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Innovations in economic assessment of drought: an application to the US southwest

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ABSTRACT

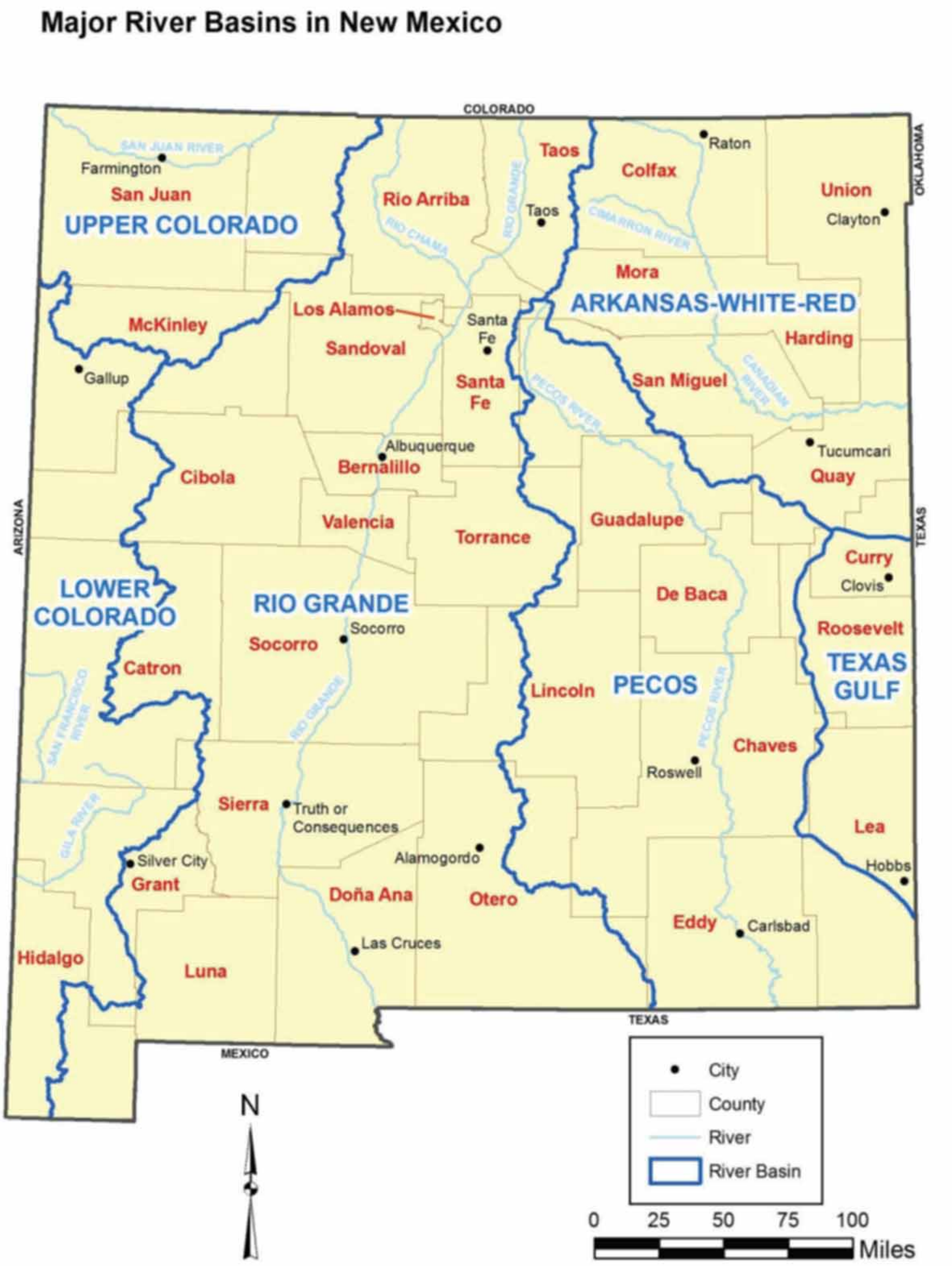
While numerous studies have examined the economic repercussions of drought, there remains a gap in integrated analyses comprehensively assessing its economic effects, especially where there is no drought adaptation policy under debate calling for a standard cost-benefit analysis. This work's first contribution comes from the development of a non-linear econometric model predicting total county income for several counties and years, for which population growth in some regions showed increasing water use despite the presence of drought. Using the arid southwest US state of New Mexico as a case study for the drought years of 2017–2019, this work develops a second innovation to assess drought damages based on comparing changes in per capita water use from 2015 to those later years. Using those two innovations, total economic damages to water users summed over the three drought years amount to $1.983 billion, just under 1% of the state's total income for that period. Overall, the effects of drought in New Mexico were more modest than anticipated partly because water users in this state showed remarkable resilience in handling water shortages due to several unique structural features of the state's income generation processes.

Key words: Drought, Economics, Hydrology, Management, Policy

HIGHLIGHTS

- This work's first contribution comes from the development of a non-linear econometric model predicting total county income for several counties and years.
- Its second contribution assesses drought damages in the face of increased water use levels observed over those years compared with the base year of 2015.

GRAPHICAL ABSTRACT



1. BACKGROUND

1.1. The drought issue

Drought has been characterized as a deficiency of precipitation over an extended period of time, typically a season or longer, resulting in a shortage of water supply and use. Drought can be an elusive process to define, for which various studies in the early part of the 1980s found in excess of 100 published definitions of drought, reflecting variability by region, uses of water and approaches taken for assessment. To be useful for informing drought management policy, a definition of drought and its economic consequences should be based on a conceptual framework that guides measurement, assessment, and policy responses.

Because drought reflects a deficiency of precipitation, rather than the occurrence of a particular event like a tornado or fire, it is a pervasive or creeping phenomenon, as it slowly affects numerous kinds of economic activity and operates over several periods of time. As part of various drought monitoring work groups in the US, there are tools in place used by the US National Weather Service to measure drought. Despite the presence and utility of these tools (Hayes *et al*., 2012), it remains hard to predict, measure, and monitor drought indicators that are useful for economic damage assessment.

1.2. Significance of drought in the US arid southwest

A 2010 article published in the *Proceedings of the National Academy of Sciences of the United States of America* (Cayan *et al*., 2010) described some of the unique elements associated with drought in the southwest US:

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

Clearly, economic assessments of drought in the southwest along with policy options for handling drought need rigorous scientific attention. For example, a 2020 New Mexico Climate Strategy Report stated the importance of the New Mexico Office of the State Engineer (NMOSE) in water resources planning (New Mexico Interagency Climate Change Task Force, 2020).

1.3. Previous work

Assessing the economic consequences of a drought has seen much attention in the peer-reviewed literature. Several recent works in the US have investigated economic impacts of drought (Umar *et al*., 2021; Alahacoon & Amarnath, 2022; Ali *et al*., 2022; Espinosa-Tasón *et al*., 2022; Felbermayr *et al*., 2022; Song *et al*., 2022; Wlostowski *et al*., 2022; Gebre *et al*., 2023; Javadi *et al*., 2023; Kumar & Varija, 2023; Manisha *et al*., 2023; Huizar *et al*., 2024; Pandey *et al*., 2024; Samuel *et al*., 2024; Shyrokaya *et al*., 2024). Other recent works have conducted formal economic assessments under various drought conditions (Eamen *et al*., 2022; Khass *et al*., 2022; Fernández *et al*., 2023; Garba *et al*., 2023; Konovalova *et al*., 2023; Lückerath *et al*., 2023; Malik *et al*., 2023; Vermeulen *et al*., 2023).

