the crop year, with the fields outside the irrigation-district polygons; Panel C: equation (9), coefficients times 100; crop years 2019–2023. Upstream and downstream fields beyond each irrigation district's distance on the irrigation network, same-owner pairs removed, 2SLS. Field and crop × time: the clusters of Table 5. Branch: one-way clusters by branch, t with $G-1$ degrees of freedom; a field on no branch is its own cluster. Branch, wild bootstrap: wild cluster bootstrap of the reduced form by branch, with the null imposed, Webb weights, 99,999 draws. Branches: branches in the sample. CAP districts with junior rights, Upper Gila, and senior rights as in Table 5.

A11 Documented Delivery Constraints in Non-CAP Systems

Table A14 collects documentary evidence from the Gila Valley, where Graham, Fort Thomas, Union, Montezuma, and San Jose are among the Upper Gila canals. For a fixed irrigation-turn duration, a smaller stream delivers less water; additional delivery time or supplemental supply can compensate. The search was directed by the study geography and results. These cases document the existence of delivery constraints; they do not measure their prevalence or independently identify the crop-outcome mechanism.

Table A14: Non-CAP Delivery Constraints: Documentary Evidence and Sample Match

System and date	Documentary record and source	Match and interpretation
Upper Gila / Safford Valley, 2021	The Commissioner recorded Cosper Crossing as dry on March 11 and next wet on July 26. When dry, the Duncan Valley's Gila flow was issued to Duncan/Virden canals; flowing conditions placed Duncan and Safford diversions under the same priority year. (Doyle 2022, p. 3; PDF p. 7)	Dated inter-valley flow and administration evidence in the region containing the five focal Gila companies. It does not imply zero supply throughout Safford or measure unequal deliveries within a canal.
Graham Canal, testimony reproduced in 1955	During scarce-water rotations, the reported stream diminished from roughly 400 "inches" at the head to 250 at the old Oregon ditch's end. Water boss Emery B. Hubbard testified: "It affects more on the lower end." (Arizona Supreme Court 1955, pp. 217–218, Udall dissent)	Direct historical testimony about downstream conveyance losses in a named sample company. The account concerns a river-and-pump system and predates the study; it is reproduced in the dissent, not a contemporary delivery measurement.
Gila Valley Irrigation District, May 2019	The modernization plan recommended equalizing basins, turnout measurement and control, and operational changes to improve the flexibility and equity of field deliveries. (ITRC 2019, recommendations 6–8)	The plan's map includes the five focal Gila companies. A case-specific engineering assessment of delivery needs; the recommendations do not measure downstream deficits or completed improvements.
Gila Valley Irrigation District, February 8, 2022	Meeting minutes attribute to GVID representative Justin Layton losses from aging gates across the eleven-canal system: existing gates reportedly leaked 10–50 miner's inches, against a typical 300 miner's-inch stream. (AWPF 2022b, attached February draft minutes, p. 4; PDF p. 13)	Contemporary operator evidence of hydraulic losses at system scale, with no individual focal canal or tail farm identified. The revised gate project covered Smithville and Dodge-Nevada; Union had been removed.

Notes: Dates identify the reported event, plan, or court opinion; the 2021 Commissioner's report was submitted August 10, 2022. GVID-wide statements are not five separate canal observations. The detailed February 2022 account is reproduced as draft minutes in the June meeting packet; the approved scope revision is recorded separately (AWPF 2022a, PDF pp. 2–3, 27–28). Historical "inches" and modern miner's inches describe stream-flow rates, retained as reported without conversion. These records concern non-CAP systems; groundwater supplementation can still occur within them.

Table A15 places the dated account beside reported diversions. Safford Valley's May–June total was 2,112 acre-feet in 2021, compared with 8,675 in 2020 and 3,975 in 2022. In 2021, diversions recovered to 5,603 acre-feet in July and 12,135 in August; the annual total slightly exceeded 2020's. The record therefore locates scarcity within the growing season. Among the five focal companies, annual changes are heterogeneous: Fort Thomas reported much lower river diversion in 2021 than its 2016–2019 mean, whereas Union's reported diversion was higher. Calendar-year diversion totals cannot reveal how water was distributed among farms when supply was tight.

Table A15: Reported Gila River Diversions and Seasonal Flow Conditions

Panel A. Seasonal conditions, entire Safford Valley

Year	Cosper dry	Next wet	May (AF)	June (AF)
2020	June 5	Dec. 31	5,659	3,016
2021	March 11	July 26	1,096	1,016
2022	April 13	June 30	1,351	2,624

Panel B. Calendar-year diversions, focal Gila companies (AF)

Canal	2016–2019 mean	2020	2021	2022
Graham	5,598	5,927†	5,204	4,812†
Fort Thomas	3,874	2,406	1,554	2,747
Union	11,846	11,320	12,555	13,237
Montezuma	8,158	7,565	6,479	7,648
San Jose	8,900	8,992	8,499	8,897

Sources: Gila Water Commissioner annual reports (Gila Water Commissioner, n.d.). Year labels link to the original reports. Panel A: printed p. 3 (PDF p. 7), Cosper status changes; printed p. 5 (PDF p. 10), Safford monthly diversions. Panel B: Plate 3, "Gila River Decreed Acreages and Diversions," Safford Valley rows; PDF pp. 28, 30, 31, 31, 28, 31, and 32 in the 2016–2022 reports, respectively. The preperiod mean uses the 2016, 2017, 2018, and 2019 reports and is rounded to whole acre-feet.

Notes: Panel A covers the entire Safford Valley reporting area, not only the five focal companies. Dates are reported status changes, not continuous daily observations; 2021 had the earliest listed dry onset but not the longest interval. Panel B includes all five focal Gila companies. Values are published calendar-year river diversions, not farm receipts, orders, or a complete groundwater-inclusive water budget. San Jose, Montezuma, and Union share a described measuring flume with Fourness; separate published totals are not independently gauged measurements. † Graham's 2020 and 2022 annual totals are reproduced as published despite unresolved unit conflicts in their monthly records. No blank cell has been treated as zero.

Additional Evidence Outside the Upper Gila Canals

Additional searches covered senior and mixed-priority systems with negative coefficients in exploratory separate-district regressions, and systems with unresolved priority classifications and negative validation estimates. Table A16 reports both delivery constraints and a qualifying account of adequate supply. North Gila Valley and Yuma Irrigation District are near Yuma, distinct from the Upper Gila companies in Table A14.

Table A16: Additional Non-CAP Delivery Records: Senior, Mixed, and Unclassified Systems

System, priority, and date	District or operator record and source	Interpretation and limits
North Gila Valley, senior, July 2018	The McPherson Lateral application reports deteriorated lining, leakage, and seepage. Enlarging and relining the lateral was proposed to increase delivery capacity and shorten irrigation turns. (NGVIDD 2018, pp. 2–4)	A delivery constraint in a senior Colorado River system. Proposed gains are not measured outcomes. Earlier phases were completed in 2016–2017; the record does not establish unchanged conditions in later drought years.
Yuma Irrigation District, senior, May 2021	General manager Rex Green described year-round demand frequently testing operational capacity, while reporting no drought-induced diversion limitations yet. The district's undated ordering policy allows delayed service when system capacity is constrained. (Irrigation Leader 2021; YID, n.d.)	Capacity and scheduling pressure despite continued access to source water. Neither account measures a head-to-tail volume difference. The undated policy cannot establish when a particular delivery was delayed.
Roosevelt Irrigation District, unclassified, April 2017	The district reports summer prorating and difficulty matching supply to demand because of canal travel time. At an existing reservoir near the canal's downstream end, stored water is pumped back when downstream demand exceeds supply. (RID 2017, pp. 1, 3)	Direct downstream supply-demand mismatch and an operating response. The record does not establish a remaining seasonal deficit after compensation. This is Roosevelt Irrigation District, not Roosevelt Water Conservation District.
Buckeye, unclassified, July 2022	The district reports that changing main-canal levels alter farm delivery rates when manual gates remain fixed during an irrigation set. It also reports longer delivery durations associated with inadequate water levels and multiple users. (BWCDD 2022, pp. 15–16)	Contemporary farm-delivery rate and timing problems in a shared system. No head-to-tail comparison or drought attribution is provided; anticipated modernization benefits are not observed delivery gains.
Mohave Valley, mixed, 2019	The district's conservation plan states that, since formation in 1963, it had never been unable to provide a contract holder's requested amount. The district does not operate the private conveyance facilities. (MVIDD 2019, pp. 38–39)	A qualifying record against a district-wide supply-shortage interpretation. It does not audit distribution within individual private systems. A negative crop coefficient alone cannot establish unmet water orders.

Notes: Priority labels follow the study's audited classifications; "unclassified" is not a senior designation. The full-period North Gila and Yuma fits use nearest-district assignment; the stricter inside-boundary screen beyond 5 km lacks drought variation for both. Roosevelt and Buckeye have negative validation estimates but positive discovery estimates; Mohave's sign changes in the other direction. These exploratory matches guide source discovery, not independent causal validation. Grant applications report existing conditions alongside proposed improvements; the table distinguishes the two. No source here measures a dated, uncompensated seasonal water deficit at a named downstream farm.

A12 The Results of Section 8 in Detail

Section 8 gives the main results in words. This appendix gives the same results in full, with each estimate, its standard error, and its tests, in the order of Sections 8.3 to 8.9. The tables and figures it cites stand in the section.

Section 8.3: Fields went fallow where the model says water fell short. I do not observe deliveries to individual fields, so I judge the model by what it predicts. The model runs on the districts of at least 10,000 acres with a monthly water record that can show a shortage. Figure 8 shows the share of fields left fallow in each. The five CAP districts run short when CAP falls, and their fallow share rose 18 to 34 percentage points from 2016–2021 to 2022–2023. The three Yuma districts have no short month under any rule, and Wellton-Mohawk has two. Their fallow share fell by 2 to 10 points. San Carlos can meet 0.78 of demand in both periods, so the model predicts no rise, and its fallow share fell 10 points. Fallowing also rose in two other districts where the model finds no shortage, one of them mostly near cities (Appendix A16). A rise in fallowing alone does not show a shortage.

The divide also follows water law (Section 2.1). A reader could predict which districts ran short without the model. I take it as the setting. The model's test lies inside the districts, where rights are the same and fields differ in their place on the canal and in their wells.

Section 8.4: Inside a district, water use follows the shortfall. In Maricopa–Stanfield in 2016–2021, CAP and the district's wells (Section 2.2) each supplied about 130,000 acre-feet a year. Together they came close to crop demand over a year, but not in every month. Central Arizona wrote that shortages "usually occur during periods of above normal temperatures in the growing season when there is high demand" (CAIDD 2022).

Figure 9 shows who gets water in the model in July of 2019, 2020, and 2022. In July 2019, 84 percent of fields are farmed, and 3 percent of these receive less than half of their claim. Those fields gather in the northwest, where a tenth of fields are that short, against 0 percent in the southwest. July 2020 is similar: 85 percent of fields are farmed, and under 1 percent receive less than half. In both years, fewer than one farmed field in ten receives its full claim. In July 2022, in the cut, only 63 percent of fields are farmed, and more than half of these receive their full claim.

The estimates use only variation within the season (equation (11)). A field's *water use* is its crop's monthly evapotranspiration from OpenET. The regression also holds the district's *shortage* for fields without a well, the share of the month's crop demand its water cannot meet. I leave out owner effects, because an owner's fields sit together on a canal and comparing them removes the variation the design uses. The sample in Maricopa–Stanfield has 67,104 field-months of 2,021 fields of 463 owners, and 1,711 fields have no well.

I do not choose the rule by hand. A search covers 51 values of κ, 51 of κ_J, and takes from 0 to 1. Each rule's *score*, in basis points, is how much its shortfall improves the prediction of water use in a year left out of the estimate. The *bar* is the 95th percentile of the best score in 200 draws that flip the sign of the residuals owner by owner. The score is blind to sign, so I report each with its slope. In Maricopa–Stanfield, the best rule scores 36.8 against a bar of 31.2, and 1 of 200 draws reaches it. It sits at a take of 0.66, κ of 0.28, and κ_J of 0.90, with a slope of -40.1 for fields without a well (standard error 11.3).

The main estimate picks no single rule and averages the shortfall over all 2,601 rules at that take. Raising the averaged shortfall from 0 to 1 lowers the monthly water use of a field without a well by 61.5 log points, about 46 percent (-61.5, standard error 19.2). The mean shortfall is 0.01 and its standard deviation 0.047, so a typical move within the season lowers water use by only 2.9 percent. The loss sits in the fields and months the model says are short. Measured from months with a shortfall of 0.01 to 0.05, water use falls by less than 4 percent at a shortfall of 0.05 to 0.20 and by 12 percent at 0.20 to 0.35. Where the shortfall is 0.35 or more, it falls by 27 to 31 percent

(Figure 10, panel b; Appendix Table A22).

Within a season, the monthly slope uses each month's actual demand, which the crops planted before the season set. Holding demand at its 2016–2021 average would give summer demand to fields whose crops were harvested in spring. The monthly design therefore does not use it. Across years, the cut design holds demand at its usual level, because supply moved most in the cut (Section 8.5).

No year can serve as a placebo. Fields without a well run short only in 2019 and 2020, and in the other years the model gives them no shortfall to test. I randomize the model's inputs instead. Reassigning each calendar month's water across the years reaches the real slope in 0 of 1,000 draws ($p = 0.001$) and the best score among the 121 rules in 7 ($p = 0.008$). Moving fields to other fields' places reaches neither in 1,000 draws, and neither does moving whole owners' fields.

The data reject equal sharing and do not pin down the exact rule. At a take of 0.66, the test rejects equal sharing (score -19.3, $p = 0.005$) and upstream first only along a line (score 5.1, $p = 0.010$). It keeps side lines first at a split (score 24.6, $p = 0.144$) and both together (score 16.5, $p = 0.055$). The test keeps takes of 0.58 and 0.64 to 0.82, κ_J of 0.5 to 1, and every κ. Water is not shared in proportion to demand. The best rule combines the named ones: the canal serves side lines first at the splits (κ_J 0.90), and along a line upstream fields take first in part (κ 0.28). It clears the bar, and no pure rule does (side lines first 24.6, both 16.5, against 31.2). The test fixes the splits but not the order along a line.

Fields with a well also use less water when their shortfall rises (-165.7, standard error 71.0), and at the same location I cannot tell the two groups apart (-59.9, standard error 37.3). That is what the district's wells predict. Farmers here mostly do not run their own wells: the district runs wells leased from landowners, almost no groundwater is pumped outside them (Section 2.2), and its canal pumps gave 92.4 percent of its 2019 well water. A well on a farmer's land is therefore not water the farmer controls. When all 331 other rated wells, or all 404 other wells on the district's map, count as local pumps, the slope for fields without a well does not move (Appendix Table A24, Appendix A14). What marks which fields keep water is how much of their need the district's canal pumps can supply (Section 8.5). Where farmers run their own wells, in Harquahala and New Magma, the loss falls on fields without one.

In New Magma the sample has 514 fields of 244 owners in 2016–2023, of which 420 have no well. The best rule scores 42.6 against a bar of 26.7, and no draw of 200 reaches it. It sits at a take of 0.72, κ of 0.76, and κ_J of 1.00, with a slope of -7.5 for fields without a well (standard error 2.7). Over all rules at that take the slopes are -6.6 (standard error 4.1) without a well and -1.9 (standard error 7.2) with one. Moving fields to other fields' places reaches the slope without a well in 10 of 1,000 draws ($p = 0.011$), moving whole owners' fields in 47 ($p = 0.048$), and reassigning each calendar month's water across the years in 59 ($p = 0.060$). No field or owner draw reaches the best score among 121 rules, and 25 date draws do ($p = 0.026$). The best takes are 0.66 and 0.72, and panel (a) of Figure 10 compares the rules at 0.66 in Maricopa–Stanfield and at 0.70 in New Magma. Equal sharing fits poorly in both, at -19.3 and -5.9. Upstream first along lines and at splits fits well in New Magma, at 39.5, above its bar, and in Maricopa–Stanfield no pure rule clears its bar. Upstream first only along a line fits poorly in both, at 5.1 and -3.3. The two districts share a rule at the splits: side lines first, with κ_J of 0.90 in one and 1.00 in the other.

Harquahala's farms pump their own wells, and the loss falls on the 78 of its 748 fields that have none. At a take of 0.68, the slope is -31.4 for fields without a well (standard error 14.5) and 0.4 for fields with one (standard error 7.0); the gap is -31.8 (standard error 15.2). Two date draws

and one field draw in 1,000 reach that slope ($p = 0.003$ and $p = 0.002$), and it lies below 95 percent of the draws that move whole owners' fields ($p = 0.051$). With so few fields without a well, the search cannot pick a rule: the best score across all fields, 30.9, stays under the bar of 37.4. The district's shortage in the same regression has the wrong sign (64.0, standard error 23.6). CAP follows demand there (correlation 0.86), so the shortage term may partly measure high demand. I have not tested that reading.

Section 8.5: Losses in the cut and the canal pumps. The cut took away the water that enters at the head. In CAP's delivery reports, Maricopa–Stanfield's CAP water fell from 122 thousand acre-feet in 2021 to 31 thousand in 2022 and 4 thousand in 2023. The district's wells, which pump into the canals, became its main supply. Figure 11 sorts fields by the share of their need that the district's pumps alone could supply in 2016–2021, in the delivery model. It compares the fields under a quarter with the rest, counting water use per acre of land, fallow land included. Before the cut, the fields under a quarter used 0.76 to 0.86 as much water as the rest. They used 0.69 as much in 2022 and 0.62 as much in 2023.

Farmers knew the cut before the season, and the districts rationed it by rule (Section 2.2), so the cut shows in annual outcomes. The design holds each field's demand at its 2016–2021 level, so that only water moves the shortfall. It sorts fields by the rise in shortfall the model predicts. Among fields without a well, a predicted rise one standard deviation larger lowers water use in 2022–2023 by 5.6 percent (standard error 2.2). That estimate is net of the same contrast in 2020–2021, which is near zero (-1.1, standard error 1.3). The farmed share falls by 4.9 points (standard error 1.3), and its earlier contrast, 1.1 (standard error 1.0), accounts for part of that fall. The loss shows first in land, because farmers decide what to plant before the season. Farmed fields may also have lost water. Take the fields farmed in at least one year before the cut and one year in it. In the years they were farmed, their water use falls by 3.5 percent per standard deviation (standard error 2.1). The loss is on fields that were farmed in some years and fallow in others. On the 613 fields farmed in all eight years the estimate is -0.4 (standard error 2.0). On all planted fields, a predicted loss of 10 percent of the season's water lowers the yield proxy in the cut by 10.3 percent (standard error 5.8) and the season's water use by 9.3 percent (standard error 2.9). Before the cut, neither falls (Appendix A17).

Growers know the year's delivery before they decide what to fallow, and they can read this year against last year. A field's *total stress* adds the share of its own demand left short last year, at the demand it had, to the share predicted short this year, at its usual demand. It runs from 0 to 2. Among fields without a well farmed the year before, one unit raises the chance of fallowing by 12.7 points within a year (standard error 6.7). With field and year effects it raises it by 18.7 points (standard error 7.9), or 3.5 points per standard deviation. The response comes from the cut years (18.0, standard error 7.8, against -6.6 in 2017–2021, standard error 15.5).

While CAP flows, a field's place on the canal matters; once CAP is gone, the pumps above it do. The delivered share's correlation with kilometers from the head is -0.63 in 2016–2021 and -0.28 in 2022–2023 (Appendix A14). Water use on the fields shows the same thing. Take the fields that depend most on CAP water: the district's pumps could supply under a quarter of their need, and none of its large pumps stands on the canal above them. In each year from 2018 to 2021, the half of them farther from the head used 20 to 35 percent less water per acre than the nearer half (Appendix Table A29). Where the pumps stand produces most of the variation in the predicted rise in shortfall. Its standard deviation is 0.173 with the pumps where they stand, and 0.062 with

the same pumped water pooled over all fields. Figure 12 enters the two side by side. Pumps where they stand predict water use in the cut (−5.5, standard error 2.2) and the farmed share (−4.6, standard error 1.3). The pooled version has the opposite sign on each. Fallowing divides the same way, as does the monthly slope in the years before the cut (−61.0, standard error 24.1, against −2.9, standard error 24.3).

Competition on the canal matters less for a field the pumps can supply. The slope on the pooled shortfall is −36.1 for the 452 fields whose pumps could supply half or more of their need (standard error 25.4). It is −75.1 for the 1,259 others (standard error 25.5). With the district's shortage by group the difference is 76.0 (standard error 30.2), and 38.9 (standard error 28.4) without it. By the share of their need the pumps could supply, the slope is −74.7 (standard error 25.9) under a quarter, −74.7 (33.1) at a quarter to a half, −28.0 (34.4) at a half to three quarters, and −47.6 (22.0) at three quarters or more (Appendix Table A23). The water the pumps could supply also marks which fields kept land and water in the cut (Appendix Figure A2). Sort the fields without a well by the share of their need that the district's pumps alone could supply in 2016–2021, in the delivery model. From 2016–2021 to the cut, fields whose pumps could supply half to three quarters of their need kept 11.6 points more of their land farmed than fields whose pumps could supply under a quarter (standard error 3.9). They used 20 percent more water (18.5 log points, standard error 5.9). In the years just before the cut their water use did not differ (−0.5, standard error 3.6), and they had been losing land against those fields (3.6 points, standard error 2.7). The difference between the two periods is 15.2 points of land (standard error 3.5). The 101 fields whose pumps could supply three quarters or more point the same way, less clearly: 7.1 points more land (standard error 5.4) and 14.3 percent more water (standard error 8.0). Fields at a quarter to a half I cannot tell from those under a quarter. The district chose where its pumps stand, so the estimates show what pump locations predict, not what moving a pump would do. The cut cannot tell one rule from another, because every rule keeps the pumps in place.

Distance is not the whole of a field's place on the canal. Two fields the same distance from the head can face different competition, because the fields and the pumps between each of them and a source differ. The model works out how much water each source can supply to each field in each year. Table A17 uses all fields and compares each field with itself over 2017–2023. It compares fields at a similar distance from the head in the same year. It compares fields that have a pump above them with each other, and fields that have none with each other. A field that loses CAP water equal to 10 percent of the water it needs from the canal is 2.2 points more likely to be left fallow (standard error 1.1). If it is farmed, it uses 2.0 percent less water with the same crop (standard error 1.1), and 2.3 percent less when only fields on the same canal branch are compared (standard error 1.2). A farmed field that gains pump water equal to 10 percent of its need has a yield proxy 2.5 percent higher (standard error 1.6), and 3.2 percent higher when only fields on the same canal branch are compared (standard error 1.6). Its water use does not differ with pump water (0.2 percent, standard error 1.5). A field that gains pump water may be less likely to be left fallow (−4.0 points, standard error 2.4). Comparing only fields on the same canal branch changes the CAP column little (Panel B). Fallowing follows CAP water, and so does water use, clearly only within a branch; the crop on farmed fields may follow pump water.

