Water, Dust, and Environmental Justice: The Case of Agricultural Water Diversions*

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Abstract

Water diversions for agriculture reduce ecosystem services provided by saline lakes around the world. Exposed lakebed surfaces are major sources of dust emissions and may exacerbate existing environmental inequities. This paper studies the effects of water diversions and their impacts on particulate pollution arising from reduced inflows to the Salton Sea via a spatially-explicit particle transport model and changing lakebed exposure. We demonstrate that lakebed dust emissions increased ambient PM_{10} and $PM_{2.5}$ concentrations and worsened environmental inequalities, with historically disadvantaged communities receiving a disproportionate increase in pollution. Water diversion decisions are often determined by political processes, and our findings demonstrate the need for analysis of distributional impacts to ensure equitable compensation.

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1 Introduction

In situ water in streams, rivers, and lakes provides a suite of valuable ecosystem services including transportation, habitat, electricity production, and nutrient and waste removal. Consumptive water use (e.g. irrigation) and the diversion of water out of basin reduce these services. Food production via irrigated agriculture accounts for the largest share of freshwater consumption, exceeding 85% of consumptive use worldwide (D'Odorico et al., 2020). While changes in the volume of available water to ecosystems decreases the provision of services, there is limited understanding of the distribution of these losses across disadvantaged populations

The effect of agriculture on ecosystem services via its use of water is illustrated clearly in the world's saline lakes where increased consumptive water use and changing patterns of water diversions have created an environmental and health crisis (Wurtsbaugh et al., 2017). When water inflows to these lakes decrease, like the Great Salt Lake in the United States and the Aral Sea in Central Asia, ecosystem services are reduced. The most costly effect is the increased dust emissions from the exposed lakebed surface, referred to as playa (Wurtsbaugh et al., 2017). Dust pollution generally is a key pollutant that has been associated with infant mortality, asthma, and cardiovascular and respiratory morbidity and mortality (Heft-Neal et al., 2020; Kittle, 2000a). Because reduced inflows increase dust pollution exposure in surrounding communities, open questions exist about whether this pollution exacerbates existing environmental inequalities by disproportionately affecting historically disadvantaged communities (Johnston et al., 2019).

In this paper, we provide a novel method for linking playa exposure to increased air pollution via particle transport models. The method allows us to estimate the effects of saline lake decline on spatially-explicit changes in air pollution and to estimate the distribution of these impacts on at-risk and disadvantaged populations. We apply our method to the case of the Salton Sea in California in order to examine the extent to which changes in patterns of agricultural water use, the key factor in saline lake decline throughout the world, drive playa exposure and resulting dust pollution.

The Salton Sea is an ideal setting to study this question as a number of different policies centering around a transfer of water from the Imperial Irrigation District (IID) to San Diego County led to declines in the water level and increased the exposed playa. As a result of the transfer program, dust-related air pollutants such as PM_{10} and $PM_{2.5}$ increased, especially after key changes in the methods and amount of transfer starting in 2012 (Ge et al., 2023). The increase in dust pollution is similar to that resulting from water transfers and agricultural diversions in Owens Lake and Great Salt Lake, as well as Lake Urmia in Iran and the Aral Sea. Furthermore, there have been concerns about air pollution driven by exposed playa and its environmental justice (EJ) consequences, where communities and state and local stakeholders have tried to raise awareness of the issue and design conservation programs to reduce these impacts.[1]

We begin by obtaining estimates of exposed playa over the period before and after water transfers began. These patches emit dust and we apply an atmospheric transport model to understand what happens to dust particles as they are released from the playa. We validate our model using pollution monitors throughout California and confirm the playa-induced dust movement predicted by the transport model corresponds to significant increases in measured particulate pollution (PM_{10} and $PM_{2.5}$).

We then analyze the environmental justice effects of dust-associated pollution by comparing particle exposure in disadvantaged census tracts (low-income and minority populations). We find particles from exposed playa disproportionately affect disadvantaged communities. We test for structural breaks and find that policy changes starting in 2012 that increased on-farm efficiency, reduced return flow, and accelerated the decline in the water level led to increased dust pollution in disadvantaged communities.

Farzan et al. (2019) state that "[t]he drying of the Salton Sea has unknown public health implications and the existing vulnerabilities of nearby populations are largely unmeasured." While some health effects associated with increased dust due to water transfers have been noted in non-academic work, the EJ implications have not been explored systematically in the academic literature. Miao et al. (2022) find that in the Coachella Valley (north of Imperial County) more vulnerable communities, as measured by a variety of indicators, are associated with higher levels of fine particulates. Imperial County's population is 80 percent Hispanic and 10.5 percent Black, meaning it is a community made up almost entirely of traditionally marginalized groups that have predominantly not been included in the political decisions to transfer the water, or in discussions of the mechanisms by which to offset negative externalities. 20 percent of children in Imperial

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[1] In February 15, 2023, Senate Bill SB 583 was proposed to create conservation programs that could decrease pollution caused by the Salton Sea, citing health and EJ concerns.

County are estimated to have asthma (versus just 8.3 percent in US population) (Lipsett et al., 2009), and Imperial County has two times the rate of pediatric asthma-related emergency room visits relative to California.[2]

Minority and low-income communities have higher pollution concentrations compared to other communities (Banzhaf et al., 2019). Most of the EJ literature focuses on how industrial air pollution exposure disproportionately affects these communities (e.g. Agyeman et al., 2016; Ard, 2015; Colmer et al., 2020; McGee et al., 2020), but it is important to understand the role of other sources of pollution as well. This paper takes a first step in understanding the EJ implications of agricultural water diversions and their effect on ecosystem services (dust pollution) by causally linking the IID-San Diego transfer to increased dust-based air pollution and then estimating the spatial distribution of these pollutants across low-income and minority populations. The paper also uses a pollution transport model to link changes in pollution sources to the impacts on communities, contributing to an increasing literature using atmospheric transport models to understand EJ effects (Cain et al., 2023).