In addition, several works have developed formal econometric models to support drought impact assessments (Lopez-Nicolas *et al*., 2017; Eyer & Wichman, 2018; Alemu *et al*., 2021; Furuya *et al*., 2021; Gebre *et al*., 2021; Jha *et al*., 2022; Mallick *et al*., 2022; Beyene *et al*., 2023; Buck *et al*., 2023; Tofu & Wolka, 2023; Zlati *et al*., 2023). Also, some works have even developed optimization models to gain insight into cost-effective drought adaptation measures (Bacaksiz *et al*., 2023; Camilo *et al*., 2023; Erfanian *et al*., 2023; Lee *et al*., 2023; Li *et al*., 2023; Luo & Zhai, 2023; Martínez-Dalmau *et al*., 2023; Nunes *et al*., 2023; Ortuzar *et al*., 2023; Rodríguez-Flores *et al*., 2023; Yang & Bayraksan, 2023; Zhu *et al*., 2023). Finally, drought mitigation policy has been the subject of some excellent works (Hussain *et al*., 2018; Botai *et al*., 2020; Senapati, 2020; Rimsaite *et al*., 2021; Somerville, 2021; Torres *et al*., 2021; Bazzana *et al*., 2022; Deng *et al*., 2022; Simpson *et al*., 2023). Overall, several important works in recent years have noted the complexity and difficulties of assessing the economic impacts of drought (Ding *et al*., 2011; Martin-Ortega *et al*., 2012; Meyer *et al*., 2013; De Silva & Kawasaki, 2018; Mora *et al*., 2018).

1.4. Gaps

The journal *Water Policy* has published a number of recent works on the economic impacts of drought (Hughes & Mallory, 2009; Stillwell & Webber, 2013; Chong, 2014; Missimer *et al*., 2014; Keshavarz, 2016; Sousa *et al*., 2022). Several other peer-reviewed journals have also published celebrated recent works on drought impacts and mitigation measures (Ahloowalia *et al*., 2004; Ding *et al*., 2011; Meyer *et al*., 2013; Jiang *et al*., 2014; De Silva & Kawasaki, 2018; Mora *et al*., 2018). Despite these contributions in the peer-reviewed literature on drought economic assessments, econometric modeling, optimization modeling, and drought mitigation policy analysis, we have observed two notable gaps in the peer-reviewed literature. First, non-linear econometric production function estimates of regional income produced by water and employment are uncommon. The second and more difficult problem occurs when there is no project, program, policy, or regulation for which an assessment is needed. In this circumstance, it becomes unclear how to apply the well-known ‘with versus without’ assessment principle that has been well-established in the literature on cost-benefit analysis, since there is no policy choice for which costs and benefits can be assessed.

1.5. Objectives

This work’s original contribution is to address the two gaps described above. First, it describes the estimation of a non-linear econometric production function predicting total income as a function of water and employment over several sectors and time periods. In addition, we estimate the economic impacts of drought when no policy choice has been considered or made for which a classical cost-benefit analysis would need implementation. Meeting these objectives provides important insights for policymakers and water resource analysts who wish to assess the economic impacts of a historical drought.

2. METHODS OF ANALYSIS

2.1. Data

2.1.1. Study area

In our study area of the state of New Mexico (Figure 1), water takes on special significance hydrologically, institutionally, and culturally. A summary by Gutzler in 2013 (Gutzler, 2013) states:

> '…Water policy in New Mexico is strongly conditioned by the unusually complex hydroclimatological setting of the state. This chapter reviews some of the salient features of the climate of New Mexico – both time-mean and variable aspects – that pose challenges for management of surface water resources in the state. The history of human society in this part of the world, in which the empty remains of once-flourishing settlements like Chaco Canyon are still visible for all to see, illustrates how difficult it has been to achieve long-term sustainability here. In addition to the natural challenges of ensuring adequate water supplies that have always faced New Mexico's residents, climate changes projected to continue in the twenty-first century are expected to both decrease surface water supplies and increase water losses associated with evapotranspiration…' (Gutzler, 2013).

Motivated by New Mexico's special conditions, our study area is the entire state of New Mexico for which we wish to assess economic damages produced by drought for the years 2017–2019.

2.1.2. Water use

Nine non-agricultural sectors were aggregated into a single water use sector. Public supply water use as a predictor of the aggregated non-agricultural use explained about 98% of that total variability for the non-agricultural sectors assessed for the years 2005, 2010, and 2015 (New Mexico Office of the State Engineer, 2009, 2014, 2019). Use of this method enabled a forecast of total non-agricultural water use for each county and year, summed over the sectors for the several water use reports for years 2005, 2010, and 2015. This method was used to subsequently predict water use for the years 2015, 2017, 2018, and 2019 by county.

2.1.3. Income

We initially secured data on value added (income) for 32 New Mexico counties and 21 sectors, later expanded to 546 sectors. We employed the widely used IMPLAN economic database (Weisskoff *et al.*, 2020), for which data were available for all New Mexico counties and years except Los Alamos County (Supplementary Appendix 1). Using that database, we worked with the years 2015, 2017, 2018, and 2019. Our mission was to investigate how predicted water use in those years as well as total county population in the same years influenced total county income summed over our nine sectors (Supplementary Appendix 2). Discovering impacts of factors influencing income changes in income by county is more rigorous than simply comparing total economic activity by county and sector in those years. It is preferred because many of those changes in income were independent of drought in those years, occurring because of growing population and related changes in economic activity that occurred in many of those counties. For example, a county's income changes are influenced by changes in export prices, changes in input costs, and from people entering or leaving the state. Population and total water use take on special significance for this work, as described below.

2.1.4. Population and water use

Along with population, our proxy for employment, water use was found to be an important predictor of total county income for each county and year for 2015, 2017, 2018, and 2019. Data used for population by county