In New Magma, where farmers run their own wells, fallowing divides by those wells. Fields without and with a well were fallow at 8.6 and 9.0 percent in 2016, 34.4 and 11.0 percent in 2022, and 45.5 and 19.0 percent in 2023, so the gap grows from nothing to 23 and then 27 points. With field and year effects, one unit of total stress raises the chance of fallowing by 13.1 points (standard

Table A17: Fallowing Follows CAP Water, Maricopa–Stanfield

	A field loses CAP water equal to 10 percent of its need	A field gains pump water equal to 10 percent of its need	Field-years
A. Fields at a similar distance from the head			
Chance the field is left fallow (points)	2.2 (1.1)	−4.0 (2.4)	16,093
Water use on farmed fields (percent)	−2.0 (1.1)	0.2 (1.5)	12,252
Yield proxy on farmed fields (percent)	−1.0 (1.0)	2.5 (1.6)	10,291
B. The same, comparing only fields on the same canal branch			
Chance the field is left fallow (points)	2.5 (1.2)	−2.3 (2.4)	16,086
Water use on farmed fields (percent)	−2.3 (1.2)	0.5 (1.6)	12,245
Yield proxy on farmed fields (percent)	−1.5 (1.1)	3.2 (1.6)	10,285
C. As Panel A, fields without a well of their own			
Chance the field is left fallow (points)	2.4 (1.1)	−4.9 (2.1)	13,608
Water use on farmed fields (percent)	−2.4 (0.9)	−0.9 (1.8)	10,504
Yield proxy on farmed fields (percent)	−1.5 (1.1)	1.4 (1.9)	8,758

Notes: A field's need is the water its crops need from the canal in a year. It is held at the field's 2016–2021 level in every year, so a fallow field keeps its need and its neighbors' fallowing does not change the water the model sends to it. The delivery model says how much water each source can supply to each field in each year. The gains and losses are the model's, since deliveries to single fields are not measured. Each field is compared with itself over 2017–2023 and with fields at a similar distance from the head in the same year. Fields that have a pump above them are compared with each other, and fields that have none with each other. Panel B also compares only fields on the same canal branch. The rows on farmed fields hold the crop fixed. Each row is one regression with field effects and separate year effects for each of ten bands of distance, for fields with and without a pump above them, for each crop class in the rows on farmed fields, and in Panel B for each canal branch. All fields farmed at least once in 2017–2021, with and without a well. Left fallow: linear probability, weighted by acres. Water use: Poisson regression on acre-feet above the year's mean on fallow fields. Yield proxy: ln of crop-season GCVI (Section 4.2), weighted by acres. Standard errors in parentheses, clustered by owner.

error 7.0), against 18.7 in Maricopa–Stanfield. Within a year in 2017–2021 the link is weaker, at 2.5 points (standard error 3.0). Its cut shows no slope on water use (−1.3, standard error 4.1). The water at its fields fell to 0.68 and 0.40 of usual demand, so fields at every place on the canal may have lost water together.

Section 8.6: Each district's rules, wells, and records. The model stays the same across districts, while the rules that divide water, who runs the wells, and the records that measure the water do not. Table A18 sets what each district's rules and records predict beside what I find.

Across the rows, three patterns fit together. First, in Maricopa–Stanfield, New Magma, Harquahala, the Upper Gila, and San Carlos, fields without a well use less water where and when the model says their canal falls short. Moving fields to other places reaches those slopes in at most 10 of 1,000 draws, and moving whole owners' fields in at most 50. Second, the best sharing rule follows each district's rules: equal sharing is rejected and side lines come first where water moves by order along canals (Maricopa–Stanfield and New Magma), equal sharing is the best rule where canals rotate (the Upper Gila), and a rule near equal sharing fits where stored water allotted by the acre mixes with natural flow by priority (San Carlos). Third, who keeps water follows who runs the wells. Where farmers pump their own wells, in Harquahala and New Magma, and for farmed land on the river's water in the Upper Gila, the loss falls on fields without a well. Where the district runs leased wells that pump into its canals, in Maricopa–Stanfield, the share of a field's need those pumps can supply marks which fields keep water. Where such wells are dense and run first, in Central Arizona, every field loses with the district's total. Where water is not short, in Wellton-Mohawk and the three Yuma districts, no field uses less water when the model says its canal is short.

Rotation on a river: the Upper Gila. The Upper Gila rotates water inside its canals (Sec-

Table A18: What Each District's Rules and Records Predict, and What I Find

District	What its rules and records predict	What I find	Match
Water falls short, and the record shows the water			
Maricopa–Stanfield	Fields without a well lose water in short months; equal sharing fails; losses in the cut follow the model; the district runs leased wells, so canal pumps mark who keeps water	Slope −61.5 (19.2). Equal sharing rejected. Pumps supply half of need or more −36.1 (25.4), less −75.1 (25.5). Cut −5.6 (2.2). Fallowing 18.7 (7.9).	Yes
New Magma	As Maricopa–Stanfield, but farmers run their own wells, so fields with one lose less	Slope −6.6 (4.1) without a well, −1.9 (7.2) with. Equal sharing −5.9, upstream first along lines and at splits 39.5, bar 26.7. Fallow gap, without minus with a well: 23 points in 2022, 27 in 2023. Cut −1.3 (4.1). Fallowing 13.1 (7.0).	Yes; cut no
Harquahala	Fields without a well lose water and the rest do not; 78 of 748 fields have no well, too few to pick a rule	Slope −31.4 (14.5) without a well, 0.4 (7.0) with; gap −31.8 (15.2). Search under its bar (30.9, 37.4).	Yes; shortage term no
Upper Gila	Equal sharing fits best; fields without a well lose farmed land where the river gives least	Equal sharing 61.0, the best rule; upstream first 28.2, bar 9.7. Slope −6.9 (2.2). River, farmed share: −6.6 (1.5) without a well, −1.3 (1.5) with.	Yes; river by month no
San Carlos	Stored water by the acre, natural flow by priority: a rule near equal sharing; fields without a well lose water in short months; fallowing follows the year's water and each field's calendar	Search 49.3, bar 40.9, near equal sharing. Slope −9.7 (4.6). Fallowing 42.9 (8.1), mostly calendar.	Yes
Senior rights: water does not fall short			
Wellton-Mohawk	No slope; no rise in fallowing	Search 1.4, bar 253.5. Slope 23.8 (8.9), the opposite sign. Fallowing −0.5 (7.7).	Yes
Three Yuma districts	No short month; no rise in fallowing	No short month. Fallow share −2.1, −9.5, −1.8 points.	Yes, all three
Water falls short, and the record misses water			
Central Arizona	The district runs 434 leased wells and records their capacity, not which ran; on such a record Maricopa–Stanfield's monthly and cut slopes vanish (Appendix Table A27)	Search 0.0, bar 8.2. Slope 5.1 (4.5). The cut follows total water: total −9.3 (2.2), pumps where they stand −1.8 (1.8). Fallowing with the total 44.4 (12.2).	Cannot tell
Hohokam	A flat cut, given half of the acres without a well farmed through 2023 on water the record does not show; no rule predicts a positive slope	Search 15.4, bar 27.6. Slope 25.8 (7.0) at its best take, 0.30; 76, 35, and 90 of 1,000 shuffles at or above it. Cut −6.0 (6.8) at a take of 1.00. Fields with and without a well fallowed alike.	Cannot tell
Count, 11 districts: yes 9 (4 with senior rights), cannot tell 2.			

Notes: Table 2 gives each district's rules and records. A district counts as a match when its main prediction holds; the last column names any part that does not. Slope: 100 times log monthly ET per unit of the shortfall, fields without a well, over all rules, at each district's best take: 0.66 in Maricopa–Stanfield, 0.72 in New Magma, 0.68 in Harquahala, 0.02 in Central Arizona, 0.56 in San Carlos, 0.30 in Hohokam, 0.98 in Wellton-Mohawk, and 1.00 in the Upper Gila; 2016–2021 in Maricopa–Stanfield, Central Arizona, Harquahala, and Hohokam, 2016–2023 elsewhere; standard errors in parentheses, clustered by owner and by year-month. Search and rule scores: held-out gain in fit, in basis points, against the district's bar. Cut: water use in 2022–2023, or farmed share where stated, per standard deviation of the predicted rise in shortfall. Fallowing: points per unit of total stress, fields without a well, with field and year effects; in Central Arizona, cut and fallowing are 2022–2023 against the district's total water, with where the pumps stand in the same regression, at a take of 0.70. Fallow share: 2022–2023 against 2016–2021. Three Yuma districts: Yuma County Water Users, Yuma Mesa, Yuma Irrigation.

tion 2.4). A rotation gives each field its turn in proportion to its demand, so the search should find equal sharing here, and it does. On each canal's reported diversions, over 45,224 field-months of 980 fields of 320 owners on ten canals, the best rule is equal sharing itself. It scores 61.0 against a bar of 9.7, at a take of 1.00 and κ and κ_J of 0. Upstream first along a line falls to 28.2. Over all rules the slope is −6.9 without a well (standard error 2.2) and −6.4 with one (standard error 1.5). Reassigning each calendar month's diversions across the years reaches the slope without a well in 2 of 1,000 draws ($p = 0.003$).

Reported diversions depend partly on what farmers ordered; the water the decree assigns each canal from the river does not. The monthly search finds nothing on the river's water (best score −4.0, bar 11.7). A daily river list may not time water inside a season, as reported diversions do. I have not tested that reading. I run the annual design on the river's water, comparing each canal with its own 2016–2021, because the Upper Gila had no 2022 cut. Per standard deviation, fields without a well lose 1.9 percent of water use (standard error 1.8) and 6.6 points of farmed share (standard error 1.5). Fields with a well lose 0.7 and 1.3 (standard errors 1.4 and 1.5). Reported diversions give nothing in that design (4.3, standard error 2.4).

Mixed rules: San Carlos. San Carlos mixes two systems: it allots its stored water by the decreed acre, natural flow goes by each account's priority date, and some CAP water arrives in short years (Section 2.4). Position along a canal should not decide who gets its stored water. The model sees neither the split of natural flow by priority date nor the CAP water of short years, which reached only some farms. The search clears its bar with a rule close to equal sharing (best score 49.3 at a take of 0.56, κ of 0 and κ_J of 0.12; bar 40.9). At that take, fields without a well use less water when their shortfall rises (−9.7, standard error 4.6); no shuffled date or moved field in 1,000 reaches that slope, and 15 draws that move whole owners' fields do ($p = 0.016$). Fallowing rises with total stress (42.9 points per unit, standard error 8.1). That stress is mostly each field's crop calendar against the year's water. The calendar explains 58.5 percent of it, and distance along the canal by year 5.7 percent. So San Carlos mixes the two systems in its results as in its rules: a rule close to equal sharing, as on the Upper Gila's canals, and water use that falls with the shortfall, as in the CAP districts.

District wells first: Central Arizona. Central Arizona has run the wells within its boundaries under 40-year leases since about 1990, and it runs them first (Sections 2.2 and 2.4). Its records give the capacity of its 434 wells but not which of them ran. On such a record, the monthly slope of Maricopa–Stanfield's run shrinks from −61.6 to −14.1 with reported totals and turns to +7.3 with a flat total, and its cut and fallowing slopes vanish (Appendix Table A27). A record that does not say which wells ran would therefore show little even where the model holds. In Central Arizona the search finds little (best score 0.0, bar 8.2), and I cannot tell the monthly slope from zero (5.1, standard error 4.5). Its wells are dense: 79 percent of fields have a canal pump within 2 km above. Its CAP water is the remainder, so when CAP fell every field lost in proportion to the district's total shortfall. The cut follows that total, not where the pumps stand. With both in one regression, at a take of 0.70, water use in the cut falls with the total (−9.3, standard error 2.2) and not with where the pumps stand (−1.8, standard error 1.8), and fallowing rises with the total (44.4, standard error 12.2).

Records that miss water: Hohokam. Hohokam is the one district the model does not fit. Its search does not clear the bar (best score 15.4 at a take of 0.30, bar 27.6). At that take, fields the model calls short use more water (25.8, standard error 7.0). Shuffled dates, fields, and owners give a slope at least as large in 76, 35, and 90 of 1,000 draws. At a take of 0.70 the slope is −1.4

(standard error 6.5). Its fallowing does not follow total stress (−10.3, standard error 7.4).

Part of the reason is in its records, which miss water, and its private wells did not cover the loss. Half of the acres without a well were still farmed in 2023, and their water use above fallow fields, 2,959 acre-feet, exceeds all the CAP water that could have reached any field that year (1,861). Fields without and with a well fallowed alike, at 39.2 and 40.2 percent of acres in 2022 and 46.8 and 50.9 percent in 2023, and private pumping did not rise when CAP fell (Appendix A15). So a shortfall here need not mean a shortage. Its rules give no order along its canals (Section 2.4), and the flat cut (−6.0, standard error 6.8) is what such rules predict.

Section 8.7: A shortage on paper. For the senior-rights districts I run the same satellite data through the same code and network rules, on water that is not short. In Wellton-Mohawk, water covers crop demand in every March–October month but two. The search finds nothing (best score 1.4, bar 253.5). The slope has the opposite sign from the short districts (23.8, standard error 8.9). Shuffled dates give a slope that large in 1 of 1,000 draws, moved fields in none, and moved owners in 26; the shortfall is above zero in only two months, so the slope rests on them. Fallowing does not follow total stress (−0.5, standard error 7.7).

I then remove water on paper. I lower the share of diverted water reaching crops from 0.7 to as low as 0.3 in the four senior-rights districts, 15 runs in all. The fields' real water does not change, so a model that finds a slope in any shortage it is given would find one here. In three of the four districts no rule clears the bar. Wellton-Mohawk, Yuma Mesa, and Yuma County Water Users stay under it in every run. Some slopes turn negative without clearing it. Wellton-Mohawk's runs from −1.3 to −12.7 at shares of 0.5 to 0.3; at 0.4 it is −12.7 (standard error 6.0), where no rule clears the bar (4.5 against 9.6). Yuma Mesa's at 0.4 is −9.5 (standard error 5.0). Fallowing does not rise. Of 12 regressions with enough stress, 9 are negative and the largest is 6.2 (standard error 5.3), against 18.7 in Maricopa–Stanfield.

Yuma Irrigation is the exception. At a share of 0.6, the highest that makes any month short, and at 0.5, the search clears the bar (19.2 against 17.4, and 28.8 against 25.5). The slopes have the right sign (−31.0, standard error 11.2, and −12.0, standard error 4.4). The result fades at lower shares. Over all rules at a take of 1.00, the slope goes from −53.9 at 0.6 (standard error 13.3) to 6.1 at 0.3 (standard error 9.4). Reclamation's accounting puts consumptive use in Yuma Irrigation and Yuma Mesa at 0.53 to 0.56 and 0.52 to 0.70 of diversions, against about 0.7 in the other two. Yuma Irrigation's short months at 0.6 fall in the peak months, as such a limit would. Yuma Mesa clears no bar, so the limit appears in one district of the two. I read it as a possible limit, not a finding.

Section 8.8: What shortfalls cost, further numbers. Of the land farmed the year before, 17,064 acres went fallow in 2022 and 12,662 in 2023. The model's shortfalls account for about 18 percent of the land left fallow, worth $1.3–1.5 million a year. Had farmers planted every field and spread the water thin, crop budgets imply a loss of $24–38 million a year. Across all planted fields, the loss of the second wave was $1.0 million in 2022 and $1.4 million in 2023 (Appendix Table A38, Panel B).

Section 8.9: What a remedy would need, further numbers. In the years before the cut, the gain from filling every shortfall falls on 23 percent of the acres of fields without a well. A new well with pipeline costs $163 per acre a year (Maricopa–Stanfield Irrigation and Drainage

District 2024). Lining the Upper Gila canals returns 1 to 4 percent of its capital. Interior's rules for 2027–2028 cut deliveries to the lower Colorado River states by 1.25 million acre-feet a year (Interior 2026; Reclamation 2026b). Covering the model's shortfalls in the cut would have kept 2,553 to 2,660 acres farmed.

A13 Estimates and Samples

Table A19 gives the samples, and Table A20 the numbers behind the scorecard of Table A18. Table A21 gives each named rule's score. In Maricopa–Stanfield, at a take of 0.66, test inversion rejects equal sharing ($p = 0.005$) and upstream first only along a line ($p = 0.010$), and it keeps side lines first at a split ($p = 0.144$) and both together ($p = 0.055$). Across the rules and takes it tests, it keeps takes of 0.58 and 0.64 to 0.82, κ_J of 0.5 to 1, and every κ. The score rises sharply to the best take and falls slowly above it: the best score is −0.8 at 0.60, 36.8 at 0.66, 33.7 at 0.70, 29.3 at 0.80, and 8.8 at 0.88. At the best rule (a take of 0.66, κ of 0.28, and κ_J of 0.90), the share of the held-out gain by year left out is −6, 1, 20, −1, 45, and 41 percent over 2016–2021. The gain comes from 2020 and 2021. Each year left out is predicted against each field's level in the other years, so 2021, a year with no short month, gains where the fields and months the model marks short in 2019 and 2020 used more water than they did then. In New Magma the best score by take is 19.8 at 0.60, 40.7 at 0.70, 29.6 at 0.80, 36.5 at 0.88, and 27.8 at 1.00, and 42.6 at 0.72, its best.

Table A19: The Monthly Samples

District	Years	e	Field-months	Fields	Owners	Fields without a well
Maricopa–Stanfield	2016–2021	0.72	67,104	2,021	463	1,711
New Magma	2016–2023	0.70	24,520	514	244	420
Harquahala	2016–2021	0.73	26,640	748	64	78
Upper Gila, ten canals	2016–2023	0.70	45,224	980	320	310
Central Arizona	2016–2021	0.73	75,592	2,072	617	1,987
Hohokam	2016–2021	0.75	27,328	771	138	119
San Carlos	2016–2023	0.70	38,832	1,111	285	763
Wellton-Mohawk	2016–2023	0.70	122,496	3,336	304	2,430
Yuma County Water Users	2016–2023	0.70	53,240	2,063	366	1,771
Yuma Mesa	2016–2023	0.70	24,248	570	239	463
Yuma Irrigation	2016–2023	0.70	17,000	616	86	255

Notes: March–October field-months on the tree with ln ET and the controls, after cells with a single observation drop out of the fixed effects. Owners count a field with no known owner as its own. The Yuma districts have no short month at $e = 0.70$, so their samples enter only the runs of Table A34. Central Arizona: the version built from its documents, whose no-well fields are those without a local pump.

Table A22 gives the estimates behind Maricopa–Stanfield's results in Section 8.4 and Section 8.5. The model predicts how short a field is as well as whether it is. Small shortfalls leave water use unchanged and larger ones reduce it. The loss grows up to a shortfall of about 0.5 and then holds.

The 2022–2023 cut in more detail. In June 2022 Maricopa–Stanfield wrote that it had cut allotments to growers by half (Maricopa–Stanfield Irrigation and Drainage District 2022b). In the other districts CAP fell to 37 (Central Arizona), 24 (Hohokam), and 9 percent (Harquahala) of its 2016–2021 mean in 2022, and to 0 to 6 percent in 2023 (CAP 2023). In a balanced panel of monitoring wells, depth to groundwater in five CAP agricultural-pool districts rose 8.33 feet more than in comparison districts from 2021 to 2023 ($p = 0.008$; Appendix A20). By 2024 Maricopa–Stanfield wrote that limits in its infrastructure, and the coming removal of wells from the Santa Rosa Canal, left some farmers as little as 0.78 acre-feet per acre (Maricopa–Stanfield Irrigation and Drainage District 2024). Other measures of who the cut reached point the same way, per

Table A20: The Numbers Behind the Scorecard

District	Water	Best score / bar	Rule at the best (τ, κ, κ_J)	Slope on the shortfall, all rules: No well	Slope on the shortfall, all rules: With a well	Fallowing on total stress
Maricopa–Stanfield	CAP, canal pumps	36.77 / 31.24	0.66, 0.28, 0.90	−61.54 (19.24)	−165.69 (71.04)	18.7 (7.9)
New Magma	CAP	42.60 / 26.72	0.72, 0.76, 1.00	−6.58 (4.12)	−1.88 (7.23)	13.1 (7.0)
Harquahala	CAP	30.90 / 37.41	0.68, 0.26, 0.08	−31.36 (14.45)	0.44 (7.01)	
Upper Gila	Reported diversions	60.98 / 9.68	1.00, 0, 0	−6.86 (2.19)	−6.39 (1.52)	10.9 (6.4)
Central Arizona	CAP, district wells	0.03 / 8.19	0.02, 1.00, 0.48	5.10 (4.54)	55.18 (20.80)	8.3 (4.3)
Hohokam	CAP	15.43 / 27.58	0.30, 1.00, 0.40	25.75 (6.98)	30.29 (37.18)	−10.3 (7.4)
San Carlos	Stored water	49.32 / 40.90	0.56, 0, 0.12	−9.74 (4.59)	−25.68 (12.92)	42.9 (8.1)
Wellton-Mohawk	Colorado River	1.38 / 253.51	0.98, 1.00, 0.22	23.79 (8.92)	9.10 (15.35)	−0.5 (7.7)
Three Yuma districts	Colorado River			No short month		

Notes: Best score and bar: held-out gain in fit, in basis points. Slopes: 100 times log monthly ET per unit of the shortfall, over all rules, at each district's best take: 0.66 in Maricopa–Stanfield, 0.72 in New Magma, 0.68 in Harquahala, 0.02 in Central Arizona, 0.56 in San Carlos, 0.30 in Hohokam, 0.98 in Wellton-Mohawk, and 1.00 in the Upper Gila; standard errors clustered by owner and by year-month. Fallowing: points per unit of total stress, fields without a well, with field and year effects, at a take of 1.00 in New Magma and San Carlos; in Central Arizona, the version built from its documents. Harquahala has no fallowing estimate on total stress. Three Yuma districts: Yuma County Water Users, Yuma Mesa, Yuma Irrigation.

Table A21: The Score of Each Named Rule

District, take	Equal sharing	Upstream first along a line	Side lines first	Both	Best at any take	Bar
Maricopa–Stanfield, 0.66	−19.26	5.08	24.58	16.51	36.77	31.24
New Magma, 0.70	−5.90	−3.28	8.52	39.50	42.60	26.72
Upper Gila, reported, 1.00	60.98	28.18			60.98	9.68
Upper Gila, reported, 0.70	41.34	20.18				
Harquahala, 0.68		1.24	−23.09	−20.20	30.90	37.41
Central Arizona, 0.02	−2.54	−8.43	−1.96	−1.38	0.03	8.19
Hohokam, 0.70	−1.66	−8.19	−11.17	−4.39		
Hohokam, 0.30	−11.90	−0.33	0.22	−3.94	15.43	27.58

Notes: Held-out gain in fit, in basis points. Equal sharing: $\kappa = \kappa_J = 0$. Upstream first along a line: $\kappa = 1$, $\kappa_J = 0$. Side lines first: $\kappa = 0$, $\kappa_J = 1$. Both: $\kappa = \kappa_J = 1$. The score is blind to sign; Table A20 gives the slopes. Blank in the Upper Gila's row: κ_J matters on only two canals, so I report the first two rules. Harquahala's equal sharing cannot be judged: its shortfall barely varies within a month, and S_t explains 72 percent of it.