While the role of other non-industrial sources on pollution burdens has been evaluated (Burke et al., 2021), less is known about changes in environmental disparities due to agricultural water use and reallocation. In this setting our results show the importance of the political economy and government mechanism for inequitable EJ outcomes discussed in Banzhaf et al. (2019). Water transfer policy is largely shaped by individuals and groups with the ability to influence government, exerting pressure that may lead to less desirable outcomes for disadvantaged communities. Policies like water transfers that change property right allocations in ways that are welfare improving in aggregate may not make everyone better off, especially where contracting costs for apportioning the gains from trade are high (Libecap, 1993). In the case of the IID-San Diego transfer, a community compensation fund and an environmental mitigation fund were created, but for dollar amounts significantly less than the magnitude of the pollution externality (Ge et al., 2023).

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[2] California Department of Public Health: `www.cdph.ca.gov/Programs/CCDPHP/DEODC/EHIB/CPE/CDPH%20Document%20Library/County%20profiles/Imperial2016profile.pdf`

2 Background

2.1 Lakebed Dust Pollution

Saline lakes contain 44% of the volume and 23% of the area of all lakes on earth (Messager et al., 2016). The drying of these lakes due to agricultural water diversions is a serious, ongoing environmental problem (Wurtsbaugh et al., 2017). Water elevation in terminal saline lakes is a balance between inflow and evaporation; saline lakes are generally shallow and can experience large areas of lakebed exposure due to small declines in water inflow. This exposed lakebed, known as playa, contains fine particles that are easily transferred via wind into dust pollution.

Saline lakes have seen reductions in inflow as a result of agricultural and other human water diversions. Prior to an investment in dust mitigation of over $2 billion dollars by the City of Los Angeles, Owens Lake — dried due to the full diversion of the Owens River — was the largest source of particulate pollution (PM_{10}) in the United States (Kittle, 2000b). In Imperial County, airborne dust has been linked via chemical markers to Salton Sea playa (Frie et al., 2017, 2019).

Dust pollution affects human health through the increase in airborne particulate concentrations of PM_{10} (diameters less than $10\mu m$) and $PM_{2.5}$ (diameters less than $2.5\mu m$). $PM_{2.5}$ particles are especially dangerous to human health, as they can make their way deep into the lungs and even bloodstream.[3] Exposure to $PM_{2.5}$ particulate pollution causes a variety of adverse health effects, especially related to the heart and lungs (Deryugina et al., 2019).

Atmospheric $PM_{2.5}$ due to dust storms has been shown to decrease birth weight and increase infant mortality (Jones, 2020; Heft-Neal et al., 2020). In Imperial County, decreases in Salton Sea elevation induced changes in $PM_{2.5}$ during the period 1998 to 2014, which led to serious health issues in the region (Fogel et al., 2021), including increases in respiratory mortality (Jones and Fleck, 2020). As Figure 1 shows, more extensive increases in air pollution occurred from 2012 to 2018, as the rate of playa exposure accelerated due to larger water transfer volumes (Ge et al., 2023). The impact of this dust and additional playa exposure is projected to create larger dust pollution problems in the future (Ayres et al., 2022; Jones et al., 2022).

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[3] Because particles are defined according to their largest size, PM_{10} measurements are inclusive of $PM_{2.5}$.

2.2 Imperial to San Diego Water Transfer

The Salton Sea sits in Imperial County adjacent to the Imperial Irrigation District (IID). IID is the largest single user of Colorado River water, the primary water source for 40 million people in the southwestern United States. The 1922 Colorado River Compact divided 15 million acre-feet (MAF) of water between seven states, apportioning 4.4 MAF to California. Subsequently, the estimated annual flow of the Colorado has turned out to be about 12.4 MAF, of which IID is the largest single water user with senior rights to 3.1 MAF. In the early 2000s, California's ongoing use was in excess of its allocation, around 5.2 MAF. The 2003 transfer agreement between IID and San Diego County Water Authority (known as the Quantitative Settlement Agreement or QSA) was designed to help California reduce its overall water use to its aggregate allocation.

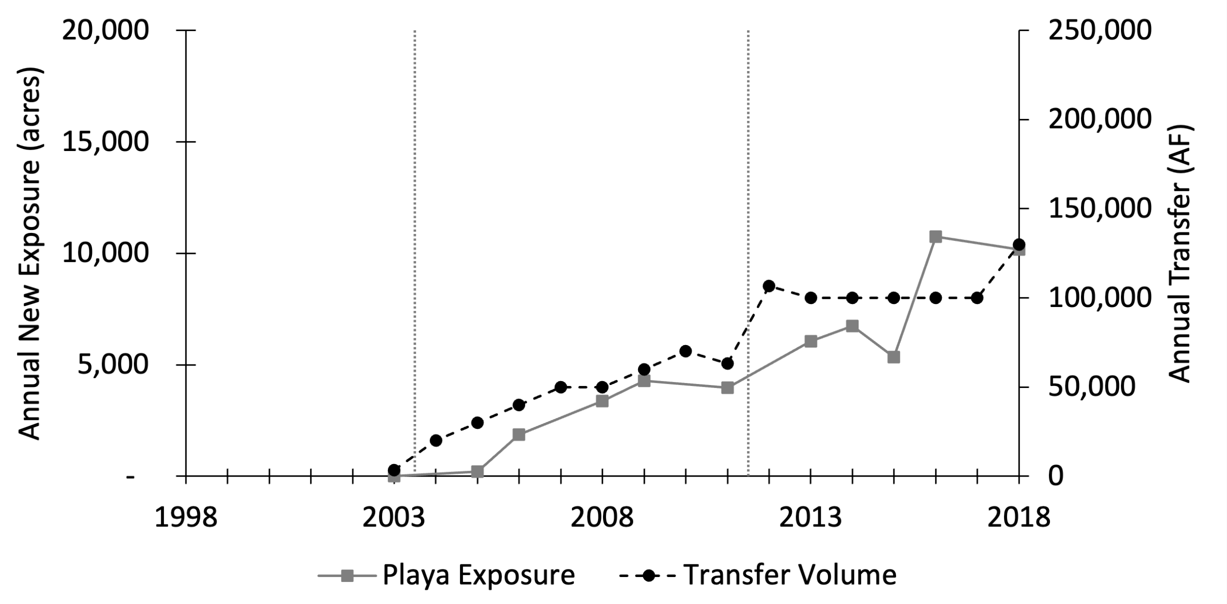
The Salton Sea itself was created by an accidental water diversion of the entire Colorado River into Imperial County from 1905 to 1907. Because the lake has extremely limited natural inflow, it is continually replenished by the "return flows" of irrigated agriculture in IID (and to a lesser extent the nearby Coachella Irrigation District). Return flows include irrigation runoff from the surface (tailwater) and underground (drainage water). Around 85% of the inflow to the Salton Sea is estimated to come from IID return flows, with around one-third (0.963 MAF) of IID's total diversions going to the lake (Jones et al., 2022).