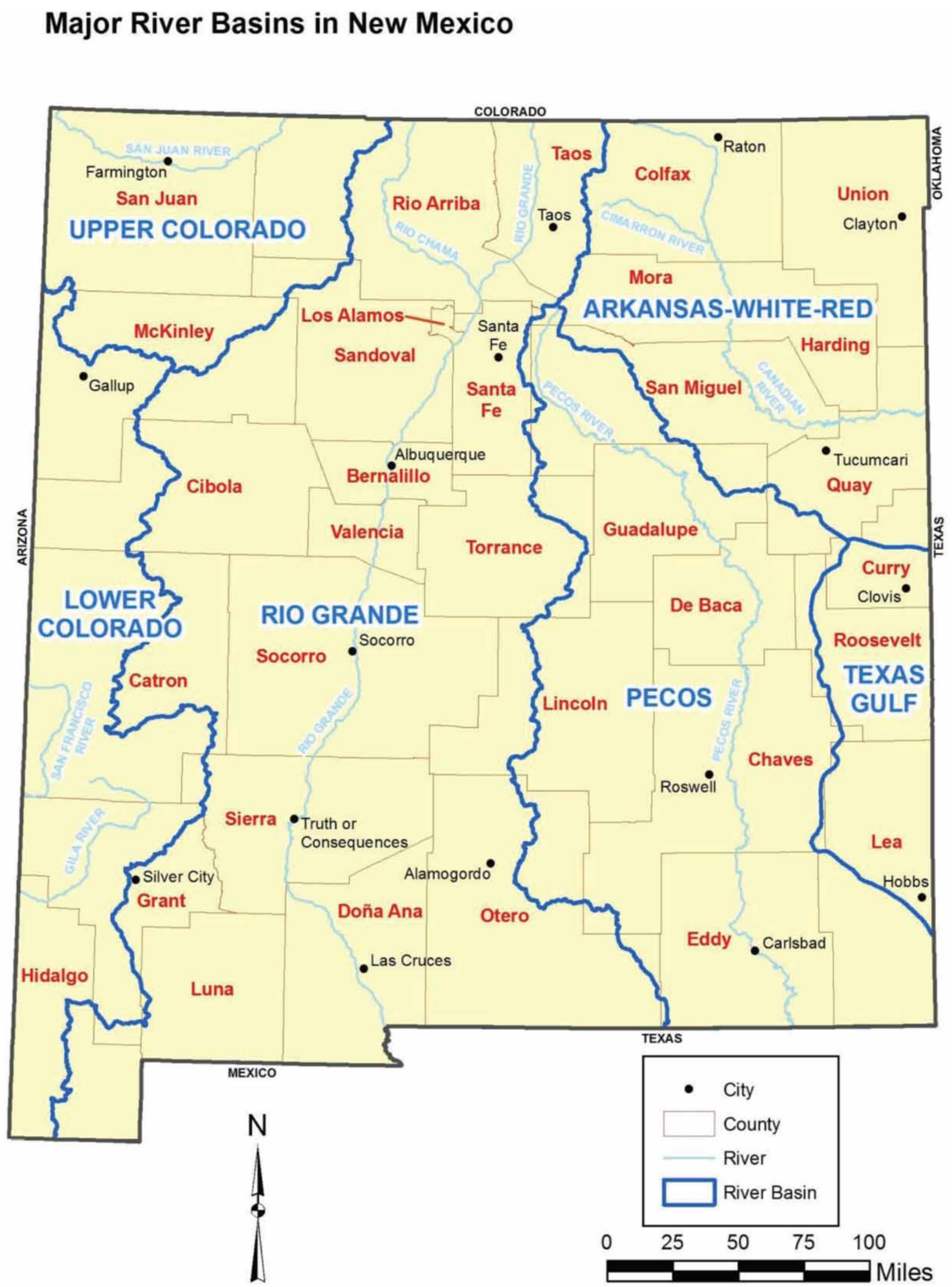


Fig. 1. | Major river basins in New Mexico, 2015 (New Mexico Office of the State Engineer, 2019).

are published by the US Census (US Census Bureau, 2020), for which an example for the year 2019 is at https://www.census.gov/newsroom/press-kits/2019/national-state-estimates.html.

2.2. Analysis

2.2.1. Natural hazards

Numerous scientific papers and other works have been published since the mid-1990s summarizing methods for conceptualizing and measuring the economic costs of drought and other natural hazards (Booker, 1995; Ahloowalia *et al.*, 2004; Booker *et al.*, 2005; Mechler *et al.*, 2010; Ding *et al.*, 2011; Mansur & Olmstead, 2012; Logar & van den Bergh, 2013; Meyer *et al.*, 2013; Jiang *et al.*, 2014; Freire-Gonzalez *et al.*, 2017; Mora *et al.*, 2018). Based on those works, we addressed the two gaps in the literature described above by investigating impacts of reduced water use on income for the various New Mexico counties and years.

2.2.2. Income, water use, and population

A review of that literature concluded that for our New Mexico work, the best method to calculate economic costs of drought of a given duration was to calculate total income and water use by county and year summed over the relevant sectors, then formulate and estimate a non-linear econometric model to assess how observed total income by county and year varied with estimated water use summed over our relevant sectors counties as well as population.

2.2.3. Econometric model

New Mexico is one of those unusual places for which total water use in any given county is likely to be a major contributor to that county's total income, because of the widespread scarcity of water in most parts of this state. Those unusual conditions in New Mexico gave us an opportunity to experiment with a simple and original non-linear econometric model that might do an acceptable job of predicting total income, summed over our nine non-agricultural sectors.

Based on data on income, water use, and population, an econometric model was used to develop an equation that explains each county's total non-agricultural income as a function of the county's population and county water use summed over sectors for which we could compile acceptable data. We implemented this experiment by specifying the following simple non-linear equation, in expected value terms, for which the coefficients (B terms) were estimated using regression methods:

$$\mathrm{VA}\ (c, t) = B_0 * [\mathrm{Pop}(c, t) ** B_1] * [\mathrm{WU}(c, t) ** B_2] \tag{1}$$

for which dummy (0–1) variables were included for selected counties and years when significantly explained by the data. These dummy variables permit adjusting the VA (income) function up or down to adapt to unique factors explaining a county's income other than population and water.

These variables are defined as:

$\mathrm{VA}(c,t)$ = expected value of total income (value added) for 32 counties (c) and 4 years (t).
$\mathrm{Pop}(c,t)$ = population, sourced from US Census data.
$\mathrm{WU}(c,t)$ = estimated water use in acre feet, based on date available from the New Mexico Office of the State Engineer, summed over the non-agricultural sectors.
B_0, B_1, B_2 = parameters (coefficients) to be estimated using the data.
* = multiplication.
** = exponent.

A restricted least squares approach (De Luca *et al.*, 2023; Oloyede, 2023; Sanguri *et al.*, 2023; Yu *et al.*, 2023) was used to estimate (1), for which the sum of the two coefficients B_1 and B_2 were constrained to equal 1.0, based on the principle of constant returns to scale, well-developed in economic production function analysis over many years for application to a range of environmental and natural resource inputs (Sharma & Thomas, 2008; Speelman *et al.*, 2008; Chen *et al.*, 2010; Isgin *et al.*, 2020; Kristáková *et al.*, 2021).

In Equation (1), each county's income, summed over our relevant sectors, is specified to be an explicit function of population and water use (Espey *et al.*, 1997; Renwick & Green, 2000; Arbues *et al.*, 2004; Hatirli *et al.*, 2006; Martinuzzi *et al.*, 2014). That is, our mission was to use Equation (1) to explain the variation in income, and estimated with statistically significant parameter estimates based on acceptably high *t*-statistics (Kumar & Jain, 2011; Konapala & Mishra, 2017; Pechlivanidis *et al.*, 2017; Hattermann *et al.*, 2018). We use population as a proxy for employment.

The Cobb–Douglas functional form used in Equation (1) is a common function to use in economic analysis of input supply changes such as water (Bakhtiari *et al.*, 2015; Saseendran *et al.*, 2015; He *et al.*, 2016; Bolandnazar *et al.*, 2020). The well-established principle of constant returns to scale states that an upscaling or downscaling of estimated water and estimated population by a given proportion scales total county income by the same proportion (Akram *et al.*, 2023; Bernstein *et al.*, 2023; Farajzadeh *et al.*, 2023; Kerstens & Sadeghi, 2024; Lu *et al.*, 2024; Podinovski *et al.*, 2024).