Table A22: Maricopa–Stanfield: The Shortfall, the Cut, and Fallowing

A. Monthly water use by size of the shortfall, fields without a well, against 0.01–0.05

Below 0.01	−4.24 (2.69)
0.01–0.05	0 (reference)
0.05–0.10	−0.14 (2.04)
0.10–0.20	−3.73 (2.54)
0.20–0.35	−12.67 (4.14)
0.35–0.50	−31.57 (10.12)
0.50 or more	−37.46 (9.95)

B. The cut, per standard deviation of the predicted rise, 1,979 fields without a well

	Water use	Farmed share
Cut minus before	−5.6 (2.2)	−4.9 (1.3)
Without kilometers from the head	−4.0 (2.3)	−4.2 (1.4)
Before, 2020–2021 against 2016–2019	−1.1 (1.3)	1.1 (1.0)
The best rule alone	−4.7 (2.3)	−4.3 (1.4)
Fifteen variants of the build, equal sharing: range	−1.6 to −5.5	−3.1 to −5.7

C. Fallowing on total stress, fields without a well farmed the year before

	Per unit	Per SD
Within a year, 2017–2023	12.7 (6.7)	2.4
Kilometers from the head by year beside it	16.7 (7.0)	3.1
Field and year effects	18.7 (7.9)	3.5
Both years at usual demand	9.9 (5.2)	2.6
Within a year, 2022–2023	18.0 (7.8)	3.9
Within a year, 2017–2021	−6.6 (15.5)	
Next year's stress, 2017–2022	5.7 (7.6)	

D. Fallowing by total stress, against below 0.01

	Within a year	Field and year effects
0.01–0.05	−0.7 (1.2)	−1.0 (1.3)
0.05–0.10	0.0 (2.2)	−0.1 (2.2)
0.10–0.20	2.3 (2.2)	1.3 (2.3)
0.20–0.35	4.0 (2.8)	2.4 (3.1)
0.35–0.50	5.3 (3.8)	5.2 (4.4)
0.50–0.75	−0.6 (4.4)	0.9 (4.9)
0.75–1	20.9 (8.3)	24.7 (8.8)
1 or more	−11.0 (20.3)	−2.4 (19.4)

Notes: All rules at a take of 0.66 unless stated. The fifteen variants use equal sharing, which gives −5.4 (2.1) for water use and −5.6 (1.2) for farmed share on the final version itself. Five variants change options that the final version does not use, so they match it. The variant with the older well rule (any registered well within 500 m) gives −1.6 (3.1) and −3.1 (2.8). Panel A: 2016–2021, specification of equation (11), clusters by owner and year-month. Against months with a shortfall below 0.01, each estimate in Panel A is 4.24 higher. Panels B to D: owner clusters. Panel B, best rule's before: water use −1.4 (1.9). Panels C and D: mean fallowing 13.3; last year's and this year's stress in one regression sum to 26.3 (28.1), joint $p = 0.123$.

standard deviation in water use: the model's CAP share in 2016–2021, −4.7 (standard error 2.1; before −0.1, 1.3), and its well share in the cut, 5.4 (2.1; before 0.0, 1.5).

A14 Robustness

Pump locations. Table A23 keeps the water and moves only its location: delivered at the pumps, or pooled over all claims each month. Delivered water matches by year (1.000 and 1.000 in 2016; 0.716 and 0.715 in 2022 at fixed demand). The monthly slope needs both location and rule. Equal sharing at the pumps and all rules pooled, in one regression, give −32.94 (standard error 31.60) and −66.82 (22.74). In the years before the cut the model separates rules from equal sharing. In the cut and in fallowing it cannot, because every rule keeps the pumps in place (fallowing on the two together: −18.2, standard error 12.9, and 35.8, standard error 12.8; correlation 0.95).

Table A23: Pumps Where They Stand Against the Same Water Pooled, Maricopa–Stanfield

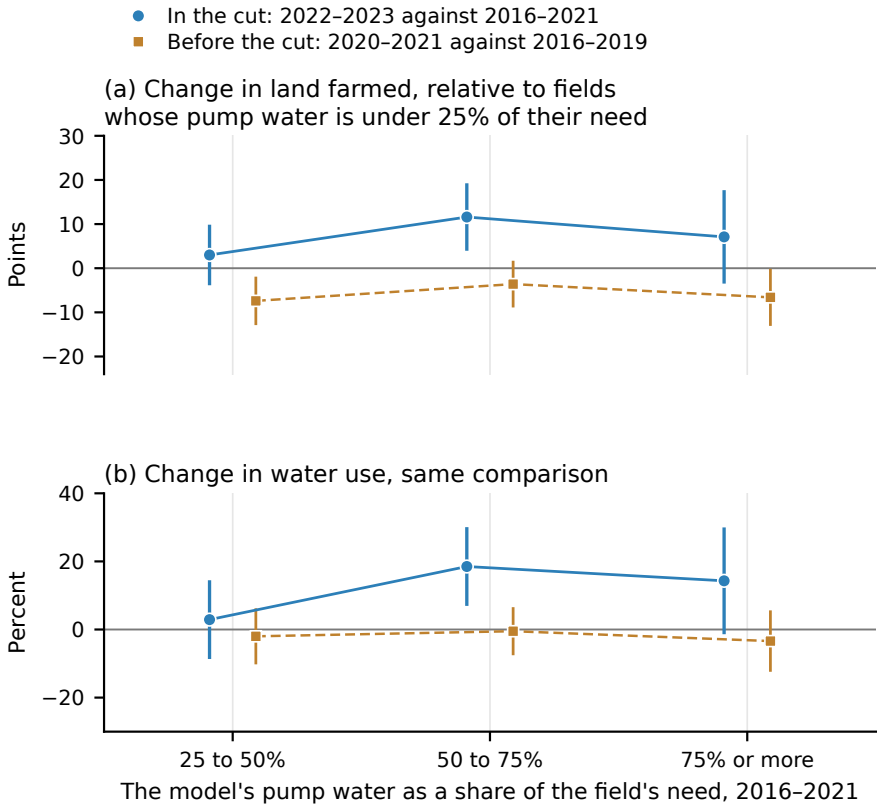
	One at a time		Together	
Fields without a well	At the pumps	Pooled	At the pumps	Pooled
Monthly slope	−61.54 (19.24)	−67.64 (23.11)	−61.00 (24.13)	−2.93 (24.25)
Water use in the cut, cut minus before	−5.6 (2.2)	2.8 (3.0)	−5.5 (2.2)	2.3 (3.0)
Farmed share in the cut, cut minus before	−4.9 (1.3)	5.1 (2.3)	−4.6 (1.3)	4.7 (2.4)
Fallowing on total stress, within a year	12.7 (6.7)	−12.2 (13.7)	15.6 (7.3)	−23.3 (14.8)
Fallowing on total stress, field and year effects	18.7 (7.9)	−25.7 (17.7)	24.6 (8.6)	−44.0 (19.0)
Slope on the pooled shortfall, by whether the pumps could supply half of the field's need				
	Half or more	Less	Difference	
Plain	−36.13 (25.35)	−75.07 (25.47)	38.94 (28.38)	
S_t times kilometers from the head beside it	−28.86 (25.99)	−64.97 (24.84)	36.11 (27.84)	
S_t times group beside it	−7.18 (24.73)	−83.17 (26.04)	75.99 (30.17)	

Notes: All rules at a take of 0.66. Monthly: 2016–2021, clusters by owner and year-month. Cut: per standard deviation of each predicted rise, owner clusters. Lower panel: 452 fields whose pumps could supply half or more of their need in 2016–2021 and 1,259 others. By the share, under a quarter, a quarter to a half, a half to three quarters, and three quarters or more (432, 827, 350, 102 fields): −74.66 (25.85), −74.67 (33.13), −28.01 (34.41), −47.64 (21.95). By a canal pump within 2 km above (1,213 fields with, 498 without): −39.26 (21.70) and −79.93 (27.58), difference 40.67 (25.91). A pump below a field cannot deliver to it: 82.48 (31.41), against 64.38 (30.30) for a pump above, both against the 185 fields with neither. The shortfalls at the pumps and pooled are correlated 0.89 in the monthly data, 0.83 for total stress, and 0.10 for the predicted rise in the cut.

The earlier version of Maricopa–Stanfield's run. Before the canal pumps were placed at their wellheads, an earlier version of the run put each of the 130 canal pumps at one point on a canal. It used the network before the lines added from the district's and Reclamation's maps, and its take was 0.70. Its monthly slope for fields without a well is −16.9 (standard error 5.2), against −61.5 (19.2) in the final version of Section 8.4. Per standard deviation of the shortfall the two are closer, −1.6 and −2.9, because the final version's shortfalls vary half as much (0.047 against 0.092). In the final version, fields without a well run short only in 2019 and 2020, in 31 and 29 percent of their field-months. In 2021, the drought year, the canals still met the planted fields' need. At usual demand about 4 percent of July–October need would have gone unmet, but July brought 42 mm of rain (at most 12 mm in the other Julys) and July and August had the lowest reference evapotranspiration of 2016–2023, which lowered crop need. Its monthly slope therefore rests on those two years. In the earlier version they also ran short in 2017 (29 percent). Every check below uses the final version. Table A25 uses the earlier placement, one point per canal pump, on the final network.

Which wells count as local. Table A24 keeps the 144 canal pumps and widens the local pumps from 149 to 331 other rated wells or all 404 other wells on the map. Each list has its own search and null, and the main list also has test inversion. The take rises from 0.66 to 0.84–0.86, and

Figure A2: Land Farmed and Water Use by the Share of Need the Pumps Could Supply, Before the Cut and in It, Maricopa–Stanfield



Notes: Each point compares fields without a well whose pumps could supply that share of their need with the 643 such fields whose pumps could supply under a quarter of it (36 of them had no need from the canal in 2016–2021). The share is the water the district's pumps alone could deliver to a field in the delivery model, up to its need in each month, over its need in 2016–2021. In the cut: the change from 2016–2021 to 2022–2023. Before the cut: the change from 2016–2019 to 2020–2021. Panel (a): the share of years farmed, in points. Panel (b): water use, in percent. Fields by share: 935, 374, and 101. Bars are 95 percent confidence intervals.

where computed the total claim on the canal stays at 92 to 93 percent of need. The slope for fields without a well does not move, though that group loses 27 percent of its fields with all wells. On the main list, a field's own well shows no protection: at the same location, such fields do not respond less. Beyond 5 km of a pump or with none above, own well minus none is −59.85 (standard error 37.29) on the main list. From before the cut to 2022–2023, that difference changes by +1.2 (standard error 11.8) for water use and by +10.5 (8.5) for the share farmed. The lists may hold idle wells.

Table A24: Three Lists of Local Pumps, Maricopa–Stanfield

	Main	Rated wells	All wells
Fields with a local pump, of 2,384	369	807	907
Best score	36.77	39.74	38.79
Best: take, κ, κ_J	0.66, 0.28, 0.90	0.84, 0.16, 0.88	0.86, 0.12, 0.82
Bar	31.24	21.48	25.70
Slope, no well	−61.54 (19.24)	−64.50 (19.24)	−58.12 (16.81)
Water use in the cut	−5.6 (2.2)	−5.1 (2.5)	−5.6 (2.6)
Farmed share in the cut	−4.9 (1.3)	−5.4 (1.5)	−5.4 (1.4)
Fallowing on total stress	12.7 (6.7)	14.0 (6.7)	13.6 (6.6)
Field and year effects	18.7 (7.9)	19.6 (8.0)	19.4 (8.0)
Total stress of 1 or more	−11.0 (20.3)	16.0 (19.6)	33.1 (28.6)
Canal claim, share of total need	0.923	–	0.929

Notes: The final version of Maricopa–Stanfield's run (144 canal pumps at their wellheads). Each column at its own best take, all rules. No draw of 200 reaches the best score on any list. The canal claim was not computed for the rated wells.

Where the canal pumps stand. Table A25 rebuilds the model with the canal pumps placed or chosen otherwise (Panel A) and shows how fields without a well respond by their distance below a pump (Panel B). In the earlier placement, a canal pump that stands by a farm ditch but not by the canal puts its water in where that ditch leaves the canal, so the water also reaches the canal below that point. Placed on its ditch instead, its water reaches only the fields of that ditch no higher than the well: 36 of Maricopa–Stanfield's 52 such pumps and 68 of Central Arizona's 95 move, and the rest, which pumped more in 2019 than the fields below them need or have no field below them, stay. The monthly slopes are then −13.4 and 15.7, against −12.5 and 17.1 in the earlier placement, and Maricopa–Stanfield's search no longer clears its bar (6.91 against 9.06). In the cut, fields without a well lose water in every row of both districts.

Maricopa–Stanfield's well records name its district wells and what each pumped in 2019. Central Arizona's do not say which wells the district runs, and its wells' volumes are in proportion to their ratings. With only Central Arizona's wells of 1,500 gallons per minute or more feeding the canal, its monthly slope is −15.5; with its ditch pumps that have no mapped turnout and stand more than 500 m from the canal serving their owners' fields instead, −3.5. Leaving out the fields those wells would serve does not move the earlier placement's slope (17.8 and 18.2), so the water, not the sample, makes the difference.

Panel B shows where the earlier placement's slopes come from. The nearer a field lies below a large pump, the less its water use falls when the canal falls short: in Maricopa–Stanfield the slope runs from −14.7 within half a kilometer to −38.4 at 2 to 5 kilometers, and in Central Arizona from 7.7 to −23.3. Central Arizona's positive slope comes from its fields more than 5 kilometers below a large pump or with none above them (26.4 and 40.4; 652 fields). Leaving out each branch in turn, or the fields within 200 m of any well, leaves those slopes in place.

Other checks in Maricopa–Stanfield. The bar flips signs by owner, so neighbors on a branch get independent signs. In a second check, groups of up to 100 neighboring fields swap places with

Table A25: Where the Canal Pumps Stand: Specifications

	Canal pumps	Fields without a well	Monthly slope	Cut, per SD		Pump within 2 km above		Pump below only
				Water use	Farmed	With	Without	
A. Specifications								
Maricopa–Stanfield								
Earlier placement	134	1,675	−12.5 (4.9)	−8.6 (2.3)	−6.4 (1.4)	−13.0 (13.7)	−35.1 (15.7)	−54.3 (25.5)
Ditch pumps on their ditch	134	1,675	−13.4 (6.7)	−9.1 (2.3)	−9.0 (1.4)	−3.2 (12.0)	−23.1 (15.9)	13.2 (18.9)
No-turnout pumps at the nearest point	134	1,675	−13.2 (5.3)	−8.8 (2.2)	−7.5 (1.3)	−14.7 (15.3)	−24.6 (13.0)	−32.7 (23.8)
Each branch out (19), range			−14.9 to −7.5	−10.2 to −6.6	−7.1 to −5.3			
No field within 200 m of a well		1,054	−20.6 (7.3)	−11.3 (2.9)	−8.2 (1.7)			
Central Arizona								
Earlier placement	218	1,467	17.1 (4.7)	−14.5 (2.8)	−3.2 (1.8)	0.1 (7.5)	4.7 (10.1)	45.5 (17.6)
Ditch pumps on their ditch	218	1,467	15.7 (4.4)	−15.5 (2.7)	−3.1 (1.8)	−2.0 (6.8)	8.5 (11.0)	51.1 (14.8)
Pumps of 1,500 gpm or more	101	1,192	−15.5 (5.6)	−10.4 (2.8)	−2.9 (1.9)	−2.0 (6.7)	−0.7 (9.7)	−8.7 (9.6)
No-turnout pumps at the nearest point	218	1,467	16.2 (3.9)	−15.7 (2.7)	−2.5 (1.6)	−1.9 (7.2)	7.1 (9.9)	47.6 (15.3)
Far no-turnout pumps as local	166	1,366	−3.5 (6.0)	−14.8 (3.1)	−3.1 (1.6)	−0.7 (8.2)	4.8 (11.0)	−7.6 (9.6)
Each branch out (17), range			13.8 to 19.8	−16.2 to −10.4	−4.9 to −0.9			
No field within 200 m of a well		863	20.2 (5.5)	−14.9 (3.4)	−2.5 (2.0)			

B. The earlier placement: slope on the pooled shortfall by kilometers below the nearest canal pump above

	Canal pumps	0–0.5	0.5–1	1–2	2–5	Over 5	None above
Maricopa–Stanfield, all	134	−8.0 (17.1)	−16.3 (16.5)	−18.5 (17.9)	−39.1 (19.0)	−41.3 (17.3)	−15.9 (24.0)
		514	187	309	293	117	255
Maricopa–Stanfield, 1,500 gpm or more	69	−14.7 (17.8)	−17.6 (16.8)	−13.6 (23.4)	−38.4 (23.1)	−23.5 (14.1)	−33.1 (18.9)
		279	127	202	314	235	518
Central Arizona, all	218	6.5 (7.9)	−34.2 (11.2)	10.7 (11.7)	−16.4 (11.1)	44.1 (14.6)	−152.2 (109.4)
		622	159	175	293	205	13
Central Arizona, 1,500 gpm or more	101	7.7 (9.2)	−7.3 (12.5)	−16.2 (13.6)	−23.3 (11.4)	26.4 (9.7)	40.4 (15.4)
		345	79	157	234	438	214

Notes: Earlier placement: each canal pump at one point, as in the earlier version of Maricopa–Stanfield's run, on the final network; in Central Arizona, version A of Table A33. All rules at a take of 0.70; each row rebuilds the model with its pumps. Monthly slope: water use on the shortfall, fields without a well, 2016–2021, clusters by owner and year-month. Cut: 2022–2023, cut minus before, per standard deviation of the predicted rise, owner clusters. Last three columns: slope on the pooled shortfall with a canal pump within 2 km above the field and without, and the difference for fields with a pump below them only. Ditch pumps are canal pumps connected by a ditch only; on the ditch, a pump's water reaches the fields of its ditch system not above the well by more than 1 m, and pumps that pumped more in 2019 than those fields need keep the earlier placement. No-turnout pumps: ditch pumps on a ditch system with no mapped turnout, which in the earlier placement put their water in at the most upstream canal point of their system's fields; at the nearest point: at the canal point nearest the well; far: more than 500 m from the canal. Central Arizona only, since Maricopa–Stanfield's well records name its district wells: with pumps of 1,500 gpm or more, or with far no-turnout pumps as local pumps, the other district wells serve their owners' fields, which then count as fields with a well. Placed on the ditch, a field below a ditch pump has that pump above it at 0 km, and fields above it on its ditch have it below them. Branches: the network's, each left out of the sample in turn. Panel B: the earlier placement; fields without a well grouped by kilometers along the canal tree below the nearest canal pump above, counting all canal pumps or only those rated 1,500 gpm or more; slope of monthly water use on the pooled shortfall in each group, 2016–2021; fields in small type.

other groups inside the same branch of up to 500 fields, so differences between branches stay as they are. In 1,000 such draws, 14 do as well as the real data on the slope of fields without a well, 175 on the all-rules score, 72 on the best of the 121 rules, and 19 on the best rule's gain over equal sharing. With S_t times kilometers from the head beside it, the slope is −56.65 (standard error 18.99), and the term itself is −11.44 (9.81). While CAP flows a field's place on the canal matters, and once CAP is gone the pumps above it do: the delivered share's correlation with kilometers from the head is −0.63 in 2016–2021 and −0.28 in 2022–2023.

The fallow measure. Section 8.4 takes a field's fallow status from the Cropland Data Layer. Table A26 reruns Maricopa–Stanfield with the water-use rule of Appendix S6 plus a test that a field it calls bare never turns green. Water use and the farmed share in the cut change little, and the monthly slope keeps its sign. The search clears its bar on the layer and with the five-day green window, and the loss in the two upper shortfall bins is smaller with the green tests.

Table A26: Three Fallow Measures, Maricopa–Stanfield

	Layer	Rule, yearly GCVI	Rule, five-day green
Best score (take)	36.77 (0.66)	21.88 (0.76)	32.70 (0.76)
Bar	31.24	23.20	27.13
Slope, no well, all rules	−61.54 (19.24)	−22.63 (12.53)	−32.83 (14.62)
Loss, shortfall 0.35 or more, percent	27 to 31	6.0 to 9.9	11.5 to 20.3
Water use in the cut	−5.6 (2.2)	−6.2 (2.2)	−6.1 (2.2)
Farmed share in the cut	−4.9 (1.3)	−3.8 (1.4)	−4.7 (1.5)

Notes: Layer: the Cropland Data Layer alone, as in the text. The rule: fallow when the layer gives no crop or the water-use rule of Appendix S6 calls the field-year bare. Rule, yearly GCVI: a field-year the rule alone calls bare counts as fallow only if the field's yearly GCVI peak, the larger of its May–September and November–April maxima, is below 2. Rule, five-day green: only if the field never reaches a GCVI of 2 in any five-day window; those curves exist for four districts, and 2016 and fields without them keep the rule's label. Best score and bar: held-out gain in fit, in basis points, at each column's best take. Slope: 100 times log monthly ET per unit of the shortfall, fields without a well, over all rules at a take of 0.66. Loss: $e^{b/100} - 1$ for the two upper bins, shortfalls of 0.35 to 0.50 and of 0.50 or more, against the bin of 0.01 to 0.05. In the cut: 2022–2023 minus before, per standard deviation of kilometers from the head, fields without a pump; standard errors in parentheses.

Shortfalls in nearby months move together, because the crops planted before the season set demand for the whole summer. Entered together, next, this, and last month's shortfalls give −36.48 (16.35), −29.29 (13.67), and −47.02 (19.68). The monthly design therefore shows which fields run short over a stretch of the season more surely than the single month. Monthly pumping is imputed, and farmers may know shortages ahead; I have tested neither, and the annual designs do not depend on it. In the cut, fields far from the head lose less, 9.2 per standard deviation of kilometers (standard error 2.4; before 3.2, 1.8). The model does not explain that, and it rests on the two end tenths. Water use responds mostly through fallowing: on fields farmed in all eight years the estimate is −0.4 (2.0). The farmed share's contrast before the cut is 1.1 (1.0). Fallowing's response comes from the cut years (18.0, standard error 7.8, against −6.6, standard error 15.5, in 2017–2021). Year by year it is 7.3 (19.7), 53.3 (34.8), −57.5 (25.6), 19.4 (13.0), and 16.0 (10.6) over 2019–2023; in 2018 the model leaves fields without a well almost no shortfall. Next year's stress is not clean in 2017–2020 alone, at 56.0 (18.0).

The record of which wells ran. Table A27 gives Maricopa–Stanfield the kind of well record Central Arizona has. A flat district total roughly halves the monthly slope (−28.02, standard error 14.62, against −61.58, 19.27) and weakens the cut's estimates (−3.9, 2.3, and −2.5, 1.6). Capacity in place of each well's 2019 volume cuts the monthly slope to a third (−20.85, 9.37), while the cut's losses hold (−7.2, 2.5, and −3.8, 1.4). Losing the record of which wells ran costs nearly everything. In one regression the 2019 volumes beat capacity (−151.13, standard error 39.96, against 106.29,

31.31). The two shortfalls move closely together (correlation 0.88), so their coefficients pull apart. Only 2019 and 2020 have short months at this take, so 2019 pumping may partly reflect that year's shortage. I cannot separate the two.

Table A27: Maricopa–Stanfield on Central Arizona's Kind of Well Record

Well record	Monthly slope	Water use in the cut	Farmed share	Fallowing
Its own 2019 volumes, reported total	−61.58 (19.27)	−6.4 (2.3)	−4.8 (1.4)	6.5 (3.6)
2019 volumes, flat total	−28.02 (14.62)	−3.9 (2.3)	−2.5 (1.6)	4.6 (3.5)
Capacity, reported total	−20.85 (9.37)	−7.2 (2.5)	−3.8 (1.4)	6.6 (3.3)
Capacity and idle wells, reported total	−14.13 (8.68)	−3.2 (2.9)	−1.7 (1.7)	1.4 (3.1)
Capacity and idle wells, flat total	7.30 (8.75)	−1.0 (2.7)	−0.6 (1.8)	−0.6 (3.1)

Notes: The final version of Maricopa–Stanfield's run. Fields without a well, 121 rules at a take of 0.66, monthly-sample fields. Cut: per standard deviation, cut minus before.

Table A28: Water Use by the Share of Need the Pumps Could Supply, Maricopa–Stanfield

	2017	2018	2019	2020	2021	2022	2023
Under a quarter, acre-feet per acre	1.52	1.74	1.43	1.52	1.50	0.97	0.73
A quarter to a half	1.98	2.02	1.79	1.95	1.67	1.28	1.00
A half to three quarters	2.00	2.11	1.94	2.10	1.87	1.57	1.36
Three quarters or more	2.13	2.18	2.00	2.04	1.86	1.50	1.50
Under a quarter, relative to a quarter or more	0.76	0.84	0.77	0.76	0.86	0.69	0.62

Notes: Water use per acre of land, fallow land included, by the share of a field's need that the district's pumps alone could supply in the delivery model, up to its need in each month, over 2016–2021: under a quarter (16,438 acres), a quarter to a half (25,016), a half to three quarters (15,006), and three quarters or more (5,000 acres). The last row is panel (b) of Figure 11. Fields farmed at least once in 2017–2021, with and without a well. Water use is OpenET evapotranspiration above the year's mean on fallow fields.

