Is Drought "in the Air"? Effect of Droughts on Water-Related Patenting Activity *

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Abstract

Concerns of a "deficit" of water-related technological innovation have raised questions over incentives to create new technologies in the water sector. In the context of the United States, I exploit temporal and spatial variation in the incidence of drought and the implementation of water technology clusters to analyze changes in water-related patenting activity. I find that innovative activity does not change following droughts, which suggests few incentives to innovate exist. I also find that current public policy efforts to boost water-related innovation show promise. These findings suggest that additional policy interventions may be warranted.

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1 Introduction

Technological innovation has played a pivotal role in addressing resource scarcities by relaxing binding resource constraints for resources such as food, copper, iron, nickel, silver, tin, coal, and natural gas through the development of new processes that enable the use of substitutes, improve efficiency, or enable access to untapped resources (e.g. Krautkraemer, 2005). In this context, longstanding concerns of a "deficit of innovation" in the water sector have led scientists and policymakers to question whether technology can deliver "solutions commensurate to the impending stresses on urban water systems" (Kiparsky et al., 2013).[1] Given the substantial welfare consequences associated with water shortages,[2] these concerns prompted the U.S. Environmental Protection Agency (EPA) to spearhead the *Water Technology Cluster Initiative* in 2011 to identify and support local efforts with funding and other types of assistance.[3]

In this paper, I analyze the extent to which water scarcity prompts innovative activity by treating droughts as observable and exogenous events that generate water scarcity and patent data as an observable measure that proxies for innovative activity and R&D expenditure. In addition, I assess the impact of the *Water Technology Innovation Clusters Initiative* as a public policy solution aimed at increasing water-related technological innovation. I construct a panel data set that allows me to describe changes in regional water-related patenting activity using variation in the timing and geographic location in both the incidence of droughts and establishment of water technology clusters. Overall, I find evidence that patenting activity does not change following the incidence of droughts, suggesting that water-scarcity alone does not induce more innovation. This finding supports the notion that there is a lack of innovation in the water sector.[4] I also find that the support provided by the EPA initiative significantly increased water-related patenting activity. Together, these findings suggest that additional policy interventions may be warranted to support innovation in the water sector.

Innovating our way out of water scarcity requires inventing (and deploying) appropriate

[1]Stressors include increased demand (Averyt et al., 2013), uncertain precipitation patterns (Milly et al., 2008), aging infrastructure (Kalogo, Monteith and Eng, 2008), and contamination of water supplies (Addams et al., 2009).

[2]Water scarcity negatively impacts energy production (Gleick, 1994; Spang et al., 2014), food security (Schmidhuber and Tubiello, 2007), and public health (Haines et al., 2006).

[3]Similar initiatives have since been launched in other parts of the world (e.g. Water Test Network in Europe).

[4]The "water sector" is used broadly to describe actors who participate and are dependent on water for day-to-day operations such as utilities, end-users, firms, and others.

technologies quickly enough to address continuously emerging needs.[5] Specifically, arguments that "necessity is the mother of invention" hinge on our ability to recognize scarcity quickly enough to act. Notably, the economic argument rests on the assumption that scarcity drives prices upwards. These increased prices then signal to innovators that they can make a profit by inventing new processes that enable the use of substitutes, improve efficiency, or enable access to untapped resources (e.g. Shumpeter, 1934). Prices in the water sector, however, are not set through the market but instead through highly political processes. As a result, water resources are often under-priced (e.g. Renzetti, 1999; Elnaboulsi, 1999; Timmins, 2002). The inability to price water using market-based principles is often cited as a reason for the lack of water-related innovative activity. In the absence of market prices, the question is whether other institutional mechanisms encourage innovation.

Some scholars have posited that the threat of scarcity itself may be sufficient to spark human ingenuity (e.g. Boserup, 1981; Simon and Bartlett, 1985). In support of this argument, previous droughts over the past few decades garnered significant media attention and triggered significant policy changes (Wiener, Pulwarty and Ware, 2016). For example, several droughts (1976-77, 1988, 1998, 2000-2004, 2011-12) have led to requirements to create water shortage response plans, long-range water plans, land-use integration policies, and other frameworks to better manage water supplies. Droughts have also spurred interest in water markets[6] and crop insurance.[7] With respect to technological innovation, previous studies have documented high financing gaps (Krozer et al., 2010) and low rates of water-related patenting activity (Ajami, Thompson and Victor, 2014). Little is known, however, on the dynamics of innovation in the water sector.[8]

I contribute to body of work on environmental innovation by shedding light on the inventive phase (i.e. the timing of inventions) of water-related technologies. This paper also connects the environmental innovation literature to the growing literature on the economic effects of natural

[5] Adoption of water-related technologies is a significant barrier to innovation. Adoption of technologies is beyond the scope of this particular study.