The agreement was set up to eventually reach 200,000 AF/year, lasting 35-70 years. To provide water as stipulated in the QSA, IID began various programs to pay farmers to conserve water. From 2003 to 2011 the programs focused primarily on fallowing. Starting in 2012, the mix of programs used to generate water for transfer shifted to system efficiency measures (e.g., canal lining projects and canal seepage recovery) and on-farm efficiency measures (e.g., precision irrigation and tailwater reuse). The initial fallowing program sent a portion of conserved water directly to the Salton Sea in an attempt to offset some negative impacts. There was no mitigation program for system or on-farm efficiency programs. The amount of water transferred is shown in the right axis of figure 1.

The result of the transfers was a decline in inflows to the Salton Sea (Fogel et al., 2021, p.22). In 2003, the elevation of the Salton Sea was around 229 feet below sea level (Formation Environmental, 2016). It remained about this level until 2009 when it began to decline; by the end of

2011 the elevation was around 230 feet below sea level and by 2018, the end of our sample, lake elevation had fallen to over 234 feet below sea level (Formation Environmental, 2016, 2022a).[4] As flows into the lake decreased, additional playa was exposed, especially after 2011, on which we focus the empirical analysis. The annual area of playa exposed is shown in the left axis of figure 1. Every year after 2011 saw more playa exposed than in any year before 2011. New playa exposure in just 2017 and 2018 exceeded the total area exposed prior to 2012. The remainder of the paper focuses on these exposed areas, estimating when they were exposed and where the dust traveled.

Figure 1: Water Transferred and Exposed Playa



Notes: Annual playa exposure in acres (non-cummulative) on left-axis and annual water transfer in acre-feet (non-cummulative) on right axis. Vertical lines in 2003 and 2011 show the start of the transfer program and start of intensification, respectively. Playa exposure data from Formation Environmental (2019a, 2020a, 2021a, 2022a, 2016, 2018, 2019b, 2020b, 2021b, 2022b). Water transfer data from Imperial Irrigation District (2021).

3 Data

Salton Sea water elevation: We obtained the exposed surface, playa, from the Salton Sea by collecting lake and lakebed elevation data. We generated a 1 km × 1 km grid for an area around the 2002 and 2018 lake shoreline, as derived from shapefiles created by the Imperial Irrigation

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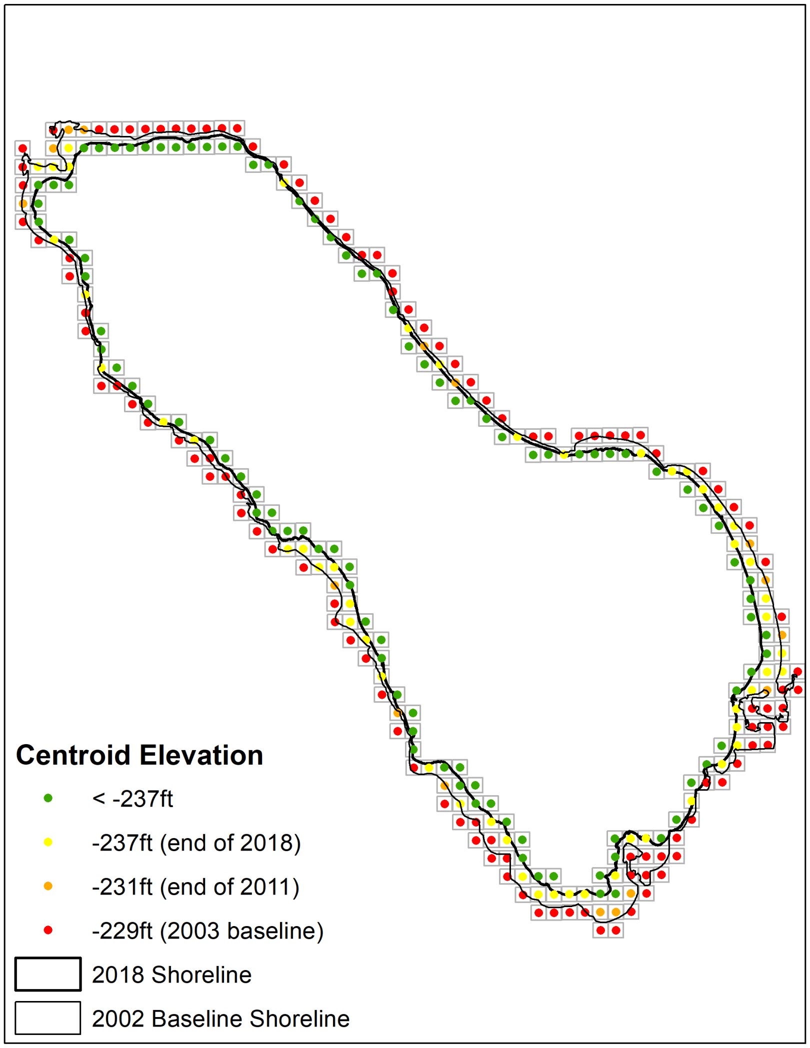
[4] Elevation reports by Formation Environmental (2016, 2022a) differ somewhat from average elevation data gathered from USGS gauge "Salton Sea NR Westmorland CA - 10254005" as shown on figure 2, likely due to within-year fluctuations in water level. The pattern of decline, however, is consistent across both measures.