Table A29: Water Use Nearer to and Farther From the Head, Fields That Depend Most on CAP Water, Maricopa–Stanfield

	2017	2018	2019	2020	2021	2022	2023
Nearer half, acre-feet per acre	1.51	1.90	1.59	1.67	1.56	0.99	0.62
Farther half, acre-feet per acre	1.44	1.36	1.15	1.08	1.25	0.82	0.63
Farther half over nearer half	0.95	0.72	0.72	0.65	0.80	0.83	1.01

Notes: The 541 fields (12,226 acres) whose pumps could supply under a quarter of their need in 2016–2021 and with no large district pump on the canal above them, farmed at least once in 2017–2021, split at the median distance from the head by acres. Water use is OpenET evapotranspiration above the year's mean on fallow fields, per acre of land, fallow land included.

Table A30 compares the water that fields near the water sources and far from them used over the season with their crops' need.

A15 Further Tests

Randomizing the model's inputs. Table A31 gives the shuffles. In the Upper Gila, the shuffle of dates is the informative test. The field draws and the owner draws spread little, at 0.55 and 0.65 of the standard error. The shortfall varies between canals, and neither shuffle moves whole canals. In Hohokam at its best take, 0.30, the wrong-signed slope has 76, 35, and 90 of 1,000 draws at or above it, and at 0.70 the slope is near zero and inside the draws. In Wellton-Mohawk the opposite-signed slope is unusual on dates and fields (1 and 0 draws of 1,000 at or above it) and less so on owners (26); its shortfall is above zero in two months only. In Central Arizona the date shuffle is not a fair test, because its CAP follows demand less wells month by month, so moving it across years creates shortages the real water never had.

Table A30: Water Use for the Crops' Need, Near the Water Sources and Far From Them, Maricopa–Stanfield

	Distance from the head of the canal			Distance below a canal pump		
	Nearest third	Middle third	Farthest third	Within 1 km	1 to 3 km	Over 3 km
2017	0.99	0.97	0.94	0.98	0.95	0.96
2018	1.08	1.07	1.01	1.07	1.02	1.03
2019	0.96	0.96	0.93	0.97	0.91	0.92
2020	0.92	0.92	0.86	0.92	0.87	0.87
2021	1.09	1.09	1.04	1.09	1.03	1.06
2022	0.99	1.02	0.95	0.98	0.93	1.02
2023	0.93	1.01	0.93	0.97	0.85	0.96
Fields	787	785	789	1,332	343	656

Notes: Planted fields, March–October. Each cell is the group's OpenET water use over its crops' need in the delivery model at the crop planted, both summed over the group's field-months, in the final model of Section 8 (all rules at a take of 0.66). The need is set by crop and month to the district's mean water use (Appendix A1), so a cell above 1 means more water than the district's fields with the same crops in the same months; against the crops' demand without stress, planted fields used about 0.68 to 0.81 of it (Appendix A19). Groups are fixed by each field's place in 2022: thirds of fields by distance along the canal from the head, and distance below the nearest large canal pump above the field. 2,361 fields; the 30 fields with no canal pump above are left out of the right panel.

Table A31: Shuffled Dates, Fields, and Owners: Draws Reaching the Real Value, of 1,000

District, take	Statistic	Real	Dates	Fields	Owners
Maricopa–Stanfield, 0.66	Slope, no well	−61.54	0 (0.001)	0 (0.001)	0 (0.001)
	All rules, score	13.84	21 (0.022)	0 (0.001)	1 (0.002)
	Best of 121 rules, score	36.76	7 (0.008)	0 (0.001)	0 (0.001)
	Best of 121 over equal sharing	56.02	21 (0.022)	0 (0.001)	0 (0.001)
New Magma, 0.72	Slope, no well	−6.58	59 (0.060)	10 (0.011)	47 (0.048)
	All rules, score	8.77	119 (0.120)	1 (0.002)	30 (0.031)
	Best of 121 rules, score	41.06	25 (0.026)	0 (0.001)	0 (0.001)
	Best rule (0.76, 1), score	42.60	0 (0.001)	0 (0.001)	0 (0.001)
Harquahala, 0.68	Slope, no well	−31.36	2 (0.003)	1 (0.002)	50 (0.051)
	No well minus well	−31.79	1 (0.002)	0 (0.001)	38 (0.039)
	All rules, score	−11.54	735 (0.735)	961 (0.961)	711 (0.711)
Upper Gila, reported, 1.00	Slope, no well	−6.86	2 (0.003)	0 (0.001)	0 (0.001)
	Slope, with a well	−6.39	0 (0.001)	0 (0.001)	0 (0.001)
	Best of 121 rules, score	60.98	2 (0.003)	0 (0.001)	0 (0.001)
	Equal sharing minus upstream first	32.80	2 (0.003)	0 (0.001)	0 (0.001)
San Carlos, 0.56	Slope, no well	−9.74	0 (0.001)	0 (0.001)	15 (0.016)
	Best of 121 rules, score	48.66	9 (0.010)	0 (0.001)	27 (0.028)
Central Arizona, 0.02	Slope, no well, at or above	5.10	187	6	144
	All rules, score	−4.39	349 (0.350)	995 (0.995)	900 (0.900)
	Best of 121 rules, score	−0.12	664 (0.664)	743 (0.743)	709 (0.709)
Hohokam, 0.30	Slope, no well, at or above	25.75	76	35	90
Hohokam, 0.70	Slope, no well	−1.38	329 (0.330)	108 (0.109)	186 (0.187)
Wellton-Mohawk, 0.98	Slope, no well, at or above	23.79	1	0	26

Notes: In parentheses, the one-sided p-value, on the side the model predicts: a negative slope, a high score. Scores are blind to sign. In Maricopa–Stanfield moved owners reach 0.28 on average (standard deviation 9.91), so the real slope lies 3.21 clustered standard errors from their mean. Maricopa–Stanfield's own best rule, 36.77, is reached by 3 date draws.

New Magma. The search clears the bar with 1,146 cells, at takes of 0.66 to 1.00, κ of 0.50 to 1, and κ_J of 0.84 to 1. Table A32 gives its slopes. Its fallowing gap opens as water falls: fields without and with a well fallow 8.6 and 9.0 percent in 2016, 34.4 and 11.0 in 2022, and 45.5 and 19.0 in 2023. The record is direct, and the district owns no wells by its audit. The cut shows no slope, while its water at the field falls to 0.68 and 0.40 of usual need. Fields with a well have the wrong sign in water use in that design (10.1, standard error 5.3), and their farmed share does not move (0.3, 2.6; before the cut 2.5, 1.9). Kilometers from the head go the wrong way both before and after the cut (8.9, 2.3; before 9.8, 2.6).

Table A32: New Magma: Slopes by Rule and Take, 2016–2023

Rule, take	S_t times no well	No well	With a well	No well minus well
Best cell, 0.72	−5.11 (7.80)	−7.46 (2.73)	−3.83 (3.44)	−3.63 (3.90)
Upstream first along a line, 0.70	−8.75 (8.14)	1.93 (1.96)	2.80 (1.87)	−0.88 (2.27)
All rules, 0.70	−4.24 (8.05)	−6.41 (4.09)	−1.94 (7.39)	−4.47 (6.49)
All rules, 0.72	−4.03 (7.98)	−6.58 (4.12)	−1.88 (7.23)	−4.71 (6.43)
All rules, 1.00	−1.54 (9.14)	−11.45 (6.20)	−3.83 (7.56)	−7.61 (9.05)
Upstream first along a line, 1.00	−8.23 (7.39)	−1.58 (1.82)	−1.06 (2.47)	−0.52 (2.85)

Notes: 100 times log monthly ET per unit of the shortfall; standard errors clustered by owner and by year-month. 24,520 field-months of 514 fields of 244 owners; 420 fields without a well.

Harquahala. Most of its fields have a well, so the search has little to find, and failing the bar says the data cannot pick a rule, not that the slope is absent. The score across all fields is a test of prediction in the district. The test of the slope is the slope itself and the draws of Table A31. At a take of 0.68, without its largest owner the slope is −22.67 (standard error 11.69), without its three largest −26.22 (16.39), and without any one year it runs from −13.68 to −38.71. At a take of 0.68, S_t times no well has the wrong sign at 63.97 (23.64) beside the slopes, but it is 23.33 (17.32) alone. Across field draws the two correlate at −0.95, so the term is tied to the slope and not a separate finding.

Central Arizona. Table A33 gives five versions of its wells. Version A is the frozen recipe from Maricopa–Stanfield. Its monthly search clears its bar (best score 19.13 against 8.42). Version C comes from its documents: wells first, then CAP. The text uses version C with each pump's feed rebuilt at its wellhead on the imagery (best take 0.02), where the search finds little (best score 0.0 against 8.2); column C of the table places the pumps as the other versions do. Wells where they stand have the right sign in all five, on water use and on fallowing, and never a wrong sign I can tell from zero. All five are versions of one dataset, not separate evidence. Without the South Main canal, water use in the cut falls by less, −5.1 to −10.2 against −7.8 to −14.5 with it; South Main alone gives −20.1 to −37.0. With baseline cotton as a control, the pooled version shrinks, from between −7.2 and −14.9 to between −0.5 and −6.8. At its best take, 0.02, the slope of the version of the text is 5.1 (standard error 4.5), and version A's, at 0.68, is 18.62 (4.82). In version A equal sharing is not rejected ($p = 0.139$). The monthly score is not a fair test either, because CAP carries no supply shock within a year. What would settle it is the district's annual withdrawal by well.

Hohokam. The search does not clear its bar (best score 15.43 at a take of 0.30, bar 27.58). Over all rules the slope is 25.75 (standard error 6.98) at that take, 14.36 (7.60) at 1.00, and −1.38 (6.47) at 0.70. In the cut, at a take of 1.00 and per standard deviation, water use gives −6.0 (6.8) and the farmed share 4.3 (4.1). The records miss water. In 2023 CAP was 2,482 acre-feet, all of it in June–August, and 1,521 of the 2,989 acres without a well were farmed. Their ET above fallow fields was 2,959 acre-feet, 1,419 of it in months with no CAP and almost no rain, against 1,861

Table A33: Central Arizona: Five Versions of Its Wells

	A. Frozen recipe	B. Wells first	C. From documents	D. Connected wells	E. CAP first
Wells	218 canal, 216 local	as A	all 434 district-run	218 connected	all 434 district-run
Monthly volume	CAP first	wells first	wells first	wells first	CAP first
Fields	1,677 no pump	1,677 no pump	2,324	2,324	2,324
Wells where they stand					
Water use	−14.5 (2.8)	−13.8 (2.9)	−9.0 (2.6)	−7.8 (2.7)	−9.9 (2.5)
with baseline cotton	−12.6 (2.7)		−8.1 (2.5)	−7.7 (2.6)	−8.5 (2.5)
without South Main	−10.2 (3.1)		−6.6 (3.0)	−5.1 (3.1)	−7.7 (2.9)
Farmed share	−3.2 (1.8)	−2.4 (1.7)	−2.2 (1.5)	−0.7 (1.9)	−3.0 (1.7)
Fallowing	7.5 (4.0)	9.4 (4.0)	12.8 (4.3)	5.9 (4.5)	10.4 (4.4)
The same well water pooled					
Water use	−14.9 (3.2)	−8.3 (2.7)	−7.3 (2.5)	−7.2 (2.5)	−13.4 (3.3)
with baseline cotton	−6.8 (3.1)		−0.5 (2.5)	−0.7 (2.5)	−2.9 (3.5)
Farmed share	−2.3 (1.8)	0.8 (1.6)	0.6 (1.5)	0.7 (1.5)	−2.7 (1.9)
Fallowing	6.9 (7.5)	27.3 (8.0)	28.7 (8.8)	29.5 (8.8)	−1.8 (11.3)

Notes: Per standard deviation of the predicted rise, cut minus before, owner clusters. Fallowing: per unit of total stress on own demand, field and year effects, fields farmed the year before. Take 0.70 where a take applies. The text uses version C with each pump's feed rebuilt at its wellhead (best take 0.02); column C places the pumps as the other versions do. No version has the record of which wells ran, and Central's network has not had my marks or the checks against decoys.

acre-feet of CAP at the field. So a shortfall there does not measure a shortage. Fields without and with a well fallowed alike, 39.2 and 40.2 percent of acres in 2022 and 46.8 and 50.9 in 2023, and private pumping did not rise when CAP fell. So a registered well may not be usable water here.

San Carlos. The search clears its bar near equal sharing: the best score, 49.32 at a take of 0.56, κ of 0 and κ_J of 0.12, lies above a bar of 40.90, and 4 of 200 draws reach it. The series falls to zero in short months while wells and CAP keep farms irrigating, so the monthly water misses water that reaches fields. Fallowing on total stress with field and year effects is 42.9 (standard error 8.1) over all rules, 24.3 (5.8) for upstream first along a line, and 96.6 (15.4) for equal sharing. Equal sharing gives the largest slope, and fields with a well move alike (50.0, 17.8). Within a field and year, equal sharing's stress, which is only the crop calendar, explains 58.5 percent of all-rules stress, and kilometers times the year's stress 5.7 percent. The 2022–2023 contrast is not clean, because 2018 and 2021 are short years in the baseline and 2023 is a full one. It gives water use of −7.2 (3.4), or −8.9 (3.4) net of the earlier contrast, and 6.9 (4.4) with a well.

Wellton-Mohawk and the Yuma districts. Wellton-Mohawk's water at the field runs 1.30 to 1.42 times usual demand over March–October. Only June and July 2022 are short, at a shortage of 0.10 and 0.12. Far fields gain water, in both periods: 7.0 per standard deviation of kilometers from the head (standard error 1.2), before 5.5 (1.4). In the Yuma districts every month is above demand at $e = 0.70$, with water at 1.43 to 2.51 times usual demand.

Shortages on paper. Table A34 lowers e in the four districts with senior rights and reruns everything. Only e changes. No case shows a negative slope everywhere that grows as e falls. Two of the 15 runs clear the bar, against fewer than one by chance, and both are in Yuma Irrigation. In Yuma Irrigation the best rule's slope shrinks as e falls (−30.95, 11.22; −11.99, 4.37; −10.80, 4.49; −8.51, 5.24), and the best take falls with it (1.00, 0.98, 0.68, 0.36). At a take near 1 that is e near 0.5 to 0.6, against consumptive use over diversions of 0.53 to 0.56 in Reclamation's accounting. Its short months at 0.6 are August 2016, May and June 2017, July 2020, June 2021, July 2022, and May, June, and July 2023. Its fallowing does not respond.

Table A34: Shortage on Paper: Lower Efficiency in the Senior-Rights Districts

District	e	Months short, of 64	Best / bar	All rules, take 0.70	All rules, take 1.00	Fallowing
Wellton-Mohawk	0.60	15	5.88 / 9.26	19.80 (6.63)	7.05 (5.07)	0.5 (5.2)
	0.50	40	5.28 / 9.87	−1.31 (4.82)	−3.66 (5.55)	6.2 (5.3)
	0.40	52	4.52 / 9.64	−12.73 (6.00)	−11.28 (5.60)	1.2 (4.2)
	0.30	63	5.64 / 7.89	−10.00 (6.13)	−9.57 (7.36)	−7.1 (5.7)
Yuma Irrigation	0.60	9	19.18 / 17.37	no short month	−53.88 (13.25)	
	0.50	22	28.77 / 25.45	−54.02 (21.02)	−15.16 (6.85)	−9.8 (5.3)
	0.40	45	33.21 / 35.96	−10.45 (6.26)	5.17 (5.52)	−4.0 (4.7)
	0.30	56	18.15 / 36.38	10.52 (6.05)	6.11 (9.36)	−17.3 (7.0)
Yuma County Water Users	0.60	1	1.26 / 3.05	22.82 (24.29)	25.25 (19.01)	
	0.50	5	9.01 / 10.60	15.10 (6.50)	9.24 (5.77)	−35.6 (22.6)
	0.40	25	3.84 / 15.50	2.11 (3.31)	3.08 (3.06)	−5.0 (5.8)
	0.30	46	13.09 / 17.32	1.58 (3.58)	1.37 (3.67)	−0.7 (4.9)
Yuma Mesa	0.50	2	4.54 / 6.15	30.30 (13.81)	15.26 (8.31)	
	0.40	12	3.57 / 8.24	−9.46 (5.00)	−10.23 (6.20)	−8.4 (5.4)
	0.30	41	13.94 / 18.30	3.30 (5.58)	3.94 (6.43)	−7.6 (3.2)

Notes: Slopes for fields without a well, 100 times log monthly ET per unit of the shortfall. Fallowing: on total stress, all rules, take 1.00, field and year effects, fields without a well; blank where there is too little stress. Yuma Mesa at 0.60 has no short month and was not run. Water in Reclamation's accounting, consumptive use over diversions: Yuma Mesa 0.52–0.70, Yuma Irrigation 0.53–0.56, about 0.7 in the other two.

A16 Other Districts

Section 8.3 runs the model on districts whose monthly record can show a shortage. Two more districts have enough water data to run it, and I report them here as a separate category: Cortaro–Marana and Salt River Valley (Table A35). Roosevelt and Buckeye have water figures for single years only, so I do not run them. The recipe is that of the districts added later (Appendix A1), on trees I did not review further.

Water. In Cortaro–Marana the monthly CAP record is a minority of the water, 22 to 33 percent. I add the district's other water from the state's annual totals: what it withdrew and received, less CAP. Its March–October part follows what the canals still need after CAP, and all of it enters at the head. That water exceeds the need in every year, by at least 17 percent. Salt River Valley has no record of farm water by month. Its one monthly series is CAP water stored at the project, at most 9.3 percent of the project's deliveries, and I do not treat it as farm water. Its allocation stayed full, stated for most years and inferred from storage for the rest. At $e = 0.70$ the full allocation of 3.3 acre-feet an acre meets the model's demand in every year but 2016, when it falls 3 percent short. So I give Salt River Valley no short month.

What the model predicts. No month runs short in either, under any rule. The shortfall is zero, so the search and the slopes have nothing to work on, as in the three Yuma districts. The water alone predicts no rise in fallowing and no loss that grows with distance from the head.

Results. Fallowing rose in both, by 16 and 27 points, about as much as in the CAP districts, although the model finds no shortage. So a rise in fallowing does not by itself mean a water shortage. Loss mostly does not grow with distance. In Cortaro–Marana farther fields kept more, not less. The exception is water use in Salt River Valley in the cut, −5.0 (standard error 2.5), which the water does not predict.

I do not test what drove the rise; land may have left farming for reasons other than water, above all the growth of cities. Of Salt River Valley's fields 94 percent are near a city, against 0 to 7 percent in Maricopa–Stanfield, Central Arizona, Harquahala, and Hohokam. There the rise began before the cut, from 13 percent in 2018 to 43 in 2021, and it did not fall in 2023, the wettest year of the period on the Salt. In Cortaro–Marana the rise sits near the city: 46 points among the 17 percent of fields near one, and 10 elsewhere. It may also apply to New Magma, the one short

Table A35: Other Districts: No Shortage in the Model, and Fallowing Still Rose

	Cortaro–Marana	Salt River Valley
Fields in the district	403	1,240
Acres in the district	10,271	16,647
Fields placed on the tree	367	781
Placed fields with a well	3	188
Short months, of 64	0	0
Percent of fields fallow		
2016–2021	12.0	23.4
2022–2023	27.9	50.5
Change	15.9	27.1
Percent of acres fallow		
2016–2021	7.1	17.8
2022–2023	16.3	42.2
Near a city		
Percent of fields near a city	17	94
Change in fallow, near a city	45.8	27.5
Change in fallow, elsewhere	9.8	20.2
Per standard deviation of km from the head, no well		
Water use, 2022–2023 against 2016–2021	12.7 (2.8)	−5.0 (2.5)
Water use, 2020–2021 against 2016–2019	9.7 (2.8)	1.4 (1.7)
Farmed, 2022–2023 against 2016–2021	17.4 (3.2)	−2.8 (1.9)
Farmed, 2020–2021 against 2016–2019	5.8 (2.0)	1.2 (1.7)

Notes: Short months: March–October 2016–2023, at the four corner rules and takes of 0.70 and 1.00; in Salt River Valley by the record of full allocations, not from a water series. Fallow: the main-sample flag, by year, all fields of the district. Near a city: at least 300 buildings within 1 km of the field's outline, from Microsoft's building footprints; changes are from 2016–2021 to 2022–2023, in points. Km: changes in the outcome, times 100, on km from the head per standard deviation, with the alfalfa share and log acres, clustered by owner. Standard deviations of km: 5.2 and 18.8.

district that lies near cities: 54 percent of its fields are near one, and its fallowing rose 24 points there and 11 elsewhere.

A17 Water Loss and the Yield Proxy

The yield proxy is each crop's GCVI from Sentinel-2 in the weeks that form its yield, from five-day curves with clouds and spikes removed, keeping hay's upward values, which are mostly the tops of real cutting cycles: for cotton the mean from July 14 to September 27, for corn and sorghum the April–October maximum, for barley and the wheats the mean from February 1 to May 20, for rye, oats, and triticale the maximum from February 1 to May 15, and for alfalfa and other hay the mean from November to October. Appendix A6 gives the reasons. A field-year's seasonal water use relative to demand is the log of its thermal-model ET (SSEBop, eeMETRIC, geeSEBAL, and DisALEXI) over its crop's demand, summed over the crop's months: cotton April–September, corn March–July, sorghum May–October, small grains March–May, and hay March–October. The crop calendars stop at March–October, so the winter months of hay and small grains are left out. This demand is the crop coefficient of the district's crop calendar times AZMET reference evapotranspiration, without the local calibration factor or rain. Within fields, the proxy rises by 1.37 percent per percent of that ratio for cotton, 0.67 for alfalfa and other hay, 1.06 for corn and sorghum, and 0.77 for small grains. Hay's mean starts in November of the year before, so its crop year 2017 falls out where the 2016 curve is missing.

The cut changed what a short month means. Before it, a field could offset a short month with more water in other months of the season; in the cut it did not. I turn each month's canal shortfall into a predicted loss of that month's water use with the monthly response g of Appendix A18, for

every field, with or without a well. A field's predicted loss for the season is that loss weighted by the month's demand over its crop's months, a share of the season's water. Table A36 regresses the season's water use relative to demand and the yield proxy on it, with field by crop group and crop group by year effects, and lets the slope change in 2022–2023. I leave out owner by year effects, because an owner's fields share a location and those effects would remove the variation.

Before the cut, a predicted loss of 10 percent of the season's water does not lower the season's water use on average (0.5, standard error 2.9), and the yield proxy even rises (12.1, standard error 5.9). Before the cut, the model predicts a loss for the season in two years, 2019 and 2020. In 2019 the season's water use rises with the predicted loss (7.8, standard error 2.8), and in 2020 it falls (−13.5, standard error 4.0). The yield proxy falls in neither year (18.3, standard error 7.0, and −2.2, standard error 4.7). On average, short months were offset in other months of the same season (Panel B). In a month the model marks short, water use falls by 7.0 percent for each 10 points of shortfall (standard error 1.7). It rises by 7.8 percent (standard error 1.9) when other months of the season are short by as much, and it is 4.1 percent higher (standard error 1.2) two months before a short month.

In the cut, the other months no longer offset a short month: their effect changes by −10.9 (standard error 2.4). A predicted loss of 10 percent of the season's water then lowers the season's water use by 9.3 percent (standard error 2.9) and the yield proxy by 10.3 percent (standard error 5.8; $p = 0.07$). The proxy falls about as much as water use, though less precisely.