[6] The first major economic investigation of water marketing and the property right to water occurred in the context of policy debate over a state and federal involvement in a California water project in the middle of a drought (Hirshleifer, De Haven and Milliman, 1969).

[7] In 2014, for example, the USDA announced additional targeted conservation assistance for areas affected by the most extreme and exceptional drought (e.g. California and Texas). https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/newsroom/releases/?cid=STELPRDB1245732 The USDA manages several insurance programs related to drought. https://www.usda.gov/topics/disaster/drought/usda-drought-programs-and-assistance

[8] The absence of academic studies on water innovation led to the publication of a special issue in the *Journal of Cleaner Production* (Volume 171, Supplement, 10 January 2018) to serve as a foundation for future studies on water innovation (Wehn and Montalvo, 2018).

disasters (Becerra et al., 2010; Kellenberg and Mobarak, 2011; Miao and Popp, 2014), further contributing to the literature on endogenous technological change by assessing the impact of droughts as a stimulus for innovation (Miao and Popp, 2014).

My approach contrasts with previous work on environmental innovation by examining innovative activity through the lens of regions instead of at the firm level (e.g. Hemmelskamp, 1999; Horbach, 2008; Di Stefano, Gambardella and Verona, 2012).[9] In doing so, I bridge the literature on environmental innovation to the body of work on Regional Innovation Systems (RIS), two literatures that have largely operated independent of each other. I ground my study in the RIS literature because firms do not innovate in isolation but through interactions with other and industry-related actors in their regional ecosystem (e.g. universities and public administrations). These interactions produce regionally specific knowledge that then generates more innovation (Cooke, 1992, 1998; Feldman and Florida, 1994; Feldman and Audretsch, 1999; Feldman, 2001; Camagni, 1995; Asheim, 1996; Crevoisier, 2004).[10] Moreover, these interactions create dense regional "learning networks" of mutually reinforcing industries that allow innovators to quickly capitalize on new ideas and innovative solutions to pressing problems in a process that Alfred Marshall once described as being "in the air." More importantly, the RIS literature explains the basis for the *Water Technology Innovation Cluster Initiative* as an explicit attempt to leverage learning networks to increase and accelerate the rate of water-related innovation.

2 Conceptual Framework

In this paper, I investigate whether droughts generate interest in creating technologies that address water scarcity. Though prices for water resources are not set through market mechanisms, water scarcity may still promote innovation because individuals, firms, and other organizations that heavily reliant on water resources for daily activities may seek to reduce the risk and uncertainty of drought-related disruptions to water supplies.

Moreover, drought-related water scarcity may generate increased competition over water resources that may in turn generate interest in water-related technologies. Resource-based theory of organizational behavior, for instance, holds that an organization faced with scarcity will engage

[9] A few studies have examined innovative activity at national levels (Miao and Popp, 2014).

[10] See Stuck, Broekel and Revilla Diez (2016) for a review of the RIS literature.

in increased competitive behavior if it can secure access to scarce resources that can confer it with a competitive advantage (Selznick, 1957; Andrews et al., 1971; Barney, 1986; Chandler, 1990).[11] Similarly, firms may seek a competitive advantage by developing technologies that increase local water supplies (e.g. process that recycle water resources) or by developing new processes or technologies that reduce the intensity with which water resources are used.[12] Innovation is therefore an important means of creating and maintaining a sustainable competitive advantage. Transaction cost economics (TCE) holds environmental uncertainty will entice firms for vertical integration (e.g. Helfat and Teece, 1987; Williamson, 1988). This theory holds that the process of vertically integration itself may help the acquiring firm reconfigure resources or integrate resources, increasing innovative activity (Iansiti, 1995). Alternatively, resource dependence theory (RDT) contends that firms will attempt to reduce environmental uncertainty by renegotiating interorganizational relationships to minimize dependency (Pfeffer and Nowak, 1976; Pfeffer and Salancik, 1978). For instance, support industries often re-purpose their technological know-how to create technologies that can be applied to other sectors of the economy (Kuramoto and Sagasti, 2006; Lorentzen, 2015).