2.3. Comparing two drought assessment methods

2.3.1. A common but erroneous method: before and after drought

From the use of the information provided by (1) to predict total county income as a function of population and water use, we wished to calculate drought damages (income losses) from water shortages brought on by drought for each of the years 2017, 2018, and 2019 by county and year for any set of conditions relative to the base year of 2015.

One straightforward method to assess economic costs of water shortages is to simply calculate the total predicted income before and after the drought conditions (Zhang *et al.*, 2011; True, 2013; Abera *et al.*, 2018; Guo *et al.*, 2019), using Equation (1). Total economic drought damages (DDs) from water shortages using the 'before and after approach' would be calculated as:

$$\mathrm{DD}(c, t_1, t_2) = \mathrm{VA}(c, t_2) - \mathrm{VA}(c, t_1) \tag{1a}$$

Based on Equation (1), where $\mathrm{DD}(c,t_1,t_2)$ is drought damages incurred by the c-th county and found by comparing the year t_1 (base year) to t_2 (drought year). In (1a), the terms

$$\mathrm{VA}(c, t_2) = c\text{−th county's total value added for drought year conditions in year } t_2 \tag{1b}$$

$$\mathrm{VA}(c, t_1) = c\text{−th county's total value added for conditions in the base year } t_1 \tag{1c}$$

for which the two value added terms in (1d) and (1e) come from parallel implementations of (1):

$$\mathrm{VA}(c, t_2) = B_0 * [\mathrm{Pop}(c, t_2) ** B_1] * [\mathrm{WU}(c, t_2) ** B_2] \tag{1d}$$

$$\mathrm{VA}(c, t_1) = B_0 * [\mathrm{Pop}(c, t_1) ** B_1] * [\mathrm{WU}(c, t_1) ** B_2] \tag{1e}$$

This simple but erroneous method compares value added incurred in water shortage conditions relative to base conditions. In (1d) and (1e), population and water use are observed for both years t_1 and t_2. Finding drought damages, DD(c,t_1,t_2) due to water shortages, would be had by simply subtracting the typically lower value added (1d) from that in (1e).

2.3.2. An innovative accurate method: with and without drought

While the above is a straightforward method of valuing drought damages from water supply changes, it presents a problem. The method ignores the fact that WU(c,t) itself is not entirely pre-determined by hydrologic conditions. Observed WU(c,t) in both periods depends on how much water is available (supply) as well as the population's use of water (demand). While the 'with and without' analysis has seen considerable development in the cost-benefit literature over the years, that approach requires a historical 'without policy' to be compared with a counterfactual 'with policy' situation. Since there is no 'with policy' to analyze in this work, the 'with and without' approach required some innovations not well-developed from our search of the peer-reviewed literature.

A second problem comes from the fact that population itself changes across years. This makes it unclear how to assess partial impacts of drought while holding population constant since population is not constant. In that light, a more sophisticated accounting of the effects of water shortage alone must be developed by purging impacts of population on water use. An accurate method must separate out changes in WU from supply from changes in WU due to changes in population (demand). Detailed results from our method for implementing this counterfactual analysis are described in more detail below.

When both population and water use change across two sequential periods, it is not entirely clear what can be done to separate out impacts of drought-stressed water supplies from that of population changes. We found few hints in the literature despite the fact that many economic assessments of drought have been published in recent years (Fernández *et al.*, 2023; Garba *et al.*, 2023; Konovalova *et al.*, 2023; Vermeulen *et al.*, 2023).

We begin a search for an innovative and accurate drought assessment method by establishing the principle that drought stress can be observed directly by watching the pattern of per capita water use across a base (non-drought) and alternative (drought) period. If both population and water use decrease by the same proportion across two periods, then per capita use is unchanged so drought imposes zero economic burden on water users no matter what happens to total water use. If, however, population grows at a faster proportion than water use, per capita use falls, indicating drought stress. So, to assess economic impacts of drought, it becomes clear that watching the pattern of per capita water use will yield more insight than watching either the absolute levels of population or water use.

It is the insight provided by watching per capita water use that motivates a description of our innovative and accurate drought assessment method used in this work, described with four examples below. If per capita water use falls in the later year, some drought damage occurred. If it does not fall, no drought damage has taken place.

2.3.3. Income, water, and population

As stated above, statistical regression methods were used to estimate coefficients of an econometric model that best explained total (non-agricultural) county income as a function of county population and county water use summed over our nine sectors. The model was estimated for the years 2015–2019 as described above. Results of that estimation produced the following equation:

$$\mathrm{VA}(c,\, t) = 43,\, 766 * [\mathrm{Pop}(c,\, t) ** 0.67022] * [\mathrm{WU}(c,\, t) ** 0.32978] \tag{2}$$

where all terms are defined previously.

Model results showed a strong statistical performance, for which Equation (2) explained more than 99% of the variance (adjusted R^2) in observed county income summed over sectors. Both the population and water use parameter estimates showed significance at better than the 99% level.

New Mexico is an unusually dry region compared with most other US states, with a long-term average precipitation of just over 13 inches. For that reason, we were not surprised to find water to have that large coefficient, meaning it is an important resource-based contributor to county incomes. This is seen by the high level of the water coefficient, 0.32978 in the income predictor (2). This high coefficient reflects the fact that water is an unusually high contributor to those incomes. Equation (2) shows that a 10% reduction in both water use and population for any given county produces a 10% reduction in that county's total income, for which about 67% comes from population (employment) and 33% from water. Water plays a big role in arid New Mexico's economic activity.

2.3.4. Drought damages when population and water use change

An important contribution made by this paper is to come to grips with the problem that occurs when population and water use are both changing across any two sequential periods of time as well as there being no policy to apply the well-established 'with and without' policy approach for a cost-benefit assessment. Clearly, 'before and after' is the wrong principle, but while the 'with and without' principle is solid, it is not obvious how to apply it properly.

For many of our counties, both population and water use grew from the base year 2015 even though reduced water use per capita occurred from 2015 to 2017. We illustrate the innovation developed for this work by formulating, illustrating, and assessing a method to calculate drought damages when actual measured total water use in some cases increased at the same time population increased. We illustrate our innovation for four cases described in detail below where (1) growing population occurs with unchanged water use, (2) population and water use grow by the same proportion, (3) population and water use are both unchanged, and (4) population and water use fall by the same proportion. Each is discussed:

2.3.4.1. Case 1: Growing population and unchanged water use. We needed an innovative development of a 'with and without' analysis for assessing economic damages from drought. The challenge presented to us came because there was no baseline policy for comparison to a proposed policy, such as a drought adaptation plan of some kind. We needed to assess the economic cost of drought occurring over a particular period, so we faced a challenge other than the need to conduct a cost-benefit analysis of a well-defined policy or program.

We achieved our mission by developing an innovative model calibration method, shown with use of the data in Table 1. The calibration method is developed by defining conditions and outcomes of those conditions that produce zero drought damages over the period 2015–2017, as described in several steps below.