Table A36: Short Months and the Season, Before the Cut and in It, Maricopa–Stanfield

	2017–2021	Change in 2022–2023	2022–2023
A. The season, per 10 points of predicted loss			
Water use relative to demand	0.5 (2.9)	−9.8 (4.4)	−9.3 (2.9)
Yield proxy	12.1 (5.9)	−22.4 (9.0)	−10.3 (5.8)
B. Monthly water use, per 10 points of shortfall			
Shortfall in the same month	−7.0 (1.7)	4.7 (2.0)	−2.3 (1.0)
Shortfall in the season's other months	7.8 (1.9)	−10.9 (2.4)	−3.1 (1.3)

Notes: Percent (log points times 100); standard errors clustered by owner. Each row of Panel A, and Panel B, is one regression on 2017–2023 with the change in 2022–2023; the last column is the sum. All rules at a take of 0.66, all fields with and without a well. Panel A: the predicted loss is the share of the season's water that the monthly response g of Appendix A18 gives for the field's canal shortfall in its crop's months, weighted by monthly demand; field by crop group and crop group by year effects; 8,110 field-years of 2,006 fields. Panel B: monthly OpenET water use in the crop's months from March to October, on the canal shortfall of the month and the demand-weighted mean shortfall of the season's other months; field by crop by month and crop by year by month effects; 51,353 field-months.

A18 The Policy Simulations

Each rule changes the model's shortfalls. A field-month's ET changes by

$$\Delta \mathrm{ET}_{it} \;=\; \mathrm{ET}_{it}\left[\exp(\beta\,\Delta\ell_{it}/100) - 1\right],$$

where β is the estimated slope of 100 times ln ET on the shortfall for the field's group and $\Delta\ell$ the change in its shortfall. The change in revenue is the crop's yield response to water (FAO-33 K_y: cotton 0.85, corn 1.25, durum 1.00, winter wheat 1.00, sorghum 0.90, alfalfa 1.10, barley 1.00, other hay 1.00) times the relative change in March–October ET, times the field's acres and the NASS Arizona revenue per acre for the crop and year. Other crops carry no dollar value. The figures are gross revenue, in partial equilibrium: slopes, pumping, and prices stay as estimated. The rules

divide the district's water at the district level and are not routed along the canals. Maricopa–Stanfield's slopes are all rules at a take of 0.66, −61.54 (standard error 19.24) without a well and −165.69 (71.04) with one, and the ranges use each group's slope plus and minus 1.96 standard errors. For all fields together both groups' slopes move at once, so that range is a sensitivity range, not a confidence interval. Table A37 gives the results for 2016–2021. These figures price each month's shortfall and give no credit for any extra water a field used in other months of the season. Before the cut fields used such water in some years (Appendix A17), so the figures for 2016–2021 are upper bounds. In the cut they did not.

The cut years. I price 2022 and 2023 on two margins, with the same delivery model at a take of 0.66 and all 2,601 rules. *Who left.* Among fields farmed the year before, the chance of fallowing rises with total stress (Section 8.2). I use three slopes for each group: the cut-year slope with year effects, 18.0 (standard error 7.8) without a well and 13.4 (11.1) with one; 2017–2023 with year effects, 12.7 (6.7) and 14.4 (8.1); and 2017–2023 with field and year effects, 18.7 (7.9) and 20.8 (10.4). A field's predicted fallow acres are the slope times its total stress times its acres. I also estimated fallowing by bins of total stress in place of one slope. Measured from the lowest bin, fallowing in 2022–2023 rises once, by 7.7 points (standard error 3.8) near a stress of 0.2, and does not rise further at higher stress. Spreading the same stress evenly across fields would therefore not have reduced the land left fallow, so there is no efficiency loss in fallowing. A rule changes this year's share in 2022 and 2023, and last year's share in 2022 for the decision of 2023. I value an acre at last year's crop. Returns over operating costs come from the University of Arizona's 2023 budgets for southern Arizona, flood irrigated, against the $50 of operating cost of fallow land (Evancho et al. 2023a, 2023b, 2023c, 2023e, 2023f, 2023d): alfalfa and other hay $607 an acre, cotton $682, corn and sorghum $690 on the silage corn budget, and grain $315, the mean of durum and barley. Gross revenue is NASS Arizona revenue per acre for the crop and year. Other crops carry no dollar value; the valued acres are 92 percent of the predicted acres at returns and 87 percent at gross revenue. *Who stayed.* Planted fields of 2022 and 2023, March–October, take the formula above with OpenET by month. Under the monthly response, a rule changes a field's monthly water use by the field's water use times $\exp(g(l_{\text{rule}}) - g(l_{\text{now}})) - 1$, where l_{rule} and l_{now} are the field's monthly shortfalls under the rule and as delivered. The function g is zero up to a shortfall of 0.03 and then joins the bins of Table A22, Panel A, measured from the lowest bin, with straight lines. The figures for 2016–2021 in Panel A of Table A37 come from the same calculation. Panel D of Table A37 prices a new well in the cut years as in the years before: the gain in the year per acre of filling every shortfall, over the yearly cost of a well. The model's monthly pumping follows the canal's claims up to a set share of the canal pumps' capacity, so their room in June and July is an assumption and not a measurement.

The loss from the land that left. The fields are Maricopa–Stanfield's 1,780 fields farmed in 2021 in alfalfa and other hay, corn and sorghum, cotton, or grain, 52,426 acres; other crops stay as they were. Crops are held at the field's 2021 class for land left fallow. The benchmark farms every field, less its crop's normal rotation to fallow in 2018–2021 (alfalfa and other hay 3.0 percent, corn and sorghum 7.2, cotton 5.4, grain 10.1). The realized set is the land farmed by the Cropland Data Layer or by water use (annual ET of at least 600 mm, as in Appendix S13). *Every field planted.* Each month the realized water, at each crop's mean water use above fallow land in 2017–2021, is shared over all fields of the benchmark in proportion to demand. The fields then get 73 to 76 percent of their water in 2022 and 62 to 72 percent in 2023. Yield is $1 - K_y(1 - \text{share})$, and

Table A37: What Shortfalls Cost and What a Remedy Would Need: Changes in Gross Crop Revenue

Rule	Fields	ET change, AF/yr	Revenue change, $/yr	$/acre/yr
A. Maricopa–Stanfield, 2016–2021 (32,746 acres without a well, 9,741 with)				
Full coverage (additional water)	no well	480	243,194 (90,368 to 409,470)	7.4
	with a well	218	130,564 (18,617 to 274,041)	13.4
	all	698	373,757 (108,985 to 683,511)	8.8
Equal sharing of the same water	all	−38	25,361 (3,765 to 77,758)	0.6
No-well fields first	no well	480	243,194 (90,368 to 409,470)	7.4
	with a well	−1,092	−495,040 (−791,829 to −91,610)	−50.8
	all	−613	−251,846 (−382,359 to −1,242)	−5.9
if fields with a well lose at the no-well slope	all	28	37,975 (7,596 to 91,564)	0.9
if their wells replace the water	all	480	243,194 (90,368 to 409,470)	5.7
Canal pumps pooled	no well	6	3,600 (717 to 8,634)	0.1
	with a well	−30	−9,366 (−11,166 to −2,054)	−1.0
Monthly response, fields without a well; their own bins on the canal shortfall, fields with a well				
Full coverage (additional water)	no well	247	137,187 (40,780 to 291,195)	4.2
	with a well	138	95,259 (−60,134 to 298,586)	9.8
	all	385	232,446 (−19,354 to 589,782)	5.5
Equal sharing of the same water	no well	221	124,477 (40,780 to 124,477)	3.8
	with a well	29	43,007 (43,007 to 68,178)	4.4
	all	250	167,483 (89,533 to 172,807)	3.9
No-well fields first	no well	247	137,187 (40,780 to 291,195)	4.2
	with a well	−1,155	−521,308 (−736,505 to −171,557)	−53.5
	all	−907	−384,122 (−445,310 to −130,777)	−9.0
Canal pumps pooled	no well	53	31,280 (16,465 to 55,809)	1.0
	with a well	−13	3,236 (1,235 to 20,164)	0.3
	all	40	34,516 (34,516 to 57,044)	0.8
B. The best rule alone, Maricopa–Stanfield				
Full coverage	no well	297	167,113 (70,703 to 275,509)	5.1
No-well fields first	with a well	−501	−223,438 (−405,918 to −5,445)	−22.9
C. Upper Gila, reported diversions, 2016–2023 (20,965 acres)				
Water reaching crops, 0.7 to 0.8	all	122	57,846 (28,376 to 87,431)	2.8
Water reaching crops, 0.7 to 0.9	all	231	109,448 (53,608 to 165,673)	5.2
Pooled river	all	−16	−6,904 (−7,690 to −4,532)	−0.3
Full coverage	all	1,883	821,843 (400,924 to 1,254,187)	39.2

D. A new well for fields without a well, Maricopa–Stanfield, monthly response

Fields	Benefit, $/acre/yr	AF/acre/yr to pump	Benefit, $/AF	Benefit / capital
2016–2021, a year				
All	4.3	0.03	157.8	3%
Least short third	0.0	0.00	0.9	0%
Middle third	0.2	0.02	10.3	0%
Most short third	15.0	0.07	201.5	9%
The cut years, filling every shortfall in the year				
2022, all	24.7	–	–	15%
2022, most short third	65.5	–	–	40%
2022, fields with any loss	49.9	–	–	31%
2023, all	52.5	–	–	32%
2023, most short third	93.7	–	–	58%
2023, fields with any loss	139.5	–	–	86%
2016–2021 on the straight line, by distance to a canal pump				
Canal pump within 2 km above	4.6	0.02	276.5	3%
None within 2 km above	15.1	0.05	282.4	9%

Notes: Ranges: each group's slope plus and minus 1.96 standard errors. Rows of the monthly response: fields without a well under the bins of Table A22, Panel A, measured from months with a shortfall of 0.01 to 0.05 and joined through each bin's mean shortfall. Their range moves the five points together by 1.96 standard errors, held at or below zero. Fields with a well: their own monthly bins on the canal shortfall, 1 − canal share, against months below 0.01, each as estimated in the same regression with the two groups switched. Their range moves all six bins together by 1.96 standard errors, and the range for all fields moves both groups at once. Each range is the lowest and highest value at the estimate and at the two ends of the shift, so it contains the estimate. The first rule, full coverage, takes more water than the district had; the others divide the same water. Full coverage for fields without a well is 0.5 percent of their March–October water use and 0.6 percent of their $42,488,948 of gross revenue a year. No-well fields first moves 1,054 acre-feet a year, or $230.8 of their gain per acre-foot; on the best rule, 1,030 and $162.2. Well: Maricopa–Stanfield's 2024 cost of $1,115,297 for one 2,000-gallon-per-minute well with pipeline, about 2,000 acre-feet a year, serving 446 acres: $2,501 per acre, $163 per acre a year at 5 percent over 30 years, and $36 per acre-foot of capacity, before energy and operation (Maricopa–Stanfield Irrigation and Drainage District 2024). Panel D: the monthly response of Table A22, Panel A, as in the rows above. A new well returns the gain per acre of filling every shortfall on the planted fields without a well (full coverage), as a share of its yearly cost of $163 per acre. The thirds are of the 2016–2021 shortfall, and the cut years use the same gain in the year; the last two rows are priced on the straight line, as the monthly response has no value by distance to a pump. Lining: the model has no loss that grows with distance, so lining appears as the share of water reaching crops, and the size of that rise is an assumption. 308.5 km of tree line on the ten canals; reclamation costs of $82,021 to $328,084 per km for a 10-foot wetted perimeter, or $5,336 to $21,342 per km a year; so a rise to 0.8 is worth 1 to 4 percent of that cost, and to 0.9, 2 to 7 percent. The model counts no return of seepage to the aquifer.

operating costs stay whole. If 30 percent of them fall with yield, fallowing avoids 54 to 60 percent of the loss from spreading, against 62 to 68 percent with costs whole. The result follows from the budgets and the FAO coefficients. Deficits of 25 to 38 percent lie at the edge of the linear FAO response, and alfalfa that goes dormant in summer may lose less.

Planted fields against their own water use. A field's normal ET in a month is its FAO demand (crop coefficient times AZMET Maricopa reference ET) times the field's own 2017–2020 ratio of OpenET to that demand, so weather and the field's level are both held fixed. Its shortfall in a month is the share of normal ET missing, zero if use is at or above normal. The June–July figure is the need-weighted mean over fields planted in the Cropland Data Layer's alfalfa and other hay, corn and sorghum, cotton, or grain, weighted by acres. It is 0.11 to 0.12 in each year of 2017–2021, 0.183 in 2022, and 0.178 in 2023.

A19 The Efficiency Loss by Response and by Water Level

Table 8 prices the efficiency loss with four quadratic functions from field trials. Trout and DeJonge (2017) fit maize yield in Colorado, and Li et al. (2023) fit alfalfa yield in the arid regions of China, each with one function in water consumed and one in water applied. I apply each function to every crop, so the ranges show how much the efficiency loss depends on the function. The last response of Table 8, Panel B, lets the loss grow slowly below a shortfall of 0.20 and much faster above it. It has a constant for any shortfall, 4.98 (2.74), and slopes of −26.57 (18.44) and −111.68 (32.01). I leave the constant out when I price the loss.

The functions are flat near the highest-yield water and steep below that level, so a field's place on the curve matters (Figure A3). I place the district's fields with the water ratio of Appendix A17, thermal-model water use over crop demand without stress. In 2017–2021, the acre-weighted median ratio in Maricopa–Stanfield was 0.68 for alfalfa and other hay, 0.70 for cotton, 0.81 for corn and sorghum, and 0.68 for small grains, with water use averaged over SSEBop, eeMETRIC, and geeSEBAL. Single models put those crop medians between 0.61 and 0.90. A second measure agrees for corn: the maize function in water consumed has an elasticity of 1.06, the within-field slope of Appendix A17, at 0.83 of highest-yield water. For alfalfa, matching the slope for alfalfa and other hay, 0.67, puts fields at 0.51 of the function's highest-yield water. That highest-yield water lies beyond the largest water use in the trials' data. Because water applied is not measured field by field, I place fields on the water-applied functions at the same relative yield, giving places of 0.67 to 0.71 for maize and 0.50 to 0.68 for alfalfa.

A field at place k receiving share s of its usual water yields $f(ks)/f(k)$ of its usual yield on trial function f. In the second wave, I price each planted field's shortfall over the season in the delivery model with that response, against an even shortfall across planted fields. The functions are seasonal, so this calculation leaves out any loss from a shortfall concentrated in particular months. In the first wave, each owner plants for the district's cut at the usual water per acre and then receives the water of that owner's place on the canal. Table A39 gives both calculations at the measured places and on a grid of places. At the top of the functions, the efficiency loss would be 23 to 76 percent of the second wave's loss in 2022, against 3 to 14 percent at the measured places. The maize function in water consumed is the most sensitive: if owners plant before knowing their water, that function gives 18.6 percent of returns in 2023 at a place of 0.9 and 9.1 percent at 0.8. In that same case, place matters for a straight line too. With fields placed at full water, an owner cannot use water above the plan, so FAO's straight lines give an efficiency loss of 10.0 to 11.8

Table A38: The Cut Priced on Both Margins, Maricopa–Stanfield

A. Who left: acres of last year's farmed land left fallow, and their value, at the cut-year slope

Rule	Year	No well	With a well	All	Returns, $M	Gross, $M
The model's total stress	2022	2,225	435	2,660	1.45	4.50
	2023	2,166	387	2,553	1.27	3.53
Full coverage (additional water)	2022	−2,225	−435	−2,660	−1.45	−4.50
	2023	−2,166	−387	−2,553	−1.27	−3.53
Equal sharing of the same water	2022	−59	+20	−39	+0.07	+0.22
	2023	+4	+25	+29	+0.11	+0.28
No-well fields first	2022	−819	+845	+26	+0.14	+0.59
	2023	−761	+791	+30	+0.13	+0.47
Canal pumps pooled	2022	−55	+19	−37	+0.05	+0.16
	2023	+27	+26	+54	+0.12	+0.28

B. Who stayed: change in gross revenue of planted fields, $M a year (range)

Rule	Year	No well	With a well	All	ET change, all, AF
Full coverage (additional water)	2022	+1.02 (+0.38 to +1.74)	+0.41 (+0.06 to +0.88)	+1.43 (+0.43 to +2.62)	+2,415
	2023	+1.30 (+0.47 to +2.26)	+0.38 (+0.05 to +0.89)	+1.69 (+0.52 to +3.15)	+3,190
Equal sharing of the same water	2022	−0.10 (−0.10 to −0.05)	−0.15 (−0.18 to −0.03)	−0.25 (−0.28 to −0.09)	+58
	2023	−0.01 (−0.03 to +0.10)	−0.27 (−0.33 to −0.05)	−0.27 (−0.27 to −0.08)	−156
No-well fields first	2022	+1.02 (+0.38 to +1.74)	−2.71 (−4.21 to −0.52)	−1.69 (−2.47 to −0.14)	−1,756
	2023	+1.30 (+0.47 to +2.26)	−2.96 (−4.29 to −0.61)	−1.65 (−2.04 to −0.14)	−2,082
Canal pumps pooled	2022	−0.05 (−0.05 to −0.03)	−0.22 (−0.33 to −0.04)	−0.28 (−0.36 to −0.08)	−22
	2023	+0.03 (−0.01 to +0.16)	−0.30 (−0.40 to −0.06)	−0.27 (−0.27 to −0.07)	−214
Monthly response, fields without a well; their own bins on the canal shortfall, fields with a well					
Full coverage (additional water)	2022	+0.66 (+0.20 to +1.39)	+0.37 (−0.11 to +1.07)	+1.04 (+0.10 to +2.46)	+1,866
	2023	+1.08 (+0.36 to +1.99)	+0.33 (+0.00 to +0.84)	+1.42 (+0.36 to +2.83)	+2,694
Equal sharing of the same water	2022	+0.63 (+0.20 to +0.63)	+0.03 (−0.18 to +0.42)	+0.66 (+0.16 to +0.66)	+1,351
	2023	+0.81 (+0.36 to +0.81)	−0.07 (−0.43 to +0.45)	+0.74 (+0.27 to +0.81)	+1,568
No-well fields first	2022	+0.66 (+0.20 to +1.39)	−3.39 (−5.09 to −0.50)	−2.73 (−3.70 to −0.29)	−3,161
	2023	+1.08 (+0.36 to +1.99)	−3.12 (−4.71 to −0.25)	−2.04 (−2.72 to +0.10)	−2,763
Canal pumps pooled	2022	+0.38 (+0.20 to +0.48)	+0.00 (−0.17 to +0.33)	+0.38 (+0.31 to +0.52)	+929
	2023	+0.73 (+0.36 to +0.77)	−0.09 (−0.43 to +0.42)	+0.65 (+0.34 to +0.78)	+1,379

C. The loss from the land that left, returns over operating costs, $M a year

Farmed count, value	Year	Every field	Realized	Loss	Share	Every field planted
Crop map, budgets	2022	30.2	21.2	9.0	30%	27.2
Crop map, NASS prices	2022	43.7	32.0	11.7	27%	30.9
Water use, budgets	2022	30.2	22.2	8.0	27%	24.1
Water use, NASS prices	2022	43.7	33.3	10.4	24%	27.4
Crop map, budgets	2023	30.2	18.1	12.0	40%	37.9
Crop map, NASS prices	2023	30.5	18.4	12.1	40%	38.2
Water use, budgets	2023	30.2	20.9	9.2	31%	28.4
Water use, NASS prices	2023	30.5	21.4	9.1	30%	28.6

Notes: All rules at a take of 0.66. Panel A: first row, the fallowing that total stress predicts; other rows, the change against it, so a negative number means fewer acres fallow or less value lost. Observed: 17,064 acres in 2022 and 12,662 in 2023 of land farmed the year before. With the other two slopes, the model's total stress accounts for 2,038 and 2,985 acres in 2022 and for 1,945 and 2,849 in 2023; returns $0.97–1.64 million, gross $2.72–5.12 million. Returns: returns over operating costs of last year's crop. Gross: NASS gross revenue. Panel B: range, each group's slope plus and minus 1.96 standard errors. Fields with a well lose at their own estimated slope. In the rows of the monthly response, equal sharing of the same water brings fields without a well 95 percent of the gain of full coverage in 2022 and 75 percent in 2023. These are not the 91 and 70 percent of Section 8.8, which come from an even delivery that gives every planted field the same shortfall (Table 8). Rows of the monthly response: fields without a well under the bins of Table A22, Panel A, measured from months with a shortfall of 0.01 to 0.05 and joined through each bin's mean shortfall. Their range moves the five points together by 1.96 standard errors, held at or below zero. Fields with a well: their own monthly bins on the canal shortfall, 1 − canal share, against months below 0.01, each as estimated in the same regression with the two groups switched. Their range moves all six bins together by 1.96 standard errors, and the range for all fields moves both groups at once. Each range is the lowest and highest value at the estimate and at the two ends of the shift, so it contains the estimate. Panel C: every field, the benchmark with normal rotation; realized, the land farmed; share, the loss over every field; every field planted, the loss if all fields stayed planted and shared the water. Crop map: Cropland Data Layer. Water use: annual ET of at least 600 mm. Budgets: University of Arizona 2023. NASS prices: NASS Arizona revenue by crop and year for alfalfa, cotton, and grain, with budget operating costs; corn and sorghum stay on the budget.

percent of returns in 2022 and 21.2 to 25.0 percent in 2023. At the measured places, the lowest and highest crop medians of the water ratio, the same straight lines give 0.0 to 0.2 percent and 0.0 to 4.1 percent. Table A40 sets these calculations beside the assumptions of other studies.

Table A39: The Efficiency Loss Depends on Where Fields Sit on the Response, Maricopa–Stanfield

		Place of the district's fields on the function						Measured
Function	Year	1.0	0.9	0.8	0.7	0.6	0.5	places
A. First wave, farmers plant before knowing their water: efficiency loss, percent of the district's returns								
Maize, water consumed	2022	7.1	7.3	2.3	–	–	–	2.8 to 3.8
	2023	18.7	18.6	9.1	–	–	–	10.3 to 12.6
Maize, water applied	2022	2.2	1.8	1.6	1.3	1.0	0.8	1.2 to 1.3
	2023	7.0	6.5	5.7	4.3	3.4	2.6	4.0 to 4.4
Alfalfa, water consumed	2022	2.7	2.4	2.2	1.9	1.5	1.2	1.2 to 1.8
	2023	7.9	7.7	7.2	6.1	4.8	3.8	3.9 to 5.8
Alfalfa, water applied	2022	2.6	2.2	2.1	1.8	1.4	1.1	1.1 to 1.7
	2023	7.5	7.3	6.8	5.8	4.6	3.6	3.6 to 5.5
Straight line, FAO coefficient 0.85	2022	10.0	3.7	0.0	0.0	0.0	0.0	0.0
	2023	21.2	11.0	2.9	0.0	0.0	0.0	0.0 to 3.6
Straight line, FAO coefficient 1.25	2022	11.8	4.3	0.2	0.2	0.1	0.2	0.2
	2023	25.0	12.7	3.3	0.1	0.1	0.2	0.1 to 4.1
B. Second wave, planted fields without a well: efficiency loss, percent of the wave's loss								
Maize, water consumed	2022	51.5	21.5	12.2	–	–	–	12.8 to 14.2
	2023	55.5	27.3	16.2	–	–	–	17.0 to 18.7
Maize, water applied	2022	22.8	13.3	8.6	5.7	3.8	2.4	5.1 to 6.0
	2023	28.8	17.6	11.5	7.6	4.9	2.9	6.7 to 7.9
Alfalfa, water consumed	2022	76.2	25.6	13.6	8.3	5.2	3.3	3.5 to 7.5
	2023	72.6	31.8	18.0	11.1	6.9	4.1	4.4 to 10.1
Alfalfa, water applied	2022	68.1	24.5	13.2	8.1	5.2	3.2	3.2 to 7.4
	2023	67.4	30.5	17.5	10.8	6.8	4.1	4.1 to 9.9

Notes: A field's place is the water the field uses at full delivery, as a share of the water that gives the highest yield on the function. A place of 1.0 puts the district's fields at the top of the function. The measured places are 0.81 and 0.83 for maize in water consumed, 0.67 and 0.71 for maize in water applied, 0.51 and 0.68 for alfalfa in water consumed, and 0.50 and 0.68 for alfalfa in water applied. For the straight lines, the top of the function is full water, where an owner cannot use water above the plan, and the measured places are the lowest and highest crop medians of the water ratio, 0.68 and 0.81. I apply each function to every crop. A dash marks a place where a shortfall of 0.4 leaves no yield on the function. Panel A reports the efficiency loss as a percent of the district's returns over operating costs on the 2023 budgets when every owner faces the same cut. Panel B prices each planted field's shortfall over the season in the delivery model. In both panels, the shortfall passes one for one into the water measure of the function. Under a straight line, the efficiency loss in Panel B is zero at every place, so Panel B omits the straight lines.