District Salton Sea Air Quality Mitigation Program.[5] After obtaining the centroid of each grid cell, we found the lakebed elevation by matching each centroid to the closest Salton Sea bathymetry contour (one foot) from the California Department of Fish and Wildlife.[6] We then compared the water level — using the elevation of the lake from United States Geologic Survey gauge 10254005 — with the elevation of the exposed playa, providing an estimate of annual time-varying playa exposure, as shown in figure 2.

Figure 2: Salton Sea Playa Exposure through 2018



Notes: This figure presents the point grids and associated centroids used to model the atmospheric transport model. The figure shows the estimates of annual-time-varying playa exposure per date of exposure.

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[5] `https://saltonseaprogram.com/aqm/data-portal/data-portal.php`

[6] `https://gis.data.ca.gov/datasets/30ab3e1e70824f21b1136d3296cf17f4/explore?location=33.313653%2C-115.832324%2C11.24`

Pollution monitor data: We use pollution monitor data from the EPA, which provides the location of all pollution monitoring stations in California. We download daily data for the state of California, which generally provides daily PM_{10} (μ/m^3) levels for 1998 to 2018, and $\text{PM}_{2.5}$ (μ/m^3) levels, generally in three-day increments from 1998-2002 and then daily from 2002 onwards.[7]

Socioeconomic vulnerability: We use the CalEnviroScreen 4.0 (CES4.0) definition of "Disadvantaged Community (DAC)." The CES4.0 considers several socioeconomic and health indicators to construct a score at the census tract level. Census tracts receiving the highest 25 percent of overall scores in CalEnviroScreen are deemed to be DAC.[8] We obtain alternative measures of vulnerable community status, linguistic variation and poverty, from the raw data used to construct the CES4.0.

Particle transport: To obtain particle trajectories, we apply the HYSPLIT model to each centroid location of the playa grid. We model forward trajectories (i.e. consider a particle released from the location in question and follow it over time) from ground-level released particles. We obtain two trajectories for each day, one at 6 AM and one at 6 PM. The HYSPLIT model provides elevation and coordinates of the particle for every hour following the initial release. Figure 3 provides examples of these trajectories originating from one individual playa location. Distance, direction, and elevation are determined by time and location-specific meteorological data. Unlike other HYSPLIT applications (e.g. Grainger and Ruangmas, 2018; Hernandez-Cortes and Meng, 2023) that link locations with estimated emissions (via emissions inventories or other data sources) we do not model actual emissions from the source. Data on the ground-level release of particulates from the Salton Sea playa do not exist. Therefore we simply model 'particles' and follow their trajectory. King et al. (2011) find that wind speed is the largest factor in particulate release in the Salton Sea, with little difference across a variety of playa regions. Therefore, our measure of exposure captures the amount of hours that particles coming from a point in the exposed Salton Sea playa are located in a specific census tract throughout California.[9]

Table 1 shows the descriptive statistics by census tract bifurcated by whether the tract is transited by a playa particle during the study period (column 1) or sees zero particles (column 2). The

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[7] `https://www.epa.gov/outdoor-air-quality-data/download-daily-data`

[8] `https://oehha.ca.gov/calenviroscreen/sb535`

[9] This measure is similar to the one used by Heo et al., 2023 who calculates the percentage of hours that particles in South Korea are coming from China.

Figure 3: Example Particle Trajectories

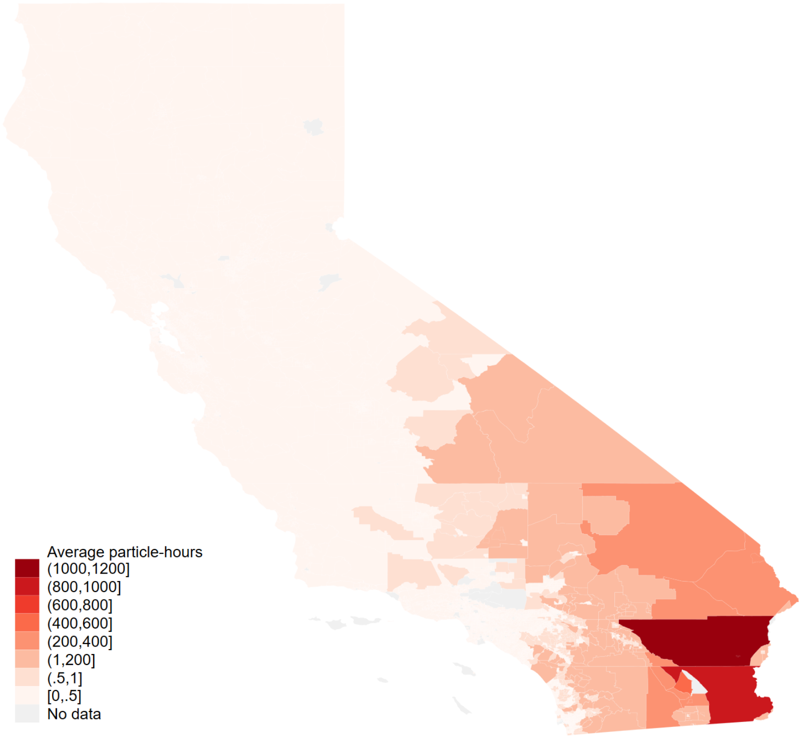
Notes: This figure demonstrates example particle trajectories from one point on the Salton Sea playa. The point is in black and the red lines indicate particle trajectories that begin at the black playa point.