We calibrated the model by defining conditions producing zero drought damages. We began by calculating counterfactual (cf) per capita water use for 2017, PCU (cf, 2017). That term is the per capita use for 2017 calibrated as the threshold value needed to produce zero total drought damages for 2017 relative to the base year 2015. The zero drought damages logic will be described below. Actual PCU (2015) is total water use in 2015, WU (2015), which is 4,864 acre feet of use divided by population for that year, 25,000. That division produces 0.19456 actual acre feet per capita for 2015. This means if PCU (cf, 2017) = 0.19456 acre feet per capita, no drought damages would have occurred in 2017 relative to the 2015 base. It is important to note that the term PCU (cf, 2017) is not PCU that actually occurred in 2017, but is the PCU for 2017 that needed to have occurred for there to have been no drought damages relative to the 2015 base.

We next calculated counterfactual total water use level for 2017, WU (cf, 2017). The term WU (cf, 2017) is the water use that would have occurred in 2017 if 2015 per capita use had been maintained. Algebraically, WU (cf, 2017) = PCU (cf, 2017) defined above as 0.19456 acre feet per capita times actual 2017 population, POP (2017), 25,250, using Table 1 data. This multiplication shows WU (cf, 2017) = PCU (cf, 2017) * POP (2017) = 0.19456 *

Table 1 | Drought damage calculations illustrated with two methods, based on population, water use, and value added.

Variable	County	2015 data		2017 data		2015 actual (A)	2017 actual (B)	2017 adjusted (2015 per capita use × 2017 population) (C)
Population (people)	Hyp 1	1.00	Times 2015 level	1.01	Times 2015 level	25,000	25,250	25,250
Water use (a–f)		1.00	Times 2015 level	1.00	Times 2015 level	4,864	4,864	4,913
Per capita use (a–f/cap)		Calculated	Pop/water use	Calculated	Pop/water use	0.19456	0.19263	0.19456
Value added ($)		Predicted by	Text equation (2)	Predicted by	Text equation (2)	637,706,652	641,973,673	644,083,718
Drought cost, '17 ref '15		From subtraction		From subtraction			*−4,267,021*	**2,110,045**
Population (people)	Hyp 2	1.00	Times 2015 level	1.01	Times 2015 level	25,000	25,250	25,250
Water use (a–f)		1.00	Times 2015 level	1.01	Times 2015 level	4,864	4,913	4,913
Per capita use (a–f/cap)		Calculated	Pop/water use	Calculated	Pop/water use	0.19456	0.19456	0.19456
Value added ($)		Predicted by	Text equation (2)	Predicted by	Text equation (2)	637,706,652	644,083,718	644,083,718
Drought cost, '17 ref '15		From subtraction		Am			*− 6,377,067*	**0**
Population (people)	Hyp 3	1.00	Times 2015 level	1.00	Times 2015 level	25,000	25,000	25,000
Water use (a–f)		1.00	Times 2015 level	1.00	Times 2015 level	4,864	4,864	4,864
Per capita use (a–f/cap)		Calculated	Pop/water use	Calculated	Pop/water use	0.19456	0.19456	0.19456
Value added ($)		Predicted by	Text equation (2)	Predicted by	Text equation (2)	637,706,652	637,706,652	637,706,652
Drought cost, '17 ref '15		From subtraction		From subtraction			*0*	**0**
Population (people)	Hyp 4	1.00	Times 2015 level	0.99	Times 2015 level	25,000	24,750	24,750
Water use (a–f)		1.00	Times 2015 level	0.99	Times 2015 level	4,864	4,815	4,815
Per capita use (a–f/cap)		Calculated	Pop/water use	Calculated	Pop/water use	0.19456	0.19456	0.19456
Value added ($)		Predicted by	Text equation (2)	Predicted by	Text equation (2)	637,706,652	631,329,585	631,329,585
Drought cost, '17 ref '15		From subtraction		From subtraction			*6,377,067*	**0**

25,250 = 4,913 acre feet. The quantity 4,913 is the water use level for 2017 guaranteeing zero drought damages for 2017 relative to 2015, because 4,913 comes from the per capita water use of 2015 applied to the actual 2017 population of 25,250. That is, had 2017 water use been 4,913 acre feet, there would be zero drought damages relative to the base 2015 year, since per capita use would have stayed unchanged over those 2 years.

We then calculated counterfactual value added (county income) for 2017, VA (cf, 2017). Algebraically, VA (cf, 2017) = WU (cf, 2017) applied to the actual 2017 population level, POP (2017), using the VA predictor in text Equation (2). The value added needed here is based on counterfactual water for 2017, WU (cf, 2017) use and actual population in 2017, POP (2017).

This exercise required using Equation (2) predicting total value added for any county and year. $\mathrm{VA}(c,t) = 43{,}766 * [\mathrm{Pop}(c,t) ** 0.67022] * [\mathrm{WU}(c,t) ** 0.32978]$. Applying this equation to find the county's total value added guaranteeing the zero drought damage was described above. That value added is calculated for our hypothetical county Hyp 1, as $\mathrm{VA(cf, 2017)} = B_0 * [\mathrm{Pop\ (2017)} ** B_1] * [\mathrm{WU(cf, 2017)} ** B_2]$, where $B_0 = 43{,}766$, $B_1 = 0.67022$, and $B_2 = 0.32978$, as described in (2). It is value added if the 2017 population maintained 2015 per capita water use. That total value added guaranteeing zero drought damage is $644,083,718. Actual value added for 2017, VA (2017) comes from applying the same equation to actual population and water use, producing a total value added of $641,973,673.

We then assessed actual drought damages for 2017 (drought year) compared with 2015 (base year): The innovative drought damage calculation developed for this work, DD (2017) is found by simple subtraction. It is DD (2017) = VA(cf, 2017) – VA(2017) = $644,018,718 – $641,973,673 = $2,110,045. This result shows a clear drought damage experienced by the county brought on by the reduction in per capita water use, by which that annual actual per capita use fell from 0.19456 to 0.19263 acre feet per capita.

The innovative method can easily be compared with the naïve drought damage calculation. The erroneous drought calculation method calculates drought damages by implementing a simple before and after comparison. It is found by comparing actual 2017 value added ($641,973,673) to actual 2015 value added ($637,707,652) = −$4,267,021. The negative value, −$4,267,021, mistakenly shows an actual gain in total county income occurring over the drought period, when, in fact, drought, by reducing per capita use, producing a net loss in county income. Both the correct and erroneous drought damage estimates are shown in Table 1 for the row 'drought cost, '17 ref '15' for the county Hyp 1 at column B (erroneous) and column C (correct). Similar calculations are shown for the other three county situations, described below.

2.3.4.2. Case 2: Population and water use rise by equal proportions. When population and water use rise by the same proportion from our base year of 2015, seen for the row county and condition Hyp 2, there is clearly no drought damage incurred, because per capita water use remained constant. The naïve erroneous approach would compare the total county value added across the 2 years under that scenario, showing a considerable increase in value added, since its two main predictors, population and water use have both increased. The erroneous drought assessment method is shown in column B, showing a value added of $644.083 million in 2017 compared with a much smaller $637.706 million produced in the base year 2015, for an erroneous gain in value added shown of $6.377 million. That apparent gain is clearly wrong, since per capita use has shown no change with this scenario. The erroneous method makes a simple comparison of column B's value added with column A's value added.