A20 Administrative Allocation Cuts: The CAP Curtailment Schedule

Central Arizona Project shortage tiers curtailed the Agricultural Settlement Pool. Realized pool deliveries were unchanged under Tier 0 in 2020, because 2019 deliveries already sat below the cap. Under Tier 1 in 2022 they fell 65 percent net of mitigation and 88 percent in realized deliveries. Under Tier 2a in 2023 they went to zero. I classify six high-use districts as treated from CAP delivery accounting. The 2004 settlement made the pool junior. The treated districts were not chosen at random and differ in groundwater access. The comparisons below therefore describe what happened in the cut districts. They are not a natural experiment.

Average outcomes. Table A41 shows a large break in fallowing. Relative to 2019 and the comparison districts, fallowing in 2022 rises 13.3 percentage points under the nearest-district assignment. It rises 18.9 points when treatment is restricted to fields inside the district polygons. The satellite indices of all fields decline as well. The boundary restriction strengthens the fallowing, Sentinel-2 GCVI, NDMI and ET estimates. It also worsens the pre-trends, and the estimates are sensitive to the comparison pool. The nearest assignment labels 31 percent of treated fields outside

Table A40: The Efficiency Loss in Each Wave Depends on What Is Assumed, Maricopa–Stanfield

Assumption	Studies that assume it	2022	2023
A. First wave, land left fallow: percent of the district's returns			
1. Farmers know their water, and an acre-foot returns the same everywhere	this paper	−1.1 to 0.9	−0.4 to 0.1
2. The value of an acre-foot differs across users	Rafey (2026), Ryan and Sudarshan (2022)	8.1	12.7
of which from moving water between places		0.0	0.8
3. Farmers plant before knowing their water, and yield follows the field-trial responses	Rafey (2023), Burness and Quirk (1979)	1.1 to 3.8	3.6 to 12.6
4. Farmers plant before knowing their water, and yield falls in proportion to water	Rafey (2023), Garcia and Belmar (2025)	10.0 to 11.8	21.2 to 25.0
B. Second wave, planted fields without a well: $ million a year			
5. Water use follows a straight line in the shortfall	the straight-line rows of Appendix A18	−0.1	−0.1
6. Yield follows the field-trial responses	this appendix	0.0 to 0.3	0.1 to 0.5
7. Water use falls by less than 4 percent until the shortfall passes 0.20	my estimate, Section 8.4; the pricing of Section 8.8	0.6	0.8

Notes: Each row gives the efficiency loss, the part of the loss that the same water, delivered differently, would have saved. A negative number means that the district's division lost less than the alternative division. Panel A is in percent of the district's returns over operating costs on the 2023 budgets, for land farmed in 2021 with a budgeted crop. In these calculations those returns are $19 to $27 million a year. Row 1 compares the district's division with divisions that the canals allow, which move only CAP water. The low end values land without a crop budget at zero, and the high end values that land at the mean crop. Row 2 compares sending water to its highest-return use across the district with each owner using that owner's water on that owner's best fields. The line under row 2 is the part of that gain that needs water to cross groups of fields by place on the canal. Rows 3 and 4 rank owners in fifths by the share of their need that the delivery model leaves short and put all land in the budgets' best crop. Each owner plants for the district's cut and then receives the water of that owner's fifth. The range in row 3 spans the four field-trial functions at the measured places in Table A39. The range in row 4 spans FAO response coefficients from 0.85 for cotton to 1.25 for corn. Row 4 places fields at full water, where an owner who receives more water than the district's cut cannot use water above the plan. Placed instead at the measured places in Table A39, the same straight lines give 0.0 to 0.2 percent of returns in 2022 and 0.0 to 4.1 percent in 2023. Rows 5 and 7 price the delivery model's monthly shortfalls on planted fields without a well as in Appendix A18, against spreading the same water evenly over those fields each month. Row 5 differs from zero only because fields differ in crop and revenue. Row 6 prices each field's shortfall over the season with the four field-trial functions at the measured places. In row 7, the efficiency loss equals the second-wave loss minus what an even delivery would still have cost, $0.1 million in 2022 and $0.3 million in 2023, as no month's mean shortfall reaches 0.20. The bins in row 7 are estimated on 2016–2021.

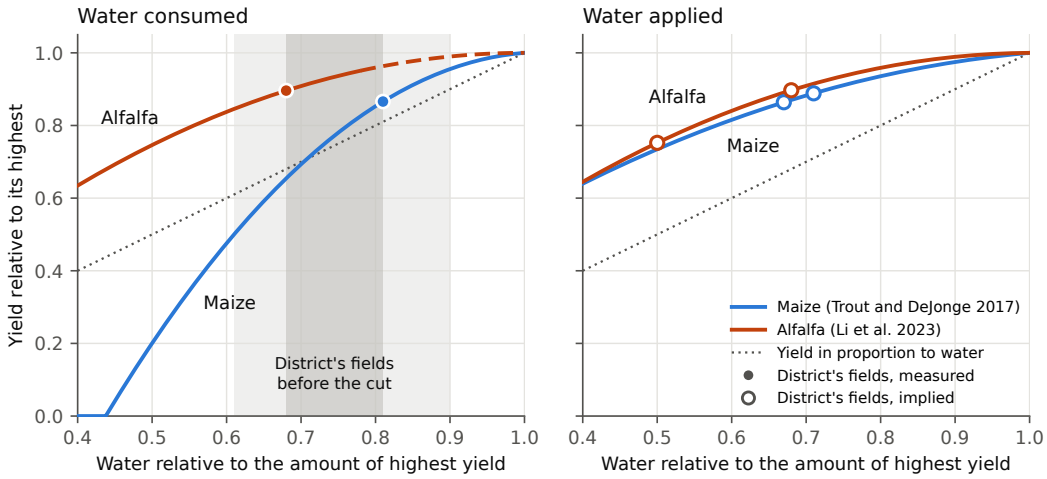


Figure A3: Maricopa–Stanfield's Fields Sit Below the Flat Part of the Field-Trial Yield Functions

Notes: Each panel plots yield relative to highest yield against water relative to highest-yield water. The left panel plots the functions in water consumed. The maize function is from Trout and DeJonge (2017), and the alfalfa function is from Li et al. (2023), dashed beyond the largest water use in that study's data. The dark band spans the median water ratios of the district's four crop groups in 2017–2021, from 0.68 to 0.81, and the light band spans the lowest and highest single thermal model, from 0.61 to 0.90. Filled dots mark corn and sorghum on the maize function and alfalfa and other hay on the alfalfa function. The right panel plots the functions in water applied from the same two studies. Open dots mark the places implied by the same relative yield, because water applied is not measured field by field. The dotted line plots yield in proportion to water.

the district polygon.

The size of the 2022 fall in GCVI depends on the sensor. Sentinel-2 gives −0.210 and −0.273. Landsat 7 gives −0.159 and −0.148, neither significant at 5 percent, and the boundary restriction does not strengthen it. By 2023 both sensors fall clearly: −0.254 and −0.371 on Sentinel-2, −0.223 and −0.282 on Landsat 7. NDMI shows no such difference between the sensors. I cannot say which GCVI is right. Sentinel-2 GCVI levels shift against Landsat across counties and years, every Landsat image from 2022 on comes from its lowered orbit, and by 2023 ET falls about as much as Sentinel-2 GCVI.

The delivery collapse coincides with a large break in fallowing in the treated districts and with a fall in GCVI that is clear by 2023. The comparison does not show that the CAP cut alone caused the full magnitudes. Conditioning on fields that stay planted removes the fallowing response and changes the crop mix, so it cannot recover a clean effect on planted fields.

Table A41: Tier 1 and Average Field Outcomes

Treatment geography	Outcome	Estimate	District SE	Webb p
2022 treated–control change relative to 2019				
Nearest-district assignment	Fallowing	+0.133	0.032	0.015
	ln GCVI, Sentinel	−0.210	0.097	0.073
	ln GCVI, Landsat	−0.159	0.077	0.107
	GCVI, Sentinel minus Landsat	−0.060	0.046	0.290
	ln NDMI	−0.087	0.034	0.130
	ln ET	−0.141	0.082	0.249
Distance-zero boundary proxy	Fallowing	+0.189	0.031	0.001
	ln GCVI, Sentinel	−0.273	0.098	0.004
	ln GCVI, Landsat	−0.148	0.081	0.100
	GCVI, Sentinel minus Landsat	−0.128	0.055	0.085
	ln NDMI	−0.095	0.056	0.189
	ln ET	−0.211	0.075	0.023

Notes: Field-weighted district-year event-study comparisons with district and year effects; 2019 is the reference year. The nearest-district assignment uses the paper's nearest-district label; the boundary restriction retains only fields geographically inside the named district polygon. Fallowing is in probability units; satellite outcomes enter as $\ln x$, missing where the value is not positive, so the NDMI rows use fewer fields. GCVI here is the May–September maximum, not the crop-year yield proxy. The Landsat 7 row uses fields with a value in all eight years, and the difference row fields with both sensors in all eight years, so the difference need not equal the gap between the two GCVI rows. Treatment varies by district and year, so standard errors cluster by irrigation district. Webb wild-cluster p-values use 9,999 null-imposed draws. The table is descriptive: joint pre-trend tests fail for several outcomes, particularly under the boundary restriction, and estimates vary with the comparison pool.

Groundwater. The ADWR Groundwater Site Inventory gives a balanced panel of 65 monitoring sites in five treated districts and 61 sites in eight comparison districts, each observed every year of 2018–2023. Every district has equal weight, and sites have equal weight within a district. Relative to 2021, depth to groundwater in the treated districts rose 8.33 feet more than in the comparison districts by 2023 ($p = 0.008$; Webb $p = 0.011$). The 2022 difference is 2.23 feet ($p = 0.546$). Net of each site's 2018–2021 trend, the 2023 difference is 12.47 feet ($p = 0.065$; Webb $p = 0.042$). The p-values cluster by district, and the Webb p-values use 9,999 null-imposed draws. Greater depth means a lower water table. The records show the aquifer falling after the cut. They do not measure pumping volumes, who pumped, or how much of the fall the cut caused.

Supplementary Material for Online Publication Only

The supplement documents the data (Appendices S1–S10) and CAP deliveries in 2008–2015 (Appendix S11). It then holds material the paper leans on less: the timing of planting, the farmed-status check, and which fields stopped farming (Appendices S12–S14).

S1 Geospatial Sources and Field Panel

- **Irrigation canal network.** NHDPlus High Resolution gives most canal lines, and county, district, and Salt River Project maps and lines traced from imagery give the rest. Appendix S2 documents the sources and how the lines are joined into the irrigation network.
- **Field boundaries.** The USDA Crop Sequence Boundaries (CSB) dataset provides satellite-derived field boundaries spanning 2016–2023, each field with a unique identifier. I keep the fields in Arizona (FIPS state code 04), across all 15 counties.

- **Digital elevation model (DEM).** USGS 1/3 arc-second elevation tiles give land heights. A linear fit of height along a canal line confirms or reverses its mapped flow direction where no map records it (Appendix S2), and the heights enter the land check of Appendix S4.

- **Crop-type classification (CDL).** The USDA CropScape Cropland Data Layer provides annual satellite-based crop-type classification at 30 m resolution for 2016–2023. The crop label sets the crop-by-year effects and each field's predicted demand. A field-year without a crop code is fallow, and the monthly water-use rule of Appendix S6 marks further field-years bare (Appendix S10). The crop sequences also train the fallow-type classifier. The Cropland Data Layer changed its method in 2019. From that year NASS trains the Arizona layer on newer land-cover data and with a narrower buffer around its training fields, 15 metres in place of 30 (NASS metadata for the 2019 Arizona layer). In my fields, land labelled fallow or idle falls from 18.5 to 9.6 percent of field-years between 2018 and 2019, and land labelled shrub, grass, barren, or developed rises from 2.1 to 14.4 percent. The samples of Sections 6 and 7 start in 2019, so their outcomes and crops come from the new version. The usual position comes from 2017 and 2018, which share the earlier one. The delivery model of Section 8 runs on 2016–2023, so it spans both versions. In Maricopa–Stanfield the labels do not shift: 14.5 percent of fields have no crop label in 2018 and 15.5 percent in 2019. In New Magma that share rises from 17.2 to 25.0 percent.

The panel contains the 54,946 fields of Section 4.1, observed in every crop year of 2016–2023. The irrigation network of Section 5 links 28,588 of them to canals. Sample counts differ across variables because satellite outcomes, drought measures, and network variables are observed on different supports.

S2 The Irrigation Network

This appendix documents the irrigation network of Section 5: its sources, how its lines are joined and oriented, how fields are placed on it, and how its branches are drawn. Appendix S3 defines the order inside a branch, and Appendix S4 reports the checks. The network files, the code that builds them, and a record of every review decision with its reason are in the replication package.

Canal sources. Table S1 lists the sources of the 6,557 canal lines. NHDPlus High Resolution gives 4,230 lines and 63 percent of the length. The Salt River Project's map of its laterals covers the Salt River Valley Water Users' Association. The county and district layers include Pinal County's water-management lines, which map farm ditches as well as canals, and the canal layers of Buckeye and Cortaro–Marana. District maps and reports give canals in Maricopa–Stanfield, Yuma ID, Central Arizona IDD, New Magma, and the Tohono O'odham farms. The lines traced in the review, 19.6 percent of the length, are canals and ditches that the aerial imagery (NAIP) shows but no map draws.

Joins and heads. The maps break where canals cross roads, pass through siphons, or run underground. I join the end of one line to the start of the next where the imagery shows the canal going on, with no limit on the length of the break. A line that ends against another canal takes water from it. I do not join canals through river reaches or washes, and drains and wasteways carry no deliveries. Each system's water enters at heads placed at documented diversions and

Table S1: Sources of the Canal Lines

Source	Lines	km	Percent of km
NHDPlus High Resolution flowlines	4,230	4,369	62.5
Traced from imagery in the review	1,271	1,371	19.6
Salt River Project lateral map (Maricopa County)	630	505	7.2
District maps and reports	103	211	3.0
County and district GIS layers	145	187	2.7
Other national hydrography (3DHP, Water Carriage)	60	161	2.3
OpenStreetMap	47	100	1.4
Reclamation conveyance lines	56	41	0.6
Other	15	41	0.6
All lines	6,557	6,988	100.0

Notes: Lines of the 46 systems' canal trees, including the 81 pieces of rivers, the CAP aqueduct, and the main canals that carry water to the heads. A line in two systems counts in each. Other national hydrography: the 3D Hydrography Program and the Water Carriage layer. Traced from imagery: lines drawn in the review from NAIP imagery and lidar, by the author or by agents whose lines the author approved.

intakes: river diversion dams, canal intakes, and CAP turnouts. The network has 109 heads: 31 CAP turnouts, 39 diversions on the Gila River and its canals, 19 intakes on the Gila Gravity Main Canal, 6 on the Colorado River, and 14 others on the Salt, Verde, and San Pedro rivers and on main canals.

Direction. Table S2 shows how the direction of each line was set. Where a source layer records the direction of flow, the line keeps it: the Water Carriage layer first, then the NHDPlus main stem, then OpenStreetMap where its first vertex sits at a diversion and the land falls along it. Lines drawn by hand, in the review, on district maps, or on the Salt River Project's lateral map, carry the direction in which they were drawn. For the remaining lines, a linear fit of land height on distance along the line confirmed the mapped direction for 1,854 km and reversed it for 541 km. An early step that turned whole canal systems to run downhill reversed correctly mapped pumped systems, such as Wellton–Mohawk, which is lifted from the Gila Gravity Main Canal. That step does not apply to any system fed from a known source.

Table S2: How the Direction of Flow Was Set

How the direction was set	Lines	km	Percent of km
Mapped direction of the source layer (Water Carriage, NHDPlus, 3DHP, OSM)	2,414	2,523	36.1
Drawn in the direction of flow (review lines, district maps, SRP lateral map)	1,947	1,977	28.3
Mapped direction, confirmed by the land slope along the line	1,476	1,854	26.5
Reversed to follow the land slope along the line	482	541	7.7
Set by the canal it leaves (the network's order)	232	67	1.0
Set by the author's edits	6	26	0.4

Notes: Lines of Table S1. Land slope: a linear fit of land height (USGS 1/3 arc-second elevation model) on distance along the line. Set by the canal it leaves: short pieces whose direction follows from the line they leave.

Intakes. A field is placed by the first rule that applies (Table S3, panel A). (1) It touches a turnout of a canal, or lies on a mapped ditch whose head on the canal is known. (2) Its mapped ditches have no drawn head, and the intake is inferred where they meet a canal upstream. (3) It touches a field already placed and takes through that field's turnout, as a farm does when one turnout serves several of its fields. (4) It takes at the nearest point of its canal, with no ditch evidence. Such fields form blocks, cut at branch points and every 800 m, and the fields of one

block take at one point. In Central Arizona IDD, the district's chains of mapped ditch blocks give the intakes: every field of a chain takes at the chain's intake on the canal, except 362 fields whose intake the review moved. Of these, 325 take at turnouts that agents found on imagery and lidar, 34 take from canal lines added from the district's 2008 map, and 3 at an intake of their own. Pinal County's layer maps farm ditches. Elsewhere the maps hold canals and the larger ditches, so rules (1), (3), and (4) do most of the work. Panel B lists the 2,543 fields of the 46 systems that are left off the network. Fields are taken off as built over when the Cropland Data Layer marks them developed or buildings cover them, and as watered by wells when district or USGS records describe their area as well-fed, or when a well or pump is their only supply.

Table S3: Where Fields Take Their Water, and Fields Left Off

	Fields	Percent
A. Fields on the network: where each takes its water		
At a turnout it touches, or at the head of its mapped ditch	14,127	49.4
Through a touching field's turnout	8,516	29.8
Nearest point of its canal, no ditch evidence	2,393	8.4
At the head of its ditch block (Central Arizona IDD)	1,890	6.6
At an intake inferred above its ditches	992	3.5
On a line drawn or an intake set in the review	670	2.3
All fields on the network	28,588	100.0
B. Fields of the 46 systems left off the network		
Built over, not farmland, or taken off in the review	1,159	3.7
No canal or ditch found that reaches it	715	2.3
Watered by wells (well-fed areas, a well or pump)	664	2.1
Other (builder exclusions, another system)	5	0.0

Notes: Panel A: the 28,588 fields on the network, by the evidence for their intake. Panel B: percent of the 31,131 fields inside the 46 systems. A line drawn or an intake set in the review: fields placed by an answer of the author's review.

Systems not in the network. The network holds about 90 percent of the farmland that canals serve in Arizona: 604,000 of 672,000 acres farmed in at least three crop years of 2016–2023. Most of the rest lies around Gila Bend (about 1,100 farmed fields), in seven districts that draw on surface water (Maricopa Water District, Roosevelt Water Conservation District, Queen Creek, Mohave Valley, St. Johns, San Tan, and Hillander-C), and in small ditch systems on the Gila, San Pedro, Santa Cruz, and Verde rivers.

Branches. Along each main canal, the units of a branch are the laterals with the lines below them, the field canals of the main's own fields, and the fields straight on the main, each at the point where it leaves the main. A unit that serves at least 2,000 acres is a branch. Consecutive smaller units join until together they serve 2,000 acres, and a remainder joins the group before it. Units that leave the main at the same point are never split. A run along a main that stays under 2,000 acres joins the nearest branch of its district, and a district with no group that large is one branch. Six branches follow the district's division instead of the rule, after my review: Lateral 46R of the Colorado River Indian Tribes, two branches of the Gila River Indian Community, the second source of the Salt River Pima–Maricopa Indian Community, and the two Tohono O'odham farms. New Magma's branches follow its turnouts along the CAP aqueduct. The 154 branches serve a median 3,095 acres, and 24 systems are a single branch. Table S4 gives the fields, acres, branches, and pairs of each system.

Table S4: The 46 Canal Systems of the Network

System	County	Fields	Acres	Branches	Pairs	Ditch (%)
Wellton-Mohawk (WMIDD)	Yuma	4,264	62,994	8	1,394,432	45
Yuma County WUA (YCWUA)	Yuma	3,369	43,870	14	463,146	50
Colorado River Indian Tribes (CRIT)	La Paz	2,948	82,140	11	619,560	55
Maricopa-Stanfield (MSIDD)	Pinal	2,384	62,789	19	175,297	74
Central Arizona IDD (CAIDD)	Pinal	2,324	73,480	17	190,919	81
San Carlos IDD (SCIDD)	Pinal	1,379	32,990	4	284,196	89
Yuma Mesa (YMIDD)	Yuma	1,061	15,784	5	116,864	68
Roosevelt ID (ROOSID)	Maricopa	952	23,288	9	53,357	48
Gila River Indian Community (GRICP)	Pinal	938	24,310	5	137,646	84
Yuma ID, South Gila (YIDD)	Yuma	908	10,416	3	177,912	37
Harquahala (HVID)	Maricopa	851	25,741	3	147,713	54
Hohokam IDD (HOHOKAM)	Pinal	819	24,510	5	71,697	86
Salt River Project (SRVWUA)	Maricopa	781	11,729	2	152,117	41
Ak-Chin Indian Community (AKCHIN)	Pinal	663	16,191	3	80,620	85
Buckeye WCDD (BUCKEYE)	Maricopa	583	18,524	3	68,828	52
New Magma (NMIDD)	Pinal	579	19,550	5	40,646	71
Salt River Pima-Maricopa (SALTRIVER)	Maricopa	534	9,643	3	62,007	47
North Gila Valley (NGVID)	Yuma	474	6,231	2	58,233	41
Cortaro-Marana ID (CORTMAR)	Pima	367	9,285	3	21,693	57
Fort Mojave Indian Tribe (FMIR)	Mohave	249	7,546	1	30,713	47
Unit B (UNITB)	Yuma	223	2,031	1	24,505	31
Union Canal (UNION)	Graham	219	5,482	1	23,660	35
Fort Thomas Canal (FORTTHOMAS)	Graham	178	2,532	1	12,357	56
Cibola Valley IDD (CVIDD)	La Paz	167	4,193	2	4,942	55
San Jose Canal (SANJOSE)	Graham	151	4,088	1	10,917	60
Sturges / Gila Monster (SGMIDD)	Yuma	138	1,623	1	7,440	57
Montezuma Canal (MONTEZUMA)	Graham	128	3,449	1	8,023	60
Fort McDowell Yavapai Nation (FTMCD)	Maricopa	119	1,742	1	7,014	51
Graham Canal (GRAHAM)	Graham	109	3,617	1	5,298	56
Arlington Canal Co. (ARLINGTON)	Maricopa	101	4,385	1	4,729	67
Tohono O'odham Nation (TON)	Pinal	91	3,021	2	2,029	56
New Model Canal (NEWMODEL)	Greenlee	78	1,149	1	2,587	62
Dodge-Nevada Canal (DODGENEVADA)	Graham	75	2,297	1	2,566	52
Curtis Canal (CURTIS)	Graham	73	1,931	1	2,356	37
Smithville Canal (SMITHVILLE)	Graham	64	2,134	1	1,584	58
Brown Canal (BROWN)	Graham	59	826	1	1,419	76
Valley Canal (VALLEY)	Greenlee	53	553	1	1,276	25
Cosper-Windham lands, Sunset and Valley canals (COSPERWINDHAM)	Greenlee	32	536	2	207	47
Tidwell Canal (TIDWELL)	Graham	25	396	1	204	84
St. David ID (STDAVID)	Cochise	19	191	1	161	5
Pomerene WUA (POMERENE)	Cochise	18	182	1	130	11
Clearwater Farms Unit 2 (CLEARII)	Maricopa	12	129	1	66	83
T. D. Burton lands, Colvin-Jones Canal (TDBURTON)	Graham	9	41	1	0	33
Fourness Canal (FOURNESS)	Graham	8	118	1	14	62
Colvin-Jones Canal (COLVINJONES)	Graham	7	70	1	10	86
Duncan lands, New Model Canal (DUNCAN)	Greenlee	5	115	1	6	0
All systems		28,588	627,842	154	4,471,096	59

Notes: Fields and acres: fields on the network. Branches: Appendix S2. Pairs: ordered pairs of fields under the filling rule (Appendix S3), same-owner pairs left out, before any distance cut. Ditch: percent of fields placed at a turnout they touch, on a mapped ditch or ditch block, or at an intake inferred above their mapped ditches.