annual total particle-hours is the average number of particle-hours from all emitted sources at the census tract level calculated using HYSPLIT. The rest of the variables were obtained from CES4.0 indicators. Census tracts with more than zero particle-hours have higher average populations than census tracts with zero particles. Both Ozone and $PM_{2.5}$ are higher in census tracts with more than zero particle-hours. Furthermore, the share of census tracts classified as disadvantaged is higher in areas with more than zero particle-hours. However, poverty and linguistic isolation measures are relatively similar between census tract types. Figure 4 shows the spatial pattern of playa dust particles transiting census tracts. Census tracts receiving at least some particles tend to be located closer to the Salton Sea, with relatively higher particle counts to the east.

Table 1: Descriptive Statistics

	(1) More than zero particle-hours	(2) Zero particle-hours
Annual particle-hours	770.902	0.000
	(15505.63)	(0.00)
Population (2019)	5075.911	4757.440
	(2389.75)	(2016.89)
Ozone (ppm, max 8 hr concentration)	0.053	0.043
	(0.01)	(0.01)
$\mathrm{PM}_{2.5}$ ($\mu g/m^3$, annual concentrations)	10.911	9.239
	(1.91)	(2.11)
Disadvantaged community (share census tracts)	0.283	0.210
	(0.45)	(0.41)
Poverty above 75th percentile (share census tracts)	0.251	0.250
	(0.43)	(0.43)
Linguistic isolation above 75th percentile (share census tracts)	0.245	0.237
	(0.43)	(0.43)
Observations	4,356	3,680

Figure 4: Average Exposure to Particle-Hours by Census Tract



Notes: This figure presents the average particle-hours exposure for the period 1998-2017 in California. Particle-hour exposure was modeled using HYSPLIT. Census tracts are based on 2010 cartography, obtained from the CES4.0.

4 Empirical Strategy

Our empirical approach links the increasing playa area of the Salton Sea to air pollution from dust. We do so by (1) applying the atmospheric transport model described above to track particles emitted at a particular spatial location and time as they travel due to atmospheric conditions; (2) validating this model by linking these particle transport paths to air pollution monitors and demonstrating a robust relationship between predicted particle paths and observed PM_{10} and $\text{PM}_{2.5}$ concentrations; and (3) tracking the concentration of particle destinations over time to different census tracks and distinguishing between disadvantaged and other communities.

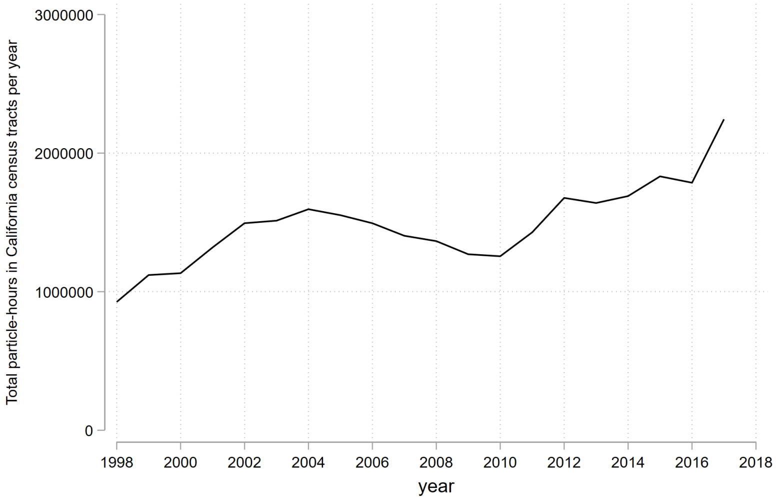
The meteorological transport model provides one source of variation for particle exposure. We add an additional source of variation arising from the timing of exposed playa due to the falling elevation of the Salton Sea. We include emissions from locations only when the elevation of the lake drops below the elevation of each playa centroid. Thus, throughout our sample period, the number of particle-emitting locations increases (see Figure 2). Figure 5 shows the total number of particle hours over the time period, that is the number of particles transiting any census tract in California. The number of particles are increasing over time, consistent with more playa points being exposed. From 1998 to 2004, there is a rise in particles moving through California from exposed playa due to both increasing playa area and meteorological conditions. Between 2004 and 2011, we observe a relative decline in particle hours due to meteorological conditions, e.g. particles exited California census tracts more quickly. From 2012 onward we see an increase in particles as more playa locations become exposed due to the accelerating decline in the water level (as seen in Figure 1).