Assuming that disruptions to water supply caused by droughts is sufficient to generate interest in creating water technologies, the question that naturally arises is where one would expect innovation to occur. One the one hand, innovative activity may not necessarily be confined to a particular geographic location. Can create a technology and market it anywhere where there is demand. Can learn about droughts through media. In the United States, for example, several droughts have received nationwide attention (Wiener, Pulwarty and Ware, 2016). Depending on where a particular firm decides to locate its R&D facility, they could be creating solutions to address problems experienced by another branch experiencing drought.

On the other hand, one would expect innovative activity to be particularly strong in geographic locations that experience drought. Droughts represent exogenously determined instances of local scarcity (i.e. unusual departures in average precipitation levels for a particular climate).[13] Power-plants, oil and gas companies, farmers, and others that are heavily dependent on water for

[11] Organizations, for instance, might adopt a "race to the bottom for extraction-profit" strategy by developing technologies to access water resources at lower depths (Maldonado and del Pilar Moreno-Sanchez, 2016).

[12] Firms may also choose to mitigate against local scarcity by importing water. Transferring water long distances, however, can be expensive and not feasible in many situations.

[13] Definitions include a lack of precipitation (meteorological drought), a lack of soil moisture (agricultural drought), or by reduced streamflow or groundwater levels (hydrologic drought) https://ca.water.usgs.gov/california-drought/what-is-drought.html

operations may invest in developing new technologies to address their particular operational concerns. Furthermore, one would expect competition over water resources to be a a largely localized phenomenon since transporting water over long distances may cost-prohibitive or illegal in some situations.

The RIS literature contends that innovation is largely a local process that arises due to both competitive and cooperative interactions between firms and other innovative agents in local economic environments. This literature describes innovation as these interactions that lead to innovation in terms of "learning networks," an interactive process determined by the interdependent choices that innovative agents, users, and other market actors make. For instance, firms often compete with each other over resources and often draw on the same labor pool but also cooperate with other each other on projects and obtain advice from neighboring firms. These "learning networks" are thought to generate and diffuses knowledge locally. Firms and organizations that are part of these networks are often interdependent and mutually reliant on each other for resources, often acting as external supply chain partners. Industries also tend to cluster spatially around universities and other public research institutions (Feldman, 1994).[14]

The RIS literature attributes the development of "learning networks" primarily to spatial proximity (e.g. Asheim and Gertler, 2005; Cooke et al., 2008; Stuck, Broekel and Revilla Diez, 2016). The importance of spatial proximity can in part be explained by the role of regional institutions. Firms and industry-related actors in close spatial proximity share a common institutional framework. In the United States, for instance, legal doctrines for water management have evolved differently in western states relative to eastern states. Moreover, state governments have significant autonomy over environmental regulation.[15] For instance, water-related technologies must get approved by each state in which it is marketed and sold. In some states, regulation may be highly localized, enacted at a municipal level rather than a state level. Institutions–both formal

[14]Firms rely significantly on academic research (Arora, Belenzon and Patacconi, 2018) and may also have a direct influence on the topics that academics work on (Furman and MacGarvie, 2007; Evans, 2010; Sohn, 2014). Universities are a key local industry-related institution as they produce skilled labor and act as engines that help create, diffuse, and deploy new knowledge in economically useful ways (Feldman et al., 2002). A key mechanism through which universities diffuse and deploy knowledge to the private sector is through licensing patents to spin-off businesses or industrial partners (university-to-industry transfers).

[15]On the one hand, the Porter-Linder hypothesis states that environmental regulation can drive innovative activity (Porter and Van der Linde, 1995). Recent regulations, for instance, motivated by water scarcity is pushing the power generation industry away from once-through cooling systems towards closed systems (White, Shelton and Dennis, 2014). On the other hand, the pollution haven hypothesis states that firms may avoid regions with strict regulations as these regulations may represent an added cost to doing business (Brunnermeier and Levinson, 2004).

and informal–are important for shaping incentives for technical innovation and provide the basis for the type of social interactions between organizations. The sharing of a common institutional framework can be also be related to sharing common social and cultural understanding necessary to build trust (Lundvall, 1992). The spatial proximity to universities and other public research institutions have been associated with positive effects on R&D expenditure (Fritsch and Slavtchev, 2011).