S3 Two Rules for the Order Inside a Branch

Let d_i be the distance along the canals from the head of field i's branch to its intake. Where a branch takes water from more than one head on one source, d_i adds the distance of the field's head along the source from the branch's first head. That distance is measured along the source's lines in their direction of flow, or along the source's mean direction of flow where its lines do not touch. Ten branches take water from more than one head.

The filling rule. Field j is upstream of field i in the same branch when $d_j < d_i - 5\,\text{m}$. Fields whose intakes lie within 5 m of each other have no order, except fields at one intake, which keep the order of their turnouts where the network records it. This is the rule of Section 5.3.

The take-in-turn rule. Every line takes in turn. Field j is upstream of field i in the same branch when j lies on i's route before i's intake, or when j's line leaves i's route before i's intake. A lateral and every field below it then take their water before the canal passes the lateral's junction, however long the lateral is.

The pairs. The filling rule gives 4,618,052 ordered pairs: 630,695 on a field's own route, 3,948,394 between lines, and 38,963 within one intake. The take-in-turn rule gives 4,429,453. The two share 3,958,345 pairs, and 467,386 point the other way. A further 192,321 pairs exist only under the filling rule and 3,722 only under the take-in-turn rule. Same-owner pairs are 3.2 and 3.3 percent of the two. A rule that keeps only the pairs on a field's own route gives 1,238,044 pairs, 5.7 percent of them same-owner.

Why the filling rule. The two rules differ only in how fields on different lines of one branch are ordered. Under take in turn, a field at the end of a long lateral is upstream of every field past the lateral's junction, even fields near the head. A district does not deliver that way. It fills its canals from the head and schedules deliveries, and the water reaches each turnout in order of its distance along the canals. The land agrees: with the same lines and intakes, 135 of the 141 branches with at least 20 fields run downhill under the filling rule, and 126 under take in turn (Figure A4). In two branches where take in turn makes the order climb, reviewers working from imagery and lidar traced the climb to the order the rule gives laterals that leave one point, not to the lines themselves.

S4 Checks of the Irrigation Network

Review. The network went through several rounds of review against NAIP imagery and, where it exists, 1 m lidar. A statewide review of the main canals fixed intakes, joins, and directions one change at a time. A district-by-district review followed, in which agents answered questions on 2,559 fields under rules I set, and I answered the questions they could not settle. I then reviewed an atlas of every district, which maps each branch and the order of its fields, page by page. In a later round I checked every district again in Google Earth and drew 145 pieces of canal and ditch. Last, agents with imagery and lidar checked the branches where the order climbs against the land, at 14 places in 8 branches. Every change is recorded with its reason. The reviews served the network's accuracy only: each change follows the imagery, the lidar, or a district's maps and records, and none was made to change an estimate.

The land. Figure A4 shows, for each of the 141 branches with at least 20 fields, the rank correlation between a field's number of upstream fields and the height of the land at its centre. A negative correlation means the fields later in the order lie lower. Table S5 lists the six branches whose order climbs under the filling rule and what explains each. The check is not fully independent of the network: the land slope set the direction of 541 km of canal (Table S2). The comparison of the two rules is free of that concern, because both use the same lines and intakes.

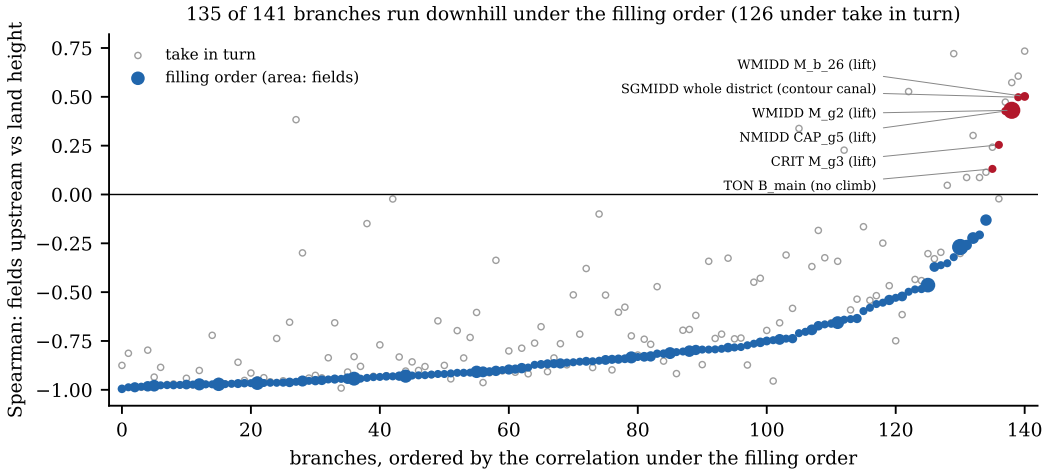


Figure A4: The Order Against the Land, by Branch

Notes: Each point is a branch with at least 20 fields. Vertical axis: Spearman rank correlation between a field's number of upstream fields and its land height (USGS 1/3 arc-second elevation model at the field's centre); negative when the fields later in the order lie lower. Filled points: the filling rule, with area proportional to the branch's fields; blue when negative, red when not. Open points: the take-in-turn rule, for the same branch. Branches are ordered by the correlation under the filling rule. Labels give the explanation of Table S5. Fields watered from wells inside a branch are left out.

Table S5: Branches Whose Order Climbs

System	Branch	Fields	Filling	Take in turn	What explains it
Wellton-Mohawk (WMIDD)	M_g2	1,096	+0.43	+0.57	Wellton-Mohawk pumping plant lifts the canal about 25 m west of the branch; the canal then falls east
Wellton-Mohawk (WMIDD)	M_b_26	190	+0.50	+0.73	Texas Hill pumping plant (4.4 m) and a second small relift
Colorado River Indian Tribes (CRIT)	M_g3	135	+0.25	-0.02	pumping plant at the end of the 42L-1 canal; a buried pipe to three centre pivots on the mesa
New Magma (NMIDD)	CAP_g5	68	+0.43	+0.47	pumping plant on the CAP; Lateral D is a buried pressure pipe that climbs east
Sturges / Gila Monster (SGMIDD)	whole district	138	+0.50	+0.61	the Gila Gravity Main Canal runs along the hills while the valley floor rises
Tohono O'odham Nation (TON)	B_main	42	+0.13	+0.24	every line runs downhill; the order across lines is flat

Notes: The six branches with a non-negative correlation in Figure A4. Filling and take in turn: the correlation under each rule. The explanations come from checks by agents working from NAIP imagery and 1 m lidar, and from the order inside each line: in every branch but the two whose lines are flat (Colorado River Indian Tribes M_g3 and New Magma CAP_g5), the order inside lines runs downhill and climbs only between lines.

Field surveys. The USGS series of crop irrigation water-use estimates for Arizona's groundwater basins digitizes fields from NAIP imagery and records each field's water source from field visits: groundwater, groundwater and surface water mixed, or other. The 2024 surveys cover fourteen basins, among them Willcox, Douglas, San Simon, the Upper San Pedro, the Lower Gila outside Wellton–Mohawk, Gila Bend, and Harquahala. They do not cover the Phoenix, Pinal, and Tucson active management areas, Yuma, or the reservations. I join the surveys to the panel's fields by field

centre. Of the 10,062 surveyed fields that the network leaves off, 89.4 percent use groundwater only. Of the 1,061 that mix in surface water, 1,052 lie in Gila Bend, where canals from the Gila River serve fields outside the network's systems, and 9 in Harquahala. Outside Gila Bend, 99.8 percent of the 8,168 surveyed fields left off use groundwater only. Of the 759 surveyed fields on the network, the 729 in Harquahala all mix canal water with groundwater. The other 30, in the St. David and Pomerene systems on the San Pedro River, are recorded as using groundwater only.

S5 The District Distance Cuts

Section 6.2 counts only the upstream and downstream fields beyond a distance cut set for each irrigation district. The cut comes from how the water use of nearby fields moves together in normal years, the years in which the district is not in drought. For every two fields of a district, I correlate their monthly log water use, net of the water model's fixed effects (field by calendar month, crop by year by month, and county by year by month), over the months both are farmed, at least twelve. I average the correlations in 250 m distance bands and subtract the district's average between fields 8 to 15 km apart. The cut is the first band from which every band to 6 km stays within 0.03 of that baseline. A district with at least 400 fields gets its own cut. The other districts share the cut of all districts pooled, 2 km (Table S6).

I chose the threshold by the following check. In normal months, the correlation between a field's own water use and the mean water use of the fields left on each side, relative to fields of the same district 8 to 15 km away, may exceed its value under a common 3 km cut by less than 0.01. Of the cuts tried (none; 1, 1.5, 2, and 3 km everywhere; and district cuts at 0.05 and 0.03), only 3 km and the district cut at 0.03 pass. The district cut keeps more fields with both an upstream and a downstream side, 20,902 against 18,212.

Table S6: The District Distance Cuts

System	Fields	Distance cut (km)
Yuma Mesa (YMIDD)	1,061	0.75
Yuma County WUA (YCWUA)	3,369	1.25
North Gila Valley (NGVID)	474	1.25
Wellton-Mohawk (WMIDD)	4,264	1.50
Yuma ID, South Gila (YIDD)	908	1.50
Buckeye WCDD (BUCKEYE)	583	1.75
Maricopa-Stanfield (MSIDD)	2,384	2.00
Gila River Indian Community (GRICP)	938	2.00
Harquahala (HVID)	851	2.00
Hohokam IDD (HOHOKAM)	819	2.25
Ak-Chin Indian Community (AKCHIN)	663	2.25
Roosevelt ID (ROOSID)	952	2.50
New Magma (NMIDD)	579	2.75
Central Arizona IDD (CAIDD)	2,324	3.00
Salt River Project (SRVWUA)	781	3.25
San Carlos IDD (SCIDD)	1,379	4.75
Salt River Pima-Maricopa (SALTRIVER)	534	5.25
Colorado River Indian Tribes (CRIT)	2,948	6.00
The other 28 systems (pooled)	2,777	2.00

Notes: Distance cut: the distance beyond which the excess correlation of fields' water use in normal years stays below 0.03 (Section 6.2). Districts with at least 400 fields on the network get their own cut; the other 28 systems share the pooled cut. Fields: fields on the network.

S6 Satellite Outcomes

Water use. Monthly evapotranspiration comes from the OpenET ensemble, version 2.0 (the gridMET-based monthly collection, band `et_ensemble_mad`), in millimetres per month. I take its mean over each field polygon at 30 m. A crop year runs from November of the year before to October, and the water model uses the months of each field's crop (Section 6.4). Crop year 2016 has no November or December. The water model uses the log of water use in active field-months and drops the few months without positive use.

Yield proxy. GCVI $= B8/B3-1$ comes from Sentinel-2 harmonized surface reflectance, through Google Earth Engine. I keep scenes with less than 20 percent cloud cover and mask cloud shadow, medium- and high-probability cloud, and cirrus with the scene-classification layer (classes 3, 8, 9, and 10). In each window I take the maximum at each pixel and then the mean over the field at 20 m. Crop year y has two windows, November 1 of $y-1$ to May 1 of y for winter crops, and May 1 to October 1 of y; the end dates are exclusive. The larger of the two maxima is the peak of GCVI over the crop year. The main text's yield proxy, crop-season GCVI, reads each field's five-day Sentinel-2 curve in the weeks of its crop (Appendix A6). Both enter in logs, on planted field-years of crop years 2019–2023. GCVI responds to the chlorophyll in the canopy, and satellite vegetation indices track harvested yield in ground data (Lobell et al. 2020).

I check the peak in two ways, for this year's change in position × drought in the CAP districts with junior rights, where Sentinel-2's peak gives -0.060 ($p = 0.005$). The first is a second satellite. Landsat 7 GCVI with the same two windows gives -0.038 ($p = 0.002$) on the same field-years, and the difference has $p = 0.11$. Over all fields neither sensor finds an effect (-0.016 and $+0.006$). By crop year, Sentinel-2 gives $+0.002$ in 2019 and -0.010 in 2021, Landsat 7 gives -0.008 and -0.022, and the two sensors do not differ at the 5 percent level in either year ($p = 0.31$ and $p = 0.37$). With each district's cut raised to at least 2 to 10 km, the two sensors differ by at most 0.021, with $p < 0.05$ at no cut. The second check is whether one image sets the maximum. Five-day Sentinel-2 curves cover 83 percent of these field-years. On them the second-highest window gives -0.057 ($p = 0.001$), against -0.062 ($p = 0.002$) for the highest, so the estimate does not rest on the single highest window.

This year's change in canal total × drought does not pass these checks. Sentinel-2 gives -0.017 ($p = 0.42$) and Landsat 7 gives $+0.026$ ($p = 0.038$), and the difference has $p = 0.001$. Landsat's estimate is positive, with $p < 0.05$ at cutoffs of 2, 5, 6, and 8 km. On the five-day curves the estimate is -0.016 ($p = 0.47$) on the highest window and -0.003 ($p = 0.88$) on the second-highest. The Sentinel-2 windows give $+0.029$ in winter ($p = 0.33$) and $+0.022$ in summer ($p = 0.22$).

Fallow. A field-year is fallow when the Cropland Data Layer gives it no crop code, or when its monthly water use shows no crop. The rule scores each month m of the calendar year by $s_m = (\mathrm{ET}_m - F)/(R - F)$. F is the median water use in that calendar month of the county's fields coded fallow/idle (CDL code 61) in 2016–2018 and 2020. R is the 90th percentile of water use of the county's annual-crop fields in that month and year. A score of 0 is the fallow level, and 1 is what the top tenth of cropped fields reach. Months with $R - F$ below 10 mm carry no information and are skipped. A field-year's activity is its second-highest monthly score, so one wet month does not make a crop. The field-year is bare when its activity falls below the county cutoff, three tenths of the way from the median activity of the county's fields coded 61 to that of its annual-crop fields in the same years. Agreement with USGS's field surveys of Harquahala changes little for

cutoffs from 0.23 to 0.43 of the way, and I use 0.3. Counties with too few fields in either group use statewide values. Tree and vine crops keep their CDL status, since their canopies never reach the water use of annual crops, and so do field-years with fewer than six informative months. The rule runs on the calendar year, and its flag applies to crop year y. A rule on May–October water use alone would call a winter crop bare, such as the vegetables grown in Yuma from November to March.

S7 Drought Measures

I take SPEI from the SPEIbase global gridded data (Vicente-Serrano, Beguería, and López-Moreno 2010), at about 0.5 degrees, sampled at each field's centroid. I use the 24-month and the 3-month index, each averaged over May–August. The window ends before the crop season ends. It covers the months when irrigation demand peaks and allocations bind. SPEI-24 follows reservoir storage and the reliability of surface water over several years. SPEI-3 marks short dry spells.

I set drought for each irrigation district and crop year. I average the May–August SPEI-24 over the district's fields on the irrigation network. Each field counts once, whatever its size. The district is in drought when the mean is below -0.6. Every field of the district then has the same drought value. An irrigation district here is whoever delivers the water, so a reservation counts as its own district. The yield and fallowing models also control for each field's own continuous SPEI-3 and SPEI-24.

Drought hits irrigation districts in different years. In 2021, 86 percent of the fields in the CAP districts with junior rights were in drought. Fields in senior-rights districts had their drought years in 2019, when 45 percent of them were in drought, and in 2022. Drought covers 59 percent of field-months in 2008–2015 and 13 percent in 2016–2023. SPEI is an atmospheric index. It marks years when surface water runs short, not deliveries or cuts. Appendix A20 reports the CAP cuts.

S8 Water Rights, Groundwater, and Irrigation Districts

- **Surface-water rights.** Surface-water rights data from the Arizona Department of Water Resources (ADWR) "Statement of Claimant Locator" database provide ownership, priority dates, and locations. These records represent Place of Use (POU) designations, the locations where water may legally be applied for beneficial use. Each field takes the priority year of the nearest recorded right.[6] A significant limitation is that water rights are recorded as point locations rather than polygons: a single point cannot precisely define which fields fall under a given right, and the service area may extend beyond the recorded coordinates. The water-rights controls therefore rely on distance-based matching from field centroids to the nearest recorded right location, introducing measurement error that likely biases toward zero the estimates of how legal priority affects crop outcomes. The nearest-neighbor match imposes no maximum distance; matches beyond 0.2 km are flagged as too distant for the water-rights controls.

- **Irrigation districts.** I obtain irrigation-district boundary shapefiles from ADWR and spatially assign each field to the nearest district, generating a district identifier, a within-district indicator, and distance to the nearest district. The nearest identifier is a geographic assignment for every field, not evidence of membership or service. The institutional profiles therefore distinguish fields inside the named boundary from outside fields and describe "inside" as a service proxy rather than a legal entitlement.

- **Grandfathered groundwater rights.** The Arizona Grandfathered Groundwater Rights database identifies historical parcel boundaries with established groundwater-extraction rights (Irrigation Grandfathered Rights, IGFR). These rights, which predate Arizona's 1980 Groundwater Management Act, provide legal access to groundwater, an important alternative source during surface-water shortages.

- **Well registry.** The ADWR Wells55 registry provides well locations, use codes, application status, and reported installation dates. I calculate the number of wells within the grandfathered-rights boundaries associated with each field as the primary access measure.

- **Groundwater conditions.** The ADWR Groundwater Site Inventory provides dated depth-to-water readings and measurement-source metadata. The monitoring panel of Appendix A20 retains direct readings with blank measurement remarks and credible agency source codes, collapses duplicate site-date records by their median, and requires the same site in every year from 2018 through 2023. Depth is a groundwater-condition outcome: greater depth means a lower water table, not a metered withdrawal volume.

- **Physical supply.** The source audit verifies ordinary agricultural water used within mapped service areas from district, Reclamation, CAP, ADWR, and related primary records. Its fixed 30-district set covers 95.6% of service-supported member fields. The strict classification retains unresolved cases; the approved broader-system sensitivity classifies six Harquahala/Gila Valley encompassing-system cases as mixed without imputing a groundwater share. The resulting division is groundwater only (3 districts), mixed (22), and surface water only (5).

[6] Fields with no matched water right are assigned a priority year of 2025, treating them as having the lowest possible seniority. This affects approximately 72% of observations, reflecting the coarse point-based matching described below.

- **Pricing and governance.** The audit records volumetric, per-acre, flat, tiered, time-based, and energy-pass-through charges, plus rotation schedules and shortage protocols. A descriptive code establishes that a mechanism is documented at some point in 2016–2023; a separate static code requires evidence suitable for a time-invariant interaction variable throughout the analysis period. Unknown, conflicted, and period-ineligible entries remain missing. The strict static view has too little yes–no support for pricing or governance interaction regressions.

- **Seniority.** Priority is classified within the district's operational allocation system rather than translated to a universal rank. The priority categories are senior (6 districts), junior (10), mixed (5), unknown (6), and not applicable (3). The CAP and senior-rights groups of Section 7.2.1 use only affirmatively junior and senior districts, and only the fields inside them. Mixed and unknown districts are in neither group, and so are fields in districts the audit does not cover and fields outside district boundaries, most of them on reservations. Within a district, the district usually holds surface priority, not individual farms. Among the 30 audited districts, systems where one district-held priority covers all member farms' surface deliveries contain 77.8% of audited fields. Reclamation, CAP, district, and decree records verify 63.9%, and 14.0% are inferred. Farm-level priority differences, at least on paper, are documented in nine districts with 15.8% of fields. They include the Salt River Project (Kent Decree land classes), San Carlos, and five Upper Gila canal companies (Globe Equity decree schedules). They also include Mohave Valley (individual present perfected rights) and Buckeye (the Benson–Allison decree). The remaining 6.4% are in three groundwater-only systems and one single-farm entity. Where a rate schedule was located, the district bills members under one schedule. The Salt River Project, Mohave Valley, and Unit B instead use differentiated charge classes, and many retail schedules were not located.

The integrated audit workbook joins the 81 live panel identifiers to pricing/governance evidence and preserves the independently reviewed 30-district priority/supply scope used for analysis. Table S7 reports the complete category distribution and the yes/known denominators; it does not code undocumented mechanisms as zero.

Table S7: Irrigation-District Characteristics and Documentation Coverage

Category or mechanism	Districts	Service-supported fields	Field share	Documented yes/known	Static yes/known
Panel A: Physical supply (broader-system sensitivity)					
Groundwater only	3	1,642	5.9%		
Mixed surface/groundwater	22	23,714	84.6%		
Surface water only	5	2,663	9.5%		
Panel B: Operational priority					
Senior	6	10,879	38.8%		
Mixed priority	5	3,588	12.8%		
Junior	10	7,870	28.1%		
Unknown	6	4,040	14.4%		
Not applicable	3	1,642	5.9%		
Panel C: Pricing and governance audit coverage					
Volumetric pricing	–	–	–	5/5	3/3
Per-acre assessment	–	–	–	26/26	18/18
Flat recurring fee	–	–	–	2/2	1/1
Tiered/progressive pricing	–	–	–	2/2	2/2
Time-based pricing	–	–	–	1/1	—
Energy pass-through	–	–	–	0/1	0/1
Rotation schedule	–	–	–	3/4	1/2
Shortage protocol	–	–	–	12/12	8/8

Notes: The fixed 30-district set accounts for 28,019 service-supported member fields (95.6% of all member fields). Physical supply uses the approved broader-system sensitivity and does not impute a numeric groundwater share. Priority categories are operational within system; mixed, unknown, and not-applicable values are not forced into the senior/junior binary. "Documented" means the mechanism is established at some point in 2016–2023; "static" requires full-period eligibility for a time-invariant regression interaction variable. Entries are yes/known district counts, so 3/3 means three documented yes districts and no documented no districts, not a three-district balanced comparison.