As was the case with case 1, the correct calculation is found by comparing value added in column B with the adjusted value added in column C, using the detailed steps described above. It finds the total value added that occurs with the new population of 25,250 applied to the unchanged use per capita of 0.19456 acre feet per capita. The 2017 adjusted value added is $644.083 million compared with the unadjusted 2017 value added of the same amount, $644.083 million. The difference is zero, correctly showing no economic damage from the drought.

2.3.4.3. Case 3: Population and water use both unchanged. The third hypothetical drought scenario is shown in Table 1, county and conditions Hyp 3, by which population shows no increase, staying at a constant level of 25,000 for both 2015 and 2017. Water use also shows no change, staying at 4,864 acre feet total for both years, for which per capita use, of course, shows no change, staying at an unchanged level of 0.19456 acre feet per person for both years. Here is a case where both the erroneous and accurate drought assessment methods produce the same answer, showing zero drought damage. It is shown by comparing column C value added with column B value added (correct method). The erroneous (but this time lucky) method compares column B's value added with that of column A. The erroneous method produces the right answer for the wrong reason.

2.3.4.4. Case 4: Population and water use fall by same proportion. For case 4, both population and water use fall by the same proportion from the base year 2015 to the drought year 2017, shown in Table 1 for county and condition Hyp 4. The erroneous method produces an estimated drought cost of $6.377 million, while the correct method shows no drought loss and no gain, reflecting the fact that per capita use is unchanged in 2017 from its 2015 base year measured use level of 0.19456 acre feet per person.

2.3.5. Special significance of per capita use

The simple hypothetical examples of four county conditions, Hyp 1–Hyp 4, have shown results from both an erroneous as well as an accurate drought assessment method. The need for making these calculations occurs because there is no proposed or actual policy, plan, or regulation for which a cost-benefit analysis needs to be conducted.

In contrast, for this work, we needed to assess the economic cost of drought itself, with no proposed policies for adapting to that drought considered. Surprisingly, the lack of a policy to assess complicates the calculation of a 'with versus without' assessment needed. Our mission was to assess damages with versus without a drought, not 'with versus without' a drought mitigation plan.

The need for an accurate method of drought assessment required separating impacts of a pure hydrological character from that of the demographic variable of population when both move from 1 year to the next. The innovative method developed for this work is based on recognizing when per capita water use is unchanged in the drought year as in the base year, no drought losses are incurred. Gains (negative losses) from drought occur when per capita water use increases over the period, while losses occur when per capita use falls. Comparing value added in column B with that of column C shows the correct method to assess drought impacts, while comparing column B to column A shows the erroneous method.

3. RESULTS

Using the innovative assessment method described above, Table 2 shows total drought damages for each of our 3 years and 32 New Mexico counties. Several patterns emerge from the table: It should be no surprise that regardless of the absolute size of a county's population, falling per capita water use from 2015 to 2017 (not shown in Table 2 to save on space) produces positive drought damages, i.e., economic damages exceeding zero, since the typical person uses less water whether that reduced use is caused by a higher water price or simply less water available. Still, the scale of population matters. A larger population to which a given reduction in per capita use applies gives rise to a larger absolute scale of drought economic damages incurred. About half the counties suffered no drought damages at all for at least one of our 3 years, for which negative drought damages were reset to zero.

Table 2 | Direct economic damages by county and year from drought 2015, 2017, 2018, and 2019, New Mexico, all non-agricultural sectors ($US per year).

County	2015	2017	2018	2019	Total
01_Bernalillo	0	0	0	356,197,029	356,197,029
02_Catron	0	1,324,594	1,001,182	813,660	3,139,436
03_Chaves	0	0	0	0	0
04_Cibola	0	6,795,333	6,065,321	16,965,534	29,826,189
05_Colfax	0	2,248,453	0	7,974,254	10,222,708
06_Curry	0	0	205,104,167	0	205,104,167
07_DeBaca	0	0	0	0	0
08_DonaAna	0	0	0	0	0
09_Eddy	0	86,061,092	0	0	86,061,092
10_Grant	0	0	0	0	0
11_Guadalupe	0	86,423,441	86,839,030	87,909,169	261,171,639
12_Harding	0	0	0	0	0
13_Hidalgo	0	9,877,195	5,098,315	13,174,849	28,150,360
14_Lea	0	116,985,535	45,313,515	0	162,299,050
15_Lincoln	0	71,044,752	40,284,462	82,138,807	193,468,018
16_Luna	0	0	0	0	0
17_McKinley	0	4,686,683	0	15,125,965	19,812,648
18_Mora	0	455,487	210,163	170,326	835,976
19_Otero	0	0	44,609,966	10,001,840	54,611,805
20_Quay	0	0	0	0	0
21_RioArriba	0	0	0	0	205,312
22_Roosevelt	0	0	0	0	0
23_SanJuan	0	0	10,596	8,792,036	8,802,632
24_Sandoval	0	0	0	0	0
25_SanMiguel	0	87,245,090	165,192,374	11,393,903	263,831,365
26_SantaFe	0	0	0	58,259,280	58,259,280
27_Sierra	0	8,002,036	4,999,043	4,327,788	17,328,868
28_Socorro	0	31,851,547	29,967,602	38,081,754	99,900,905
29_Taos	0	0	8,583,141	9,474,013	18,057,152
30_Torrance	0	23,093,431	45,279,047	36,559,481	104,931,961
31_Union	0	345,298	187,627	631,522	1,164,449
32_Valencia	0	0	0	0	0
Statewide total	0	536,439,967	688,745,551	757,991,210	1,983,382,041
Total state income		78,022,459,933	72,964,403,657	85,161,357,653	
Pct of income lost		0.69%	0.94%	0.89%	

While the largest damages were suffered by the state's most populated county (Bernalillo), some of the lightly populated counties, such as Guadalupe County, also suffered large losses ($261.172 million summed over our 3 years), for which its population varied between four and five thousand people. As described earlier in this work, large drought damages come from either modest reductions in per capita uses applied to large populations or from large reductions in per capita use applied to modest populations.

About one third of the counties (10 out of 32) experienced no damages whatsoever, meaning that per capita use was the lowest in our base year of 2015, possibly indicating remarkable water supply drought anticipation and management capacity in those counties. For example, a comparatively highly populated Dona Ana County (population just over 200,000 in all 3 years) showed lower per capita water use in the base year (0.230 acre feet per capita) than in any of our 3 drought years (0.255 in 2017, 0.257 in 2018, and 0.248 in 2019). Dona Ana County presents one example of a water utility in New Mexico that is well-organized and hires a large number of professional water managers.

The drought damage calculation approach described here required numerous simplifying assumptions to make headway. Clearly, it is a simplified representation of drought itself as well as its economic impacts. Changes in water use occur for many different reasons depending upon the sector, and these changes come from hydrologic, economic, policy, or behavioral changes. For instance, if a city repairs leaks in its distribution lines, there is a reduction in water deliveries needed to send the same amount of water to households and businesses, with little change in income except for the increased costs of fixing the leaks. The table presents several other important messages.

3.1. Scale effects

Other things equal, the direct economic impacts of drought for any given county increases with that county's population when per capita water use fell from 2015 to 2019, as shown in the table, for which Bernalillo County has the largest economic damages for 2019 ($356.537 million). That impact is considerably higher than for most other counties in the same year. Bernalillo County's losses for other years would have shown similar high results except for the fact that per capita water use went up in those years for Bernalillo County, effectively producing zero drought losses for those 2 years.