The importance of spatial proximity for innovation can also be explained by the reductions in transaction costs associated with exchanging and communicating knowledge and information locally. This gives rise to locally specific tacit knowledge that is facilitated through face-to-face contact with individuals or organizations in close spatial proximity. There is substantial evidence that the importance of local relationships are important for innovation even in the context of modern information and communication technologies (e.g. internet) (e.g. Kaufmann, Lehner and Tödtling, 2003). Though internet-based communication technologies lower transaction costs of cooperating with potential innovation partners around the world, they are not perfect substitute for face-to-face interaction. Notably, innovation requires interactions between innovators with different sets of specialized knowledge (Grant, 1996) and the development of a shared language and overlapping knowledge structures that cannot be easily accomplished using internet-based communication technologies (Kaufmann, Lehner and Tödtling, 2003). Moreover, physical proximity can facilitate "serendipitous encounters" that in turn lead to creative opportunities (Campa, 2008; Brinks et al., 2018).

The emphasis on local knowledge is especially relevant for the water sector as water availability is largely determined by local physical and social processes. Differences in institutions, culture, and conceptualizations of what solutions may be socially acceptable play an important role in how water is managed (Cosgrove and Loucks, 2015). Solutions are therefore contingent on local factors and would depend on local knowledge for appropriate design of technologies and products to address local challenges (Andersen, Marìn and Simensen, 2018). To motivate this anecdotally, many Israeli innovators–leaders in water-related technologies–have moved to California to work on solutions to address the issue of water scarcity locally instead.[16] Firms may locate in proximity to suppliers and customers to better market their technologies to downstream customers (e.g. Fujita, Krugman

[16] http://jewishjournal.com/cover_story/240749/can-california-embrace-israeli-water-technology/

and Venables, 1999) or to facilitate testing and prototype work (Howell and Higgins, 1990).

Instead of studying innovation at an individual firm-level, I draw on the RIS literature and study innovative activity through the lens of regions. I model each region's capacity for innovation, i, at time t, as:

$$C_{it} = f(I_i, F_{it}, W_{it}) \tag{1}$$

where I represents the presence of key institutional actors (e.g. universities), F represents overall economic activity in the regional economy, and W represents the presence of water resources. In this paper, I use Metropolitan Statistical Areas (MSA) as the geographically relevant spatial unit to capture regions.[17]

I draw on the natural hazards literature to model the effect of drought. Previous studies have found that experience with natural disasters shape the perceived risk associated with the disaster. In order for a drought to elicit a response, however, organizations must first notice and recognize the incidence of a drought as a significant event that affects their respective objectives (Cowan, 1986). This information is processed at the organization level and converted to response (Gresov and Drazin, 1997). For instance, the severity level of a natural disaster can play an important role in shaping responses (Perry and Lindell, 2008). This suggests that more severe droughts may have a greater impact on innovation than less severe droughts.

The perceived risk of drought can also be affected by previous experience with the particular hazard. On the one hand, previous experience with natural disasters may increase risk perceptions and levels of preparedness, though these increases may often be short-lived in nature (Perry and Lindell, 1986). On the other hand, previous experience may have a desensitizing effect.

I model the perceived risk of drought, R_{it}, is as a function of attributes of contemporaneous drought and experience with prior droughts, given by (2):

$$\begin{aligned} R_{it} &= f(d(l,s)_{it}, h_{it}) \qquad (2) \\ h_{it} &= \sum_{x=0}^{t-1} d_{i,x} \end{aligned}$$

where d_{it} represents drought episodes experienced in MSA, i, in year, t, with each drought episode modeled as a function of its duration, l, and severity level, s. Experience with prior droughts is

[17]MSAs represent localized and economically coherent areas based on commuting and employment information therefore would be large enough to capture "learning networks."

given by h_{it}.

Using this, I express regional-level innovative activity, P_{it}, as:

$$P_{it} = f(C_{it}, \sum_{t=0}^{t-1} R_{it}, d_{-it}) \tag{3}$$

where d_{-it} represents drought conditions in other regions. This model can then be simplified as the following reduced-form model:

$$P_{it} = f(I_i, F_{it}, W_{it}, d_{it}, h_{it}, d_{-it}) \tag{4}$$

The lag between d_{it} and innovation, P_{it} is of particular interest because pressing concerns over relatively low patenting activity would be allayed if patenting activity increases following instances of scarcity. Specifically, this finding would lend credence to the argument that the threat of scarcity is sufficient to spark "human ingenuity," suggesting that innovators are attuned to the needs of the water sector and the presence of institutions and economic infrastructure necessary to support innovative activity.