Table S8 widens the CAP and senior-rights groups with districts outside the audit's classes. New Magma's class is unknown, but CAP water is 96 to 98 percent of its farm deliveries in 2016–2022 and 86 percent in 2023. Buckeye's class is also unknown. It diverts Gila River water under a system dating from 1885, and CAP's 2021–2023 reports show no deliveries to it. The Upper Gila group already holds the seven smaller canals that the same article of the 1935 Globe Equity decree names junior with the other five. With New Magma, the CAP results hold: -0.009 ($p = 0.001$) for water use relative to the crop's need, -0.055 ($p = 0.007$) for this year's change in position on the yield proxy at its crop-year peak, and 0.80 points ($p = 0.007$) for fallowing. On that peak, the usual position's estimate goes from -0.018 to -0.015 ($p = 0.054$). Adding Buckeye leaves the senior-rights results as they are.

S9 Soil, Market Access, and Secondary Controls

- **Soil quality (SSURGO).** The USDA NRCS Soil Survey Geographic Database provides each field's soil properties: salinity (EC), clay and sand content, organic carbon, available water storage, bulk density, pH, erosion factors, and a productivity index.
- **Market access (OpenStreetMap).** I calculate distances from each field centroid to the nearest city, large city, highway, and rural place, and to the nearest irrigation district.
- **Land status.** Distances to reservations, state trust land, Reclamation land, and protected areas (GAP status 1–2).
- **Community Water System service areas.** An indicator for whether the field centroid lies inside an ADEQ CWS service-area polygon.

The yield and fallowing models hold these variables in their control set, with field acres, slope, coordinates, distance to the canal, network degree and head/tail indicators, and the water-right

Table S8: Position on the Canal and Drought: Wider Rights Groups

	(1)	(2)	(3)	(4)
	CAP, junior rights		Senior rights	
	Strict	+ New Magma	Strict	+ Buckeye
Panel A. Water use relative to the crop's need, months of the crop, ln				
Position × drought	−0.0111***	−0.0086***	0.0026	0.0026
	(0.0028)	(0.0026)	(0.0026)	(0.0026)
Canal total × drought	0.0052*	0.0055**	0.0011	0.0010
	(0.0029)	(0.0028)	(0.0034)	(0.0034)
Field-months	102,791	114,668	248,960	268,248
Fields	5,410	5,842	9,598	10,162
Smallest first-stage F	3,686	4,344	501	519
Panel B. Yield proxy, ln of GCVI at its crop-year peak				
This year's change in position × drought	−0.060***	−0.055***	0.070	0.070
	(0.021)	(0.020)	(0.057)	(0.057)
Usual position × drought	−0.018**	−0.015*	0.002	0.003
	(0.007)	(0.007)	(0.003)	(0.003)
This year's change in canal total × drought	−0.017	−0.018	0.081	0.081
	(0.021)	(0.019)	(0.065)	(0.065)
Usual canal total × drought	0.002	0.001	−0.003	−0.003
	(0.008)	(0.008)	(0.005)	(0.005)
Field-years	21,296	23,195	48,038	50,820
Fields	5,629	6,090	10,157	10,726
Smallest first-stage F	1,391	1,477	161	171
Panel C. Fallowed, percentage points				
Usual position × drought	0.83***	0.80***	0.01	0.01
	(0.29)	(0.28)	(0.16)	(0.15)
Usual canal total × drought	−0.55	−0.46	−0.09	−0.09
	(0.61)	(0.60)	(0.27)	(0.26)
Field-years	30,565	33,400	51,445	54,360
Fields	6,113	6,680	10,289	10,872
Smallest first-stage F	19,151	18,805	149,792	150,321

Notes: 2SLS. Models, samples, and clustering as in Table 5, except Panel B, which uses the peak of GCVI over the crop year (Appendix A6). In Panels A and C, columns (1) and (3) repeat that table's CAP and senior-rights columns. Each column is estimated separately. Column (2) adds New Magma to column (1). Column (4) adds Buckeye to column (3). Adding also Cortaro–Marana, where CAP is a minority of supply, gives −0.008 ($p < 0.001$) for water use relative to the crop's need, −0.065 ($p = 0.003$) for this year's change in position on the yield proxy, and 0.60 points ($p = 0.081$) for fallowing. $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.

and well variables. The soil, distance, and land variables do not change within a field, so the field effects absorb them. The water-right and well variables enter interacted with drought (Section 6.4), and SPEI-3 and SPEI-24 enter as they are (Appendix S7). The water model has field by calendar month effects and the controls of equation (7). The complete control list is in the replication package.

S10 Fallow Classification

A field-year has a crop code when its CDL code lies outside a 24-code non-crop set (fallow/idle, water, developed, barren, forest, shrubland, pasture, wetlands, and similar categories, plus missing codes). It is **active** when it has a crop code and the monthly water-use rule of Appendix S6 does not mark it bare, and **fallow** otherwise. Activity sets the fallowing outcome and predicted demand, which is zero for a fallow field.

Not all fallow is equally informative. Fallow type comes from a machine-learning classifier trained on 8-year crop-sequence patterns, which assigns each fallow field-year a predicted rotation probability: **non-rotation (stress) fallow** requires probability < 0.3, likely fallowed due to water constraints or economic stress, and **rotation fallow** requires probability > 0.7, representing planned agronomic rotation. Fallow field-years with predicted probabilities in the middle band $[0.3, 0.7]$ are excluded from both classifier-based shares. These two shares, within 3 km, are the nearby-fallowing controls of the yield model (equation (8)).

The shares are computed in geographic space: for each field-year, the shares of fields within 3 km that are stress-fallow and rotation-fallow, regardless of canal direction. They absorb local shocks that spread across nearby fields. The fallowing model (equation (9)) leaves them out, since they measure fallowing too.

S11 Water Deliveries, 2008–2023

Table S9 records CAP deliveries in 2008–2015. In 2008–2014, CAP agricultural deliveries stayed within 1 percent of schedule and no shortage was declared, although SPEI drought in 2010–2014 was more severe than in 2020–2022. The 2015 reduction was voluntary and compensated. Realized deliveries first fell under Tier 1 in 2022. The facts come from official records compiled in the replication package.

S12 Planting Decided Before the Season

Predicted demand (Section 6.3) and the crop demand of the delivery model (Section 8.1) count what each field planted that year, from the Cropland Data Layer, with the calendar of its crop. The Cropland Data Layer gives one status per field and year, assigned after the season. If farmers had decided during the season whether to farm a field, in response to the water they received, upstream planting and a field's water in the same months would be set together. The Sentinel-2 vegetation index shows when the status was set. I use the five-day GCVI composites of all 6,818 fields inside the boundaries of the four CAP districts in 2017–2023 and call a field green in a window when its GCVI is at least 3.0 (Table S10). Thresholds of 2.5 and 4.0 give the same pattern.

Land fallowed in the shortage years was not planted first. Of the fields fallow in 2022 and farmed in 2021, 11.7 percent were green at some time from March through June. Among newly fallowed fields, the share was 12.9 to 19.0 percent in 2017–2019 and 10.3 percent in 2021. The

Table S9: Institutional Water-Delivery Timeline, 2008–2023

Years	Deliveries and storage	Source
2008–2014	CAP agricultural-pool deliveries within ≈0.9% of the 400 kAF schedule; no shortage declared	CAP delivery reports
2010–2014	Meteorological drought more severe than 2020–22 by SPEI; Lake Mead year-end 10.301–14.644 MAF (1,086.30–1,132.83 ft), above the 1,075 ft shortage trigger	Reclamation RISE
2015	CAP agricultural-pool deliveries fell to 318,279 AF; Forbearance I conservation of 80,922 AF, voluntary and compensated (not a shortage cut)	CAP delivery and conservation ledgers
2008–2023	SRP Salt–Verde allocation 3.0 AF/acre (2008–14), raised to 3.3 in 2015–23; available schedules show no allocation cut	Phoenix Water Resource Plan
2020	Tier 0 declared; realized CAP ag-pool deliveries flat against 2019 (255,415 versus 256,143 AF); the reduction was absorbed by credited forbearance (CAWCD DCP contribution 180,608 AF) and unused pool headroom, so orders sat near the reduced cap	Reclamation accounting; CAP delivery ledgers
2022	Tier 1 shortage (projected Mead 1,065.85 ft); CAP ag pool realized 30,825 AF (≈88% year-over-year fall)	Reclamation Tier 1 determination; CAP delivery report
2011–2022	San Carlos Reservoir below 1% of usable capacity (2011–13, 2015, 2018–19, 2021 zero in July, 2022)	USGS station 09469000
2023	Tier 2a; wet-year refill (San Carlos to 226 kAF); no mandatory Yuma senior (Priority 1–3) cut documented in 2021–23	USGS 09469000; Reclamation

Notes: Compiled from official records in the replication package's delivery-fact audit; CAP and Reclamation series are high-confidence, post-2019 SRP schedules and Yuma senior-priority status medium-confidence. Sources: CAP delivery and conservation ledgers (https://library.cap-az.com); Bureau of Reclamation RISE reservoir series and shortage determinations (https://data.usbr.gov); USGS daily storage, station 09469000 (https://waterservices.usgs.gov); City of Phoenix 2021 Water Resource Plan.

median ET of the newly fallowed fields from January through June 2022 was 177 mm, close to that of newly fallowed fields in other years and far below the 477 mm of farmed fields. Fields that were planted stayed planted. Of the cotton fields green by July 14, 2.2 percent had no green window from July 15 through October 31 in 2022 and 1.5 percent in 2021, against 0.5 to 2.1 percent in 2017–2019. The share of all fields that are green fell more after mid-July than in spring in 2021 and 2022, by 5.6 and 7.3 points relative to 2017–2019. It fell even more in 2020, by 10.5 points, when deliveries were near normal. This drop does not follow the shortage. Corn is a large part of it: in every year from 2017 to 2022, half or more of the corn fields green by July 14 had no green window after it.

In 2021 and 2022, what fields planted was set before the canal water fell short. The response within the season is in water use, the outcome of the design. The year 2023 differs: 24.1 percent of its newly fallowed fields were green in spring and idle afterwards, and 4.1 percent of its green cotton fields had no green window after mid-July.

Table S10: Planting and Fallowing Were Set Before the Season

	2017	2018	2019	2020	2021	2022	2023
Panel A. Fields fallow in the year							
Newly fallowed fields	416	498	636	601	551	1,407	1,545
percent green at any time March–June	19.0	12.9	15.4	16.6	10.3	11.7	24.1
median ET, January–June (mm)	150	161	168	180	143	177	227
Fallow two years in a row: median ET, January–June (mm)	114	98	188	190	129	121	212
Farmed fields: median ET, January–June (mm)	459	444	461	494	493	477	487
Panel B. Fields planted in the year							
Cotton fields green by July 14	1,314	1,141	698	674	931	626	314
percent with no green window July 15–October 31	0.5	2.1	1.4	0.4	1.5	2.2	4.1
Corn fields green by July 14	338	546	623	643	740	408	446
percent with no green window July 15–October 31	50.6	51.8	66.1	80.7	83.0	61.8	42.4
All fields: change in the share green, late season minus spring (points)	−0.6	3.4	−2.9	−10.5	−5.6	−7.3	−14.5

Notes: All 6,818 fields inside the boundaries of Central Arizona, Maricopa–Stanfield, Hohokam, and Harquahala, in every year 2017–2023. Status in the year (fallow or farmed, and the crop) from the Cropland Data Layer; newly fallowed: fallow in the year and farmed the year before. Green: Sentinel-2 GCVI of at least 3.0 in a five-day composite with at least half of the field observed. ET: OpenET ensemble, sum over January–June, median over fields. Panel B, last row: the share of fields green in each five-day window minus its 2017–2019 mean, averaged over July 15–October 31, minus the same average over March–June, in percentage points. CAP deliveries to the four districts first fell short in 2022 (Section 2; Appendix Table S9).

S13 The Farmed Status Against Satellite Records

The Cropland Data Layer gives one label per field and year, farmed or fallow. The fallow rule of Appendix S6 starts from it, and the fallowing of Appendix S14 counts fields by it. Two errors are possible. A crop label on land that grew nothing hides fallowing. A fallow label on land that grew a crop adds fallowing that did not happen. Satellite records can find both. I check the label of all 6,818 fields inside the four CAP districts in 2017–2023 against two of them: the Sentinel-2 green windows of Appendix S12 and annual OpenET (Table S11).

Crop labels on land that grew nothing are rare. Over the seven years, 3.4 percent of farmed acres have no green window, between 2.2 and 4.5 percent in each year (Panel A). Grain labels fail most often, on 6 to 7 percent of grain acres in 2019, 2020 and 2022. Cotton labels fail on at most 1.8 percent of cotton acres. Farmed fields with no green window used a median of 512 mm of water a year. That is about half the 959 mm of green farmed fields and more than the 328 mm of fallow fields with no green window. Some are fallow land with a crop label, and some are thin crops. At a GCVI threshold of 2.0, 1.7 percent of farmed acres have no green window, and their median of 376 mm is close to the 311 mm of fallow land.

Fallow labels on green land are more common. Over the seven years, 28 percent of fallow field-years have a green window. Most turn green in winter. Of these fields, 68 percent peak between December and March, and the median one stays green for 35 days. Fallow fields green for less than 30 days used a median of 425 mm of water a year, about 100 mm more than fallow fields that never turn green. They are weeds after winter rain. One fallow field-year in six stays green for 30 days or more, with a median of 605 mm, nearly two thirds of a farmed field (Panel B). In these records a short winter crop and a dense stand of weeds look alike.

Counted from satellite records, farmed land fell as much in 2022 as the Cropland Data Layer says, and less in 2023 (Panel C). In 2022, farmed acres were 75 percent of their 2017–2019 level by the Cropland Data Layer, 77 percent counting fields green for 30 days or more, and 77 percent counting fields with at least 600 mm of annual ET. In 2023 the three counts are 57, 67 and 64 percent. The gap is widest in Maricopa–Stanfield, 57 percent against 67 percent by water use. Water use per farmed acre stays between 3.2 and 3.4 acre-feet under every count and in every year. The Cropland Data Layer and the water-use count agree on 90 percent of field-years. The 2022 fallowing and the flat water use per farmed acre hold when farmed land is counted from satellite records. The Cropland Data Layer may overstate the 2023 fallowing by 7 to 10 points of the 2017–2019 level.

Table S11: The 2022 Fallowing Holds Under Satellite Counts

	2017	2018	2019	2020	2021	2022	2023
Panel A. Fields the crop map calls farmed							
Farmed fields	5,860	5,858	5,597	5,471	5,409	4,304	3,328
percent of farmed acres with no green window	2.2	3.5	4.2	3.4	3.0	4.5	3.5
percent of grain acres with no green window	0.8	2.1	6.0	6.4	3.6	7.2	2.1
percent of cotton acres with no green window	0.3	0.9	0.9	1.3	1.0	1.8	1.2
median annual ET, green fields (mm)	964	975	963	947	952	935	969
median annual ET, fields with no green window (mm)	525	503	493	469	485	501	641
Panel B. Fields the crop map calls fallow							
Fallow fields	958	960	1,221	1,347	1,409	2,514	3,490
percent with a green window	20.1	22.9	27.4	35.2	27.7	23.3	32.5
percent green for 30 days or more	12.1	13.0	12.0	18.3	13.1	15.0	22.2
median annual ET, fields with no green window (mm)	241	292	312	293	328	345	362
median annual ET, fields green for 30 days or more (mm)	870	651	633	546	663	608	587
Panel C. Farmed acres (2017–2019 = 1) and ET per farmed acre (acre-feet)							
Farmed acres, crop map	1.01	1.02	0.97	0.95	0.95	0.75	0.57
Farmed acres, green for 30 days or more	1.03	1.02	0.96	0.97	0.97	0.77	0.67
Farmed acres, annual ET of at least 600 mm	1.02	1.02	0.96	0.96	0.97	0.77	0.64
ET per farmed acre, crop map	3.29	3.29	3.26	3.25	3.28	3.22	3.32
ET per farmed acre, green for 30 days or more	3.34	3.36	3.35	3.29	3.33	3.25	3.18
ET per farmed acre, annual ET of at least 600 mm	3.35	3.37	3.35	3.33	3.34	3.28	3.31

Notes: All 6,818 fields inside the boundaries of Central Arizona, Maricopa–Stanfield, Hohokam, and Harquahala, in every year 2017–2023. Farmed or fallow from the Cropland Data Layer. Green window: Sentinel-2 GCVI of at least 3.0 in a five-day composite with at least half of the field observed, over the calendar year, as in Table S10. ET: OpenET ensemble, January–December sum. Panel C counts a field as farmed by the Cropland Data Layer, by at least six green windows, or by annual ET of at least 600 mm (about 2 acre-feet per acre). Farmed acres are relative to their 2017–2019 mean, and ET per farmed acre is the ET of the counted fields divided by their acres. GCVI thresholds of 2.5 and 4.0 leave 2.4 and 6.0 percent of farmed acres without a green window over the seven years.

S14 Who Left Fields Fallow

This appendix asks which CAP fields stopped farming when CAP water was cut. A field enters year t when it was farmed in $t-1$, and the outcome is whether it is fallow in t. The sample is the 4,641 CAP fields inside the boundaries of the four districts in 2018–2023. Each field trait enters with its own slope in every year, with district by year effects and the crop of the year before. Table S12 reports how each slope changed in 2022 and in 2023 against its 2018–2021 mean. Standard errors are clustered by branch of the canal network, of which there are 42, and 35 in the three Pinal districts.

The crop of the year before carries most of the change. Against alfalfa, a cotton field was 24 points more likely to stop in 2022 than in 2018–2021, and a corn or sorghum field 18 points (Panel A). Measured against 2017–2019 rates, about 27,000 acres were added to fallow land in 2022. Cotton fields account for 40 percent of them, corn and sorghum fields for 23 percent, fallow fields that did not return for 20 percent, and alfalfa for 11 percent. Smaller fields stop more in every year, and the gap does not widen in the shortage years.

In the three Pinal districts, more old wells in the field's groundwater right lowered stopping in 2023, when CAP deliveries were near zero, by 4.5 points per standard deviation. In 2022 the change is about zero. Deeper groundwater went with more stopping in 2022 (4.6 points per standard deviation, standard error 2.0). Service by a district pump shows no clear change in either year.

Fields near the head of the canal network stopped more in 2022. One standard deviation toward the end lowered stopping in 2022 by 2.6 points (standard error 1.4); in 2023 the change is 2.6 points (standard error 1.8). The canal tree of Section 5 starts where CAP water enters each district's canals. For the 4,445 fields on the tree, one standard deviation farther down it, relative

to the other fields below the same head, lowered stopping by 2.6 points in 2022 (standard error 1.3, $p = 0.048$) and by 3.2 points in 2023 (standard error 2.2) against 2018–2021 (Panel B). In 2022, 32.5 percent of the farmed fields in the fifth nearest the head stopped, against 27.2 percent in the farthest fifth. Per standard deviation of kilometers from the head, the change is −6.8 and −9.0 points ($p = 0.06$ and 0.05). With the field's place toward the end of the canal network in the model, the change relative to the head's fields is −2.1 and −2.7 points. Straight-line distance to the aqueduct does not predict stopping. Fields lower below the aqueduct stopped less in 2022, and height and place on the canal overlap. Maricopa–Stanfield varied its 2022 allotments by where a grower's fields were (Section 8.5), and the allotments by grower are not public.

Neighbors' planting does not move fallowing through the canal. For every field, farmed or not, I measure the crop water demand of the land linked to it through its district's canals: the farmed share of that land weighted by crop coefficients, upstream of the field minus downstream, leaving out land of the same owner and linked land within each district's distance (Section 6.2). I build it from two expectations of what the competing land will plant. One is its planting the year before. The other is the chance that each neighboring field is farmed, given its own history and what fields with the same history in its district did that year. For upstream minus downstream land with no district pump in between, neither changes fallowing in any period (Panel C). With allotments per acre the season's water is fixed, and competition moves water between months among the farmed fields. Among fields served by the same district pump, the expected planting of nearer sharers against farther ones does not move fallowing either: 0.5 points per ten points in 2022 and 3.0 in 2023 (standard errors 2.1 and 3.2), against 1.5 in 2020–21. Crop choice moves with the expected planting of the land downstream, already in 2020–21, which points to crop patterns shared along a canal, not to competition.

In five of the Upper Gila canals (Fort Thomas, Graham, Montezuma, San Jose, and Union; 638 fields), fallowing follows the river. In the short springs of 2018 and 2021, 21 and 19 percent of the fields farmed the year before were left fallow, against 6 to 10 percent in the other years. Across canal-years the share that stopped rises with the share of March to June months with canal water below normal (correlation 0.41). In 2022, also short in spring, 8 percent stopped. The same crops left first. In 2021, 57 percent of the corn and sorghum fields and 34 percent of the grain fields were left fallow, against 10 percent of the alfalfa and other hay fields.

Table S12: Who Left Fields Fallow

	All fields		Pinal, with groundwater	
	2022	2023	2022	2023
Panel A. Field traits; change of the slope against 2018–2021, percentage points				
Cotton the year before (against alfalfa)	+24.1* (3.8)	+21.5* (3.1)	+24.2* (4.9)	+19.2* (4.6)
Corn or sorghum the year before	+17.7* (3.5)	+16.8* (4.2)	+20.3* (3.8)	+8.0 (5.6)
Small grains the year before	+1.2 (4.2)	+14.1* (5.1)	−2.0 (5.4)	+2.7 (5.7)
Toward the end of the canal network, per SD	−2.6 (1.4)	−2.6 (1.8)	−1.7 (1.9)	−0.9 (2.5)
Lower below the CAP aqueduct, per SD	−3.9* (1.4)	−4.0 (2.9)	−2.5 (2.5)	−2.7 (3.6)
Log acres, per SD	+0.3 (1.1)	+1.2 (1.2)	−1.0 (1.6)	+2.3 (1.4)
Served by a district pump	+7.8 (6.9)	+4.9 (7.4)	+2.8 (8.2)	−9.8 (10.0)
Old wells in the groundwater right, per SD	–	–	−0.6 (1.4)	−4.5* (1.8)
Depth to groundwater, per SD	–	–	+4.6* (2.0)	+1.0 (3.1)
Panel B. Farther down the canal tree from where CAP water enters, per SD; change against 2018–2021				
Relative to the head's fields	−2.6* (1.3)	−3.2 (2.2)		
In kilometers from the head	−6.8 (3.5)	−9.0 (4.5)		
Relative, with place toward the network end	−2.1 (1.5)	−2.7 (2.2)		
Panel C. Neighbors' planting and fallowing, per ten points; change against 2017–2019				
Canal, upstream minus downstream, expected	−0.8 (2.1)	−3.2 (2.2)		
Canal, upstream minus downstream, previous year	−1.3 (1.2)	−0.6 (1.2)		
Pump sharers, near minus far, expected	+0.5 (2.1)	+3.0 (3.2)		

Notes: Panels A and B: fields of the 4,641 farmed in year $t-1$ (Panel A: those on the canal tree of Section 5); linear probability of being fallow in t, in percentage points. Each trait enters with its own slope in every year from 2018 to 2023, with district by year effects and the crop of $t-1$; a cell is the 2022 or 2023 slope minus the 2018–2021 mean slope. Continuous traits per standard deviation; crop against alfalfa or other hay. Panel A also controls for distance to the canal, a field above its canal, distance to the nearest town, soil organic carbon, normal upstream farming, and the pump capacity serving the field. The Pinal columns add depth to groundwater (2008–2014), old wells in the groundwater right and an own registered well, on the fields of Central Arizona, Maricopa–Stanfield and Hohokam with groundwater data. Panel B: distance down the canal tree from the head where CAP water enters the district's canals, for the 4,445 fields on the tree, relative to the nearest and the farthest field below the same head, or in kilometers; fields off the tree enter with an indicator. Standard errors in Panels A and B clustered by branch. Panel C: fields with linked land farmed in 2016–2019 (6,105; 2,277 served by a district pump with sharers on both sides in Central Arizona and Maricopa–Stanfield); exposure of June to August; field and district by year effects; standard errors two-way by field and branch by year. * $p < 0.05$.