We test whether these emissions correspond to measured pollution by linking pollution monitor data with the modeled particle trajectories. We create 5 km buffers around each EPA pollution monitor and count the number of modeled particle-hours in these buffers each day. We then regress both PM_{10} and $\text{PM}_{2.5}$ concentrations on the number of particles arriving each day using the following model:

$$y_{idmt} = \beta T_{idmt} + \gamma_i + \mu_t + \theta_m + u_{idmt} \tag{1}$$

In the above equation, i indexes a specific monitor, d indexes the specific day, while m and

Figure 5: Total Particles by Exposed Playa



Notes: This figure presents the total number of particle hours in California census tracts over time. Increases in particle hours come from both increasing the amount of source pollution (as more playa is exposed) and from meteorlogical conditions that lead to particles spending more time in CA census tracts.

t index month and year respectively. The outcome variable y_{idmt} is the monitor-specific reading of PM_{10} and $PM_{2.5}$ in a given day and the explanatory variable of interest is T_{idmt}, the number of particle-hours measured in the monitor's buffer that day. The coefficient β captures the relationship between the total particles and the PM concentrations and provides our test of the transport model. Small and statistically insignificant estimates would indicate that the HYSPLIT-modeled particulate paths have little relationship to ambient PM concentrations. Significant positive estimates, however, indicate that the modeled particulates increase PM concentrations. We include monitor-specific fixed effects, year fixed effects, and month fixed effects. All standard errors are clustered at the monitor level.

After validating the transport model, we track all particle emissions as they transit different census tracts. We categorize census tracts by their DAC status from CES4.0 as well as measures of poverty and linguistic variation. We plot trends in pollution exposure (via modeled particles) for these different categories of census tracts and test whether trends or differences in trends correspond to policy changes from different phases of the QSA.

Our statistical analysis of changing DAC exposure focuses on the changing number of playa particles transiting DAC and non-DAC tracts after 2011 when additional water transfers via on-farm and system conservation measures began. We use the following equation to estimate this trend break:

$$p_{jt} = \tau \times t + \rho I_{t>2011} \times t + \lambda I_{t>2011} + \sigma_j + u_{jt} \tag{2}$$

Where the outcome p_{jt} is the number of particle-hours in a census tract j in year t coming from exposed playa points. $I_{t>2011}$ is an indicator for post-2011, σ_j captures census tract effects, and t is a linear time trend. A positive coefficient estimate for ρ indicates that there is a change in trend post 2011; we run with a combined set of tracts as well as DAC and non-DAC tracts separately to understand changing trends. We present results from these exercises in the following section.

5 Results

5.1 Particulate Pollution

We first analyze whether an increase in the number of particle-hours modeled with HYSPLIT increases pollution levels using equation 1. Table 2 shows these results for PM_{10} (columns 1 and 2) and for $PM_{2.5}$ (columns 3 and 4). We find that an increase of 1 particle-hour increases PM_{10} concentrations by 0.824 or approximately 2.46% in the buffer area of the PM_{10} monitors and increase $PM_{2.5}$ concentrations by 4.58% in the buffer area of the $PM_{2.5}$ monitors.

These results provide important validation of our particulate transport model. Despite the absence of data on actual source emissions discussed above, the modeled particulate transport has a significant relationship with ambient pollution concentrations.

5.2 Exposed playa and environmental justice outcomes

We now turn our attention to the spatial distribution of the dust emitted from the Salton Sea playa. Figure 4 shows the average number of particle-hours in each census tract from Salton Sea exposed playa during 1998-2017. Most of the effects are concentrated in East Southern California, in areas of Imperial, Riverside, and San Bernardino counties. Some areas of Los Angeles and San Diego counties are also affected. However, coastal areas of Southern California and most of Northern California have zero modeled particle-hours.

Table 2: Exposed Playa and Polution Outcomes

	(1) PM_{10}	(2) PM_{10}	(3) $PM_{2.5}$	(4) $PM_{2.5}$
Particle-hours	0.756*** (0.195)	0.824*** (0.188)	0.502*** (0.105)	0.474*** (0.104)
Mean	33.418	33.418	10.905	10.905
Obs.	658,486	658,486	696,604	696,604
R-squared	0.038	0.040	0.213	0.245
Year FE	Yes	Yes	Yes	Yes
Month FE	No	Yes	No	Yes
Site FE	Yes	Yes	Yes	Yes
Cluster level	Site	Site	Site	Site

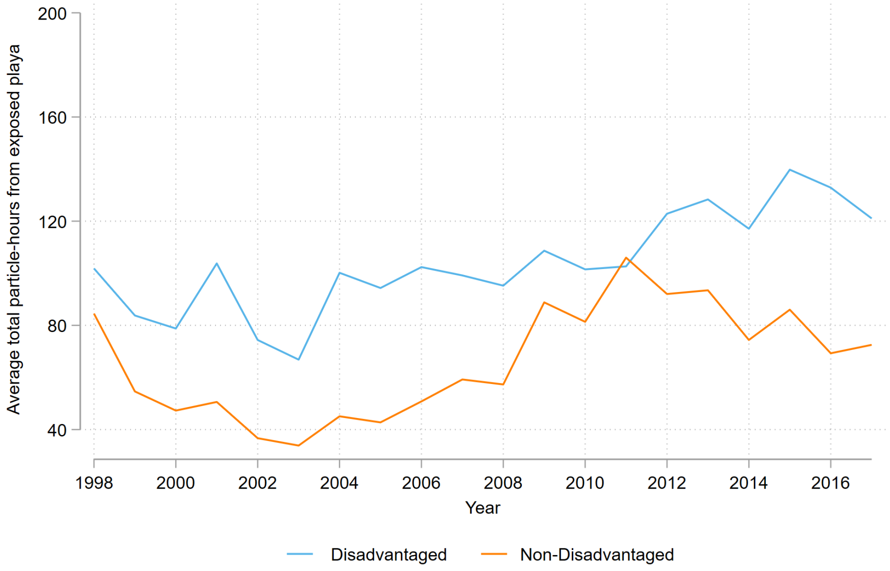
Notes: Above are coefficient estimates of β from Equation (1). Columns (1) through (3) use PM_{10} concentrations and Columns (4) through (6) use $PM_{2.5}$ as outcome variables. Fixed effects are indicated by column labels and all standard errors are clustered at the monitor level. The mean indicates the average pollution concentration for the respective pollutant.