Patents are generally filed at the end of the applied research phase. If water scarcity does lead to an increase in patenting activity, one would expect to see an increase approximately 6-8 years following a drought as that is the average duration of the applied research phase for water technologies (O'Callaghan et al., 2018).[18]

3 Data

3.1 Hydrological Drought

I measure droughts using the Palmer Drought Severity Index (PSDI), a measurement of dryness based on a physical water-balance model, to capture water stress and relative dryness.[19] The index ranges from -10 (extreme dryness) to 10 (extreme wetness). A major strength of this index is its effectiveness in quantifying long-term drought.[20] This accounts for possibility that it may take several rain cycles to refill reservoirs and aquifers or restore soil moisture conditions. I follow the

[18]Patents are generally filed at the end of the Applied Research Stage when the scientific basis for the technology can be proven (proof of concept).

[19]The model uses primarily relies on precipitation and temperature as inputs.

[20]Other measures include PHDI, SDI.

United States Drought Monitor in their classification of drought, shown in Table 3.1.[21]

Table 3.1: Drought Classification using Palmer Drought Severity Index

Classification	**Range**	**Definition**
Abnormally dry	-1.0 to -1.9	Lingering water deficits
Moderate drought	-2.0 to -2.9	Streams, reservoirs, or wells low; some water shortages developing or imminent; voluntary water-use restrictions typically requested
Severe drought	-3.0 to -3.9	Water shortages common; water restrictions generally imposed
Extreme drought	-4.0 to -4.9	Widespread water shortages or restrictions
Exceptional drought	-5.0 or less	Shortages of water creating water emergencies

Notes: Values between -0.9 and 0.9 indicate normal conditions. Values greater than 1 indicate wet conditions.

A historical time series of the PDSI is collected from the National Oceanic and Atmospheric Administration (NOAA) from 1930-2018.[22] I define drought episodes as two or more years of uninterrupted drought, where a year of drought is defined as a calendar years with at least 6 months with PDSI $\leq$ -2.0 (moderate, severe, extreme, or exceptional drought). Table 3.2 summarizes drought characteristics for all MSAs by Census Region. For each drought episode, I identify the most severe drought year.

3.2 Patent Data

Following standard practice in prior work on innovation, I use patent data to proxy for innovative activity. Patents are the most commonly used proxy used in the literature on innovation as they represent innovations that are: (i) novel; (ii) nonobvious; and (iii) useful (Brunnermeier and Cohen, 2003; Jaffe and Palmer, 1997; Horbach, 2008; Johnstone, Haščič and Popp, 2010; Horbach, Rammer and Rennings, 2012). Patenting activity has been shown to be a good proxy for general innovative activity since they are strongly correlated with R&D spending (e.g. Griliches, 1998). Though patents do not cover innovation in financial or managerial practices, innovation in these areas may

[21]The United States Drought Monitor is a collaboration between National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Agriculture (USDA). Drought classification can be accessed at https://droughtmonitor.unl.edu/About/AbouttheData/DroughtClassification.aspx.

[22]These data are available at the USGS climate division level. For MSAs that intersect with multiple climate divisions, PDSI values are weighted averages, using the percentage of the MSA that intersects with each climate division as weights.

Table 3.2: Drought Characteristics

	Census Region of the United States			
	MIDWEST	***NORTHEAST***	***SOUTH***	***WEST***
	Drought Episodes			
Duration (years)	1.60	1.89	1.65	1.73
	(0.90)	(1.24)	(1.01)	(1.15)
Years Between Episodes	11.18	13.83	8.14	5.21
	(7.22)	(11.02)	(7.61)	(5.39)
Total Count (since 1950)	4.83	3.71	7.28	10.71
	(1.63)	(1.44)	(2.08)	(3.18)
	Years Spent in Drought Since 1950			
Any	7.72	7.07	12.04	18.60
	(3.11)	(1.86)	(4.29)	(7.14)
Mild	4.35	4.68	7.17	10.21
	(2.15)	(1.47)	(2.62)	(4.01)
Severe	3.38	2.39	4.88	8.38
	(1.82)	(1.31)	(2.73)	(4.45)
	MSAs Experiencing Drought (%)			
1950s	0.86	0.54	0.94	0.79
1960s	0.83	1.00	0.60	0.79
1970s	0.57	0	0.28	0.90
1980s	0.67	0.14	0.81	0.92
1990s	0.20	0.71	0.60	0.83
2000s	0.59	0.54	0.92	0.98
2010s	0.54	0.32	0.76	1.00
Number of MSAs	69	28	121	52

Note: 27 MSAs intersect more than one Census region. These MSAs are assigned to the region with the largest overlap. Where appropriate, Combined Statistical Areas (CSAs) are used instead of MSAs.

positively impact technological innovation (Benner and Tushman, 2002). More importantly, there are very few examples of inventions that have had significant economic and social welfare impacts that have not been patented (Pakes and Griliches, 1980; Griliches, 1990; Gallini, 2002).