3.2. Damage predictors

Direct impacts of drought damages increase with a county's population, other things equal. Direct impacts of drought damages vary by year, showing lowest aggregate impact in 2017 and the highest absolute damages in 2019, reflecting the most pronounced drought conditions in 2019.

3.3. Aggregation

Total direct economic damages, summed over counties, vary from a low of 0.69% of total income (2017) to a high of 0.94% of total income (2018). These are remarkably high proportions, indicating the very considerable economic importance associated with adequate water use. This is an important finding, because of deep uncertainties with important policy debates that face New Mexico's future water supply planning.

4. DISCUSSION

4.1. Goals and means

The goal of this article was to address gaps in the drought economic assessment literature with two innovations, using a case study of the southwestern US state of New Mexico for the drought years 2017–2019. The means were to implement those innovations to assess economic costs of water shortages. We achieved this goal using this approach: For all (non-agricultural) sectors, economic impacts of drought were assessed using mathematical models explaining income as a non-linear function of estimated water use and population. This model was used to assess the economic impact of drought shortages in the years 2017–2019 compared with a base year of 2015 comparing value added with versus without drought. Results are shown with considerable detail by county and year in Table 2 along with interpretations presented above.

4.2. Scope and limits

4.2.1. Drought resilience

One reason for lower-than-expected costs of drought for New Mexico's nine sectors analyzed found here is the remarkable resilience to drought by the community of New Mexico's water users. This resilience comes from New Mexico's unique cultural, institutional, economic, and hydrologic characteristics:

- Even where water is expensive or scarce, its economic cost is a small part of most New Mexico's (non-agricultural) business activities. Increased water shortages in New Mexico are likely to have minimal economic impact on most production costs for most business activities. Many New Mexico businesses other than irrigation or food production use water for little more than drinking, cooking, minor cleaning, and flushing, all of which use little water per dollar of revenue received.
- New Mexicans may be more accustomed to water-stressed conditions than people in other parts of the US, so are better prepared to handle drought conditions with minimum economic cost of adjustment. A number of technologies are available and used in New Mexico for substituting labor, land, or capital for water when water shortages occur, for example cleaning driveways or streets with labor or capital rather than water.
- Other than irrigated agriculture and food processing, economic sectors with high levels of water use per dollar of revenue are limited in scale in New Mexico.
- Important future work would take a serious look at drought impacts on the state's irrigated agriculture, which, according to the Office of the State Engineer, uses more than 75% of the state's water.
- A wide diversity of local, state, and federal government jobs, as well as research and military facilities are widespread in New Mexico, for which incomes and spending show little to no reduction in conditions of increased water scarcity.
- Most well-run water utilities, water suppliers, and other large water users who plan for long-term economic viability in New Mexico, adapt to drought, especially for a short-term drought.

4.2.2. Groundwater level declines

One element affecting income changes from drought is pumping depth. Greater pumping depths experienced in drought raise the energy cost of pumping and reduce income compared with incomes that would have been earned with no increases in pumping depth. The US Geological Survey (USGS) made some data available to us on pumping depths over time for several aquifers in New Mexico for several years. However, the USGS data were not peer reviewed, so we elected not to use it.

We secured peer-reviewed work on increased pumping depth from other drought years (Steward & Allen, 2016). That work showed an increase of just under 2.2 feet per year in certain parts of Eastern New Mexico. Since no peer-reviewed studies were found that covered our contract study years for New Mexico, we used the peer-reviewed data with pumping depth changes for this report, realizing that this piece of information is an over-simplification for all our study years for all aquifers in New Mexico.

4.2.3. IMPLAN data

The IMPLAN data is part of an economic impact assessment software system that has been under development since the 1970s. IMPLAN is a well-developed and tested system. For this analysis, our team used the IMPLAN database to assess direct impacts of drought in New Mexico by investigating how county incomes depend on water use and population. One of the most highly valued characteristics of IMPLAN is the level of detail of its economic datasets. The database includes information for more than 500 detailed sectors, based on the North American Industrial Classification level. We did not use the IMPLAN economic impacts assessment package, but only used its raw data on value added by county, sector, and year.

4.2.4. Limitations of water use data

Data on water use for all nine sectors analyzed for this work for the years 2017–2019 were not available, so estimation was based on the limited data we had on public water supply by county for those years. Estimated water use data are not the same as observed data.

4.2.5. Non-water income determinants

One of the challenges faced in the present work was that several non-water elements were influencing income at the same time as the 2017–2019 drought occurred in New Mexico. Any given county has several non-water income determinants not measured for this analysis. A few include education levels, access to research facilities, strength of the business culture, as well as easier-to-measure data such as prices of energy, industrial output, and mineral export prices.

The result of this paper's findings is that numerous events were occurring in New Mexico at the same time there was a drought in process, for which rising incomes in our (non-agricultural) sectors overrode effects of the drought. For many sectors and counties, our calculations showed a negative impact of drought, reset to 0 as seen in Table 1.

4.3. Improved capacity for economic assessment

4.3.1. Drought adaptation planning

As seen in this paper, drought can have large economic impacts on communities, industry, and the environment. Drought adaptation measures are strategies that can help people better withstand drought conditions and reduce their negative economic effects. Future work needs to look at drought adjustment mechanisms that can be applied where water shortages loom, food security is at risk, and effectiveness of water conservation policies is debated. Future work along these lines will inform debates over the design of drought adaptation mechanisms for New Mexico and elsewhere, for which policymakers need to reduce economic damages from future climate variability and change (Ward, 2014). Some important drought adaptation measures for which future economic analysis can profitably assess include:

- Water conservation: This can be achieved through a variety of methods, such as fixing leaks, installing low-flow appliances, and shifting from lawns to xeriscape for residential water users.
- Water storage: Building, resorting, or improving reservoirs, dams, and aquifer development infrastructure can help capture and store water during wet or flood periods, which can then be used during drought conditions.
- Water reuse: Reusing or recycling water, such as greywater, storm water, and indirect potable reuse, can contribute to reduced demands placed on freshwater resources during drought.
- Early warning systems: Drought early warning systems can help alert communities and decision makers to the onset of drought conditions, allowing for timely planning and response.

- Drought preparedness plans: Developing drought preparedness plans can help communities better prepare for and respond to drought conditions.
- Water market reforms: Implementing water market reforms, such as water trading, water transfers, and water pricing, can help allocate water resources away from low valued uses to higher valued uses more efficiently during drought, as these mechanisms rely on financial incentives to move water to where it is economically most valued.
- Drought insurance: Drought insurance can help protect communities, businesses, and individuals from the financial burdens imposed by drought.

While all these drought adaptation measures could work if managed professionally, it requires serious economic analysis to discover which ones pay in the sense of their economic benefits exceeding costs.

4.3.2. Importance of cost-benefit analysis for drought adaptation plans

Since implementation of the Flood Control Act of 1936 (Merritt, 1990; Black, 2012), cost-benefit analysis in the US has taken on a growing role informing the design, implementation, and assessment of federal water resource projects, programs, and policies. One of the important features of new Circular No A-4 is its language on page 4 that states:

> '…A regulatory analysis should, all else equal, aim for specificity in identifying how the state of the world in the regulation's presence would differ from the state of the world in its absence…' (The White House, 2023).