In order to analyze the impacts of increases in exposed playa on environmental justice outcomes, we first show that total particle-hours increased after 2011, consistent with the increases in exposed playa shown in figure 1. Figure 6 shows the number of particle-hours for both disadvantaged and other communities. Disadvantaged communities experience a higher average number of particle-hours during most of the 1998-2017 period. Pre-2012, there are some fluctuations in year-to-year number of particle-hours. However, after 2011, the number of particles increase in disadvantaged communities, while the number of particle-hours in non-disadvantaged communities decreased.

We estimate these differences using other measures that have been used in the environmental justice literature as indicators of social and economic vulnerability: poverty and linguistic isolation. Figure A1 shows these results. Panel a) shows differences by poverty level (communities in the top 25th poverty percentile in blue and the rest of the communities in orange) and Panel b) shows differences by linguistic isolation (communities in the top 25th percentile of linguistic isolation in blue and the rest of the communities in orange). Both figures show that communities with higher levels of vulnerability have higher levels of particle-hours exposure, consistent with the results in figure 6.

We formalize these findings in figure 7 by estimating a two-way fixed effects model (with

Figure 6: Exposure to Particle-Hours by Disadvantaged Status

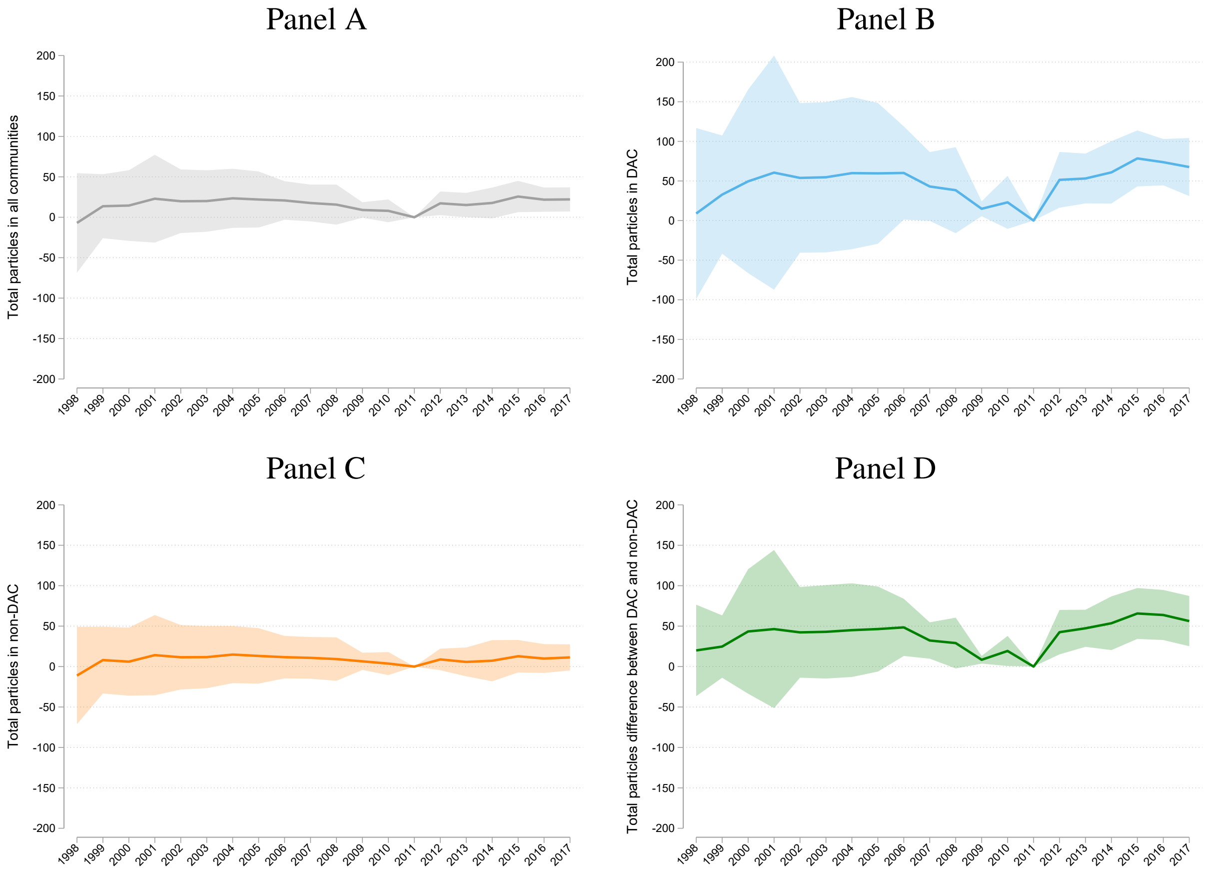


Notes: This figure presents the average particle-hours exposure for the period 1998-2017 in California for Disadvantaged (blue) and non-disadvantaged (orange) communities. Particle-hour exposure was modeled using HYSPLIT. Disadvantaged communities classification was obtained from CES4.0.

both census tract and year-fixed effects) and plot the year fixed effects estimates relative to a 2011 baseline, where the dependent variable is the number of total particle-hours. We estimate this model for all communities (Panel A) and separately for disadvantaged communities (Panel B) and other communities (Panel C). Panel D interacts year-specific coefficients with an indicator variable on whether the community is disadvantaged or not. Panel A shows that before 2011, there were no differences in total particle-hours exposure, however, we see an increase after 2011. Panel B shows that before 2011 there are only statistically significant differences in total particles in one year. After 2011, there is a constant increase on average particle-hours in DAC communities. This pattern is not present when we restrict our sample to non-DAC communities (Panel C), suggesting the post-2011 increase in Panel A is due to increases in DAC communities. Panel D confirms the difference between DAC and non-DAC communities, although there are some statistically significant differences prior to 2011.