Patent data used in this study consists all utility patents filed in the U.S. between 1976 and 2018, compiled from bulk data files made available by USPTO's Bulk Data Storage System.[23] Patents are published with an average publication lag of 18 months after the actual filing date. This would primarily affect the ability to observe many of the patents filed during 2018 and would

[23] I restrict the data to utility patents to as they protect the way a manufactured article is used and works (35 U.S.C. 101) as opposed to design patents that protect the way the article looks (35 U.S.C. 171). I exclude patents that are marked as being reissued or reexamined. Information on all patent applications published as of September 26th 2019 are obtained from XML and PDF files https://bulkdata.uspto.gov/.

also affect 2017, though to a more limited extent.

Following Hascic and Migotto (2015), water-related patents are identified using sets of International Patent Classification (IPC) and Cooperative Patent Classification (CPC) codes that are closely associated with specific types of inventions. The main advantage of using these codes is that they are heavily reliant on the detailed knowledge of patent examiners (Haščič and Migotto, 2015). Technologies produced in the water sector are produced for a variety of different end-users, including residential, industrial, and agricultural users. Technologies range from low-flow devices, aimed at reducing water consumption, and smart meters, devices to help monitor water usage to water purification and treatment technologies developed for industrial users and utilities to help meet stricter environmental standards and reduce costs of compliance. Water reuse and water recycling technologies, for example, help relieve pressure on traditional sources of water (Bichai, Grindle and Murthy, 2018). Water-related are therefore further categorized as technologies that promote conservation, technologies that augment water supply, and technologies that aim to improve water quality (also referred to as water pollution abatement or treatment technologies).[24] All IPC and CPC codes used to identify water-related patents are presented in Appendix 3.[25] Between 1975 and 2018, a total of 4,336,280 patents were filed by inventors in the the United States.[26] Of these, 4,215,624 patents were filed by at least one inventor living in an MSA. Of the patents with at least one inventor geographically located within an MSA, 121,197 patents are identified as water-related.[27]

I measure of innovative activity using the count of patents filed in each year by MSA. Where appropriate, Combined Statistical Areas (CSAs) are used instead, resulting in a total of 270 geographic regions. I use the location information associated with the patent inventor(s) listed on the patent application to assign each patent to a MSAs. This location reflects the inventors' location at the time the patent was filed. If the patent had two or more inventors located in the same MSA, the patent count for the MSA is only incremented by one to avoid counting the same

[24] Droughts affect water quality by increasing the concentration of point source pollution—sewer outfalls, industrial discharges, and thermoelectric power plant return flows—and non-point source pollution—stormwater runoff. This makes it harder to filter and decontaminate drinking water. Furthermore, reduced water flows can lead to saltwater intrusion, further burdening most water treatment plants, many of which are not equipped to remove salts (Mosley, 2015).

[25] The categorization a patent is mutually exclusive as the same patent can have multiple IPC or CPC codes assoicated with different areas of innovation.

[26] Entire database consists of 8,427,024 patents.

[27] 160,298 patents in the entire database were identified as water-related.

invention more than once for a particular region. If the patent had two or more inventors located in the different MSAs, the patent count for each MSA associated with the patent is incremented by one to reflect that each location was involved in the creation of the invention. The average yearly patent count for each MSA is displayed by decade in Figure 3.1. There has been an increase in water-related patenting since the 1990s. This trend is observed in MSAs located in the West, Northeast, and the Midwest regions of the US.

I trim the data to remove outlier MSAs at the bottom of the distribution for patenting activity. Specifically, I remove MSAs in the lowest percentile of overall innovative activity (unrelated to water) and MSAs in the top 5% percentile of zero water-related patents to exclude MSAs that don't have the necessary economic infrastructure in place to support innovative activity in the water sector. This removes a total of 29 MSAs from the sample.

3.3 Water Technology Clusters