That is, analysis should be performed 'with versus without' the proposed action in place. While this approach has been well-understood as a foundation of project appraisal for many years, it provides little guidance on how 'with versus without' should be performed when there is no proposed policy, such as for the current work whose mission is to assess the economic cost of the drought as it occurred. So, the principle described in Circular A-4 provides no guidance for meeting this paper's objectives.

Emerging over many years of federal guidance beginning in 1950 (Senate Subcommittee on Benefits & Costs, 1950), with follow ups in 1962 (Senate Select Committee on National Water Resources, 1962) and in many later documents, Circular No. A-4 (The White House, 2023), was issued in November 2023. That latest document provides guidelines for federal agencies on the development of regulatory analysis for water as well as for other federal programs. By adhering to the principles and guidelines set forth in Circular No. A-4, federal agencies can enhance the quality and consistency of regulatory analyses, leading to more effective and accountable regulatory policies. Its main goals and uses include:

4.3.2.1. Standardization of regulatory analysis. The Circular establishes a consistent framework for conducting cost-benefit analyses of proposed and final regulations. This helps ensure that the analyses are comprehensive, transparent, and comparable across different agencies and regulations. This common framework can give rise to more consistent comparisons of alternative uses of federal taxpayer dollars.

4.3.2.2. Improving decision-making. By providing a clear methodology for evaluating the economic impacts of regulations, the Circular aims to improve the quality of regulatory decisions. It enables federal agencies to better assess the potential benefits and costs of regulations. This can give rise to more informed and effective policymaking. This can ultimately lead to improved decision-making.

4.3.2.3. Enhancing transparency and accountability. The Circular requires agencies to document their analytical processes and the assumptions used, promoting transparency. This accountability ensures that stakeholders, including the public, can understand and scrutinize the rationale behind regulatory decisions.

4.3.2.4. Supporting legislative and judicial review. The standardized framework aids in the review of regulations by Congress and the judiciary. The Circular is designed to ensure that various regulatory analyses meet certain quality standards, facilitating more effective oversight and evaluation.

4.3.2.5. Agency rulemaking. Federal agencies are encouraged to use the Circular's guidelines to conduct regulatory impact analyses when developing new regulations or amending existing ones. When conducted, use of the circular provides a roadmap for identifying and quantifying the anticipated benefits and costs of regulatory actions.

4.3.2.6. Public and stakeholder engagement. Stakeholders, including businesses, non-profits, and the public, can use the analyses guided by the Circular to understand the potential impacts of proposed regulations. This information can be used to provide informed feedback during public comment periods, likely improving stakeholder understanding of program design and assessment.

4.3.2.7. Policy evaluation and research. Scientists as well as policymakers can use the data and methodologies outlined in the Circular to study the effects of regulations. It serves as a reference for scientific and policy research on regulatory impacts.

4.3.2.8. Legislative oversight. Members of Congress and their staff can use the regulatory analyses prepared under the Circular to review and assess the implications of proposed regulations. So, the Circular helps in legislative decision-making and oversight functions.

4.3.3. Drought damage assessment

The present paper has the limited mission of assessing economic consequences of an existing drought, and makes no attempt to assess costs and benefits of various drought adaptation policies, despite the importance of that activity for future years. So, despite the impressive gains since the early 1950s in US federal cost-benefit planning documents described above beginning in 1950 (Senate Subcommittee on Benefits & Costs, 1950), one important innovation developed for this work is to assess damages of an existing drought, which required developing new methods described above.

4.3.4. Addressing deep uncertainty in future water supplies

Climate and related water stress in the southwestern US continue to produce an important planning and policy challenge for water managers and stakeholders. Innovative developments beyond the two modest ones developed for this work are needed to support various kinds of robust water decision-making. This would be characterized as a quantitative decision-informing approach for supporting decisions under conditions of deep-water supply uncertainty (Lempert & Groves, 2010; Herman *et al.*, 2014; Maier *et al.*, 2016).

Future altered precipitation, temperature, humidity, and demographic patterns will change the water supply and alter the complex water distribution systems for the foreseeable future. Nevertheless, the extent, timing, and outcomes of these changes are deeply uncertain, all of which challenge the formulation of choices on investments in water infrastructure and related system improvements. This especially holds true for those choices in backstop technologies such as imported desalinated seawater (Fritzmann *et al.*, 2007; Khawaji *et al.*, 2008; Greenlee *et al.*, 2009; Elimelech & Phillip, 2011; Lee *et al.*, 2011; Alkhudhiri *et al.*, 2012) or substitute water supplies when the primary sources become less reliable.

We also did not address what part of water shortages were addressed by the use of water from storage to make up any water deficits in the 3 years of drought we analyzed. In other words, some of the economic damages from drought may simply be attributable to changes in water storage patterns for those cases where there is reservoir or groundwater storage available for use. While we do not know what part of the drought was addressed through changes in reservoir release patterns, we did observe changes in per capita water use. If per capita water use fell from 2015 to a later period, we can say that the water user suffered consequences of water shortages.

Drought and climate adaptive strategies are a well-principled solution, but principles often present little support for application to practice. One work from 2010 found that up-scaled efforts in expanding the size of water suppliers' or users' groundwater banking programs and implementing various recycling programs could help. Such actions should occur while keeping track of a region's water supply and demand balance, opening the viability for new investments in measures such as stormwater capture as well as water importation. This approach could present a promising robust adaptive strategy for reducing the expense of high cost outcomes (Lempert & Groves, 2010).

In this study, we did not ask 'Was the short-term drought economically damaging?' Rather, we had reason to believe from the start this was the case, so we asked, 'How economically damaging was the short-term drought to the non-agricultural sectors'. To determine this, we ignored all economic gains during the drought years, and we attributed all the water-related economic losses to the drought. We concluded that a 3-year drought for those sectors for the years 2017–2019 was economically damaging to New Mexico to the extent of $1.983 billion, about 1% of total state income for that period.

5. CONCLUSIONS

Climate stressed drought poses a number of economic burdens in several regions internationally, impacting affordable water supply, an important input in many economic activities. Unlike immediate economic disruptions caused by most natural disasters, drought exerts a gradual influence on economic activities. This work's first contribution emerged from a non-linear econometric model of drought applied to predict total county income for all non-agricultural sectors, counties, and years for which population growth in some regions showed increasing water use despite the presence of drought.

Using the southwestern US state of New Mexico as a case study for the drought years of 2017–2019, this work developed a second innovation to assess drought damages despite some increased water use levels observed over those years compared with the base year of 2015. Overall effects of drought in the dry state of New Mexico were more modest than anticipated partly because water users in this state showed remarkable resilience in handling water shortages combined with some unique structural features of the state's income generation processes. The economic price paid for water is a small part of most New Mexico (non-agricultural) business activities. Outside of irrigated farming, most New Mexico businesses use water for little more than drinking, cooking, minor cleaning, and flushing, all of which use little water per dollar of sales revenue earned. Future work is needed to investigate drought adjustment mechanisms, such as finding substitute water sources including aquifer development, recycling and reuse, water conservation, and water importation.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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