To examine whether there is a statistically meaningful trend break after 2011, we estimate equation 2 for the entire time period (columns 1-3 in table 3) and the post-2003 period following the enactment of the QSA (columns 4-5 in table 3). We show results for all communities (columns

Figure 7: Difference in Total Particles Relative to 2011



Notes: This figure presents the annual difference in particle-hours exposure for the period 1998-2017 in California for all communities (Panel a), Disadvantaged communities (Panel b) and non-disadvantaged (Panel c) communities. Panel d shows the interaction between year and disadvantaged communities indicator. Particle-hour exposure was modeled using HYSPLIT. Disadvantaged communities classification was obtained from CES4.0. Census tracts are based on 2010 cartography, obtained from the CES4.0.

Table 3: Trend-Break Model

	(1) All	(2) DAC	(3) Other	(4) All	(5) DAC	(6) Other
Trend × post 2011 (ρ)	2.541	9.087**	1.117	4.688***	14.526***	2.650
	(1.73660)	(3.82626)	(2.22939)	(1.63574)	(4.60892)	(1.95095)
Post 2011 (λ)	-8.661***	-11.187*	-7.677***	0.030	10.925	-1.480
	(2.12349)	(6.30961)	(1.86186)	(2.69692)	(6.69644)	(1.97052)
Trend (τ)	0.100	-0.629	0.243	-1.922	-5.856	-1.191
	(1.61634)	(3.39492)	(1.47684)	(1.52090)	(4.53306)	(1.42539)
Mean	66.843	103.308	60.094	70.864	108.608	63.736
Obs.	444,901	69,476	375,425	335,082	53,228	281,854
R-squared	0.771	0.560	0.808	0.771	0.580	0.805
Census tract FE	Yes	Yes	Yes	Yes	Yes	Yes
Cluster level	County	County	County	County	County	County
Period	1998-2017	1998-2017	1998-2017	2003-2017	2003-2017	2003-2017

Notes: This table shows the results for equation (2) separately for All (columns 1 and 4), Disadvantaged (columns 2 and 5) and non-Disadvantaged (columns 3 and 6) communities. Columns 1-3 show the results for the entire study period and Columns 4-6 show the results for the 2003-2017 period. isadvantaged communities classification was obtained from CES4.0.

1 and 4), for DAC communities (columns 2 and 5), and for non-DAC communities (columns 3 and 6). The main coefficient of interest, ρ, shows that after 2011 and accounting for existing trends, disadvantaged communities experienced an increase in the number of particle-hours. The change in trend exists using data from the entire time period and only data for the 2003-2017 period. Consistent with the results in figures 6 and 7, results from columns 2 and 3 suggest that the increasing trend in the total particle-hours after 2011 is occurring in DAC communities.

6 Conclusion

Water diversions for agriculture pose significant risks to the environment and public health when they lead to reduced lake levels and increased dust pollution in downwind communities. This paper examines whether dust pollution from water diversions for agriculture increase environmental disparities by studying a particular water transfer in Southern California. We find that transfers from the Imperial Irrigation District to San Diego County increased pollution in disadvantaged communities, overall and relative to non-disadvantaged communities.

By using an atmospheric transport model linking exposed lakebed after the water transfer to patterns of dust pollution, we show that lakebed dust increases the number of particle-hours and PM_{10} and $PM_{2.5}$ pollution levels around nearby monitoring stations. Given that the Salton Sea is located in a rural area near low-income and predominantly minority communities, we examine which communities experience an increase in total particle-hours after 2011, where changes in the water transfer implied lower flows into the Salton Sea, decreasing its water levels. We find that the number of particle-hours coming from exposed playa disproportionately increased in disadvantaged communities, and we find that non-disadvantaged communities did not experience an increase in particle-hours exposure. These results suggest the need for distributional analyses in water transfer programs to evaluate and potentially compensate disadvantaged communities for negative external effects.

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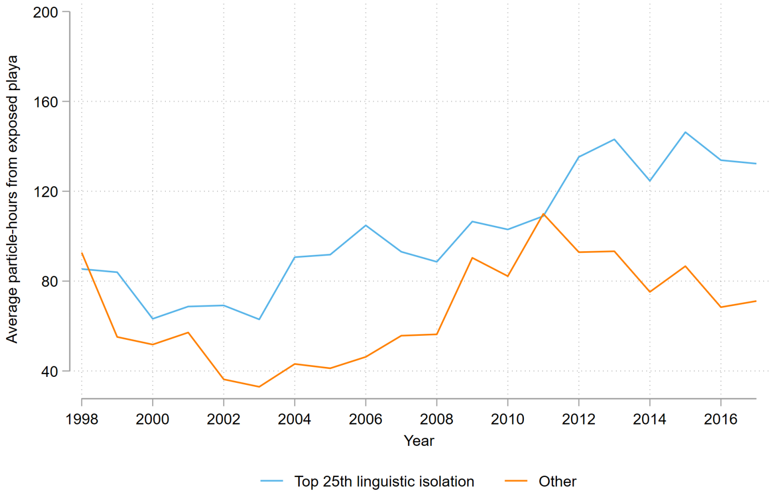
7 Appendix

Figure A1: Exposure to Particle-Hours by Socioeconomic Indicators

Panel a)

Panel b)



Notes: This figure presents the average particle-hours exposure for the period 1998-2017. For two different indicators: poverty (Panel a) and liguistic isolation (Panel b) in California. Panel a shows average particle-hour exposure for the top 25th poverty percentile (blue) and remaining communities (orange). Panel b shows average particle-hour exposure for top 25th linguistic isolation percentile (blue) and remaining communities (orange). Particle-hour exposure was modeled using HYSPLIT. Percent poverty and linguistic isolation indicators were obtained from CES4.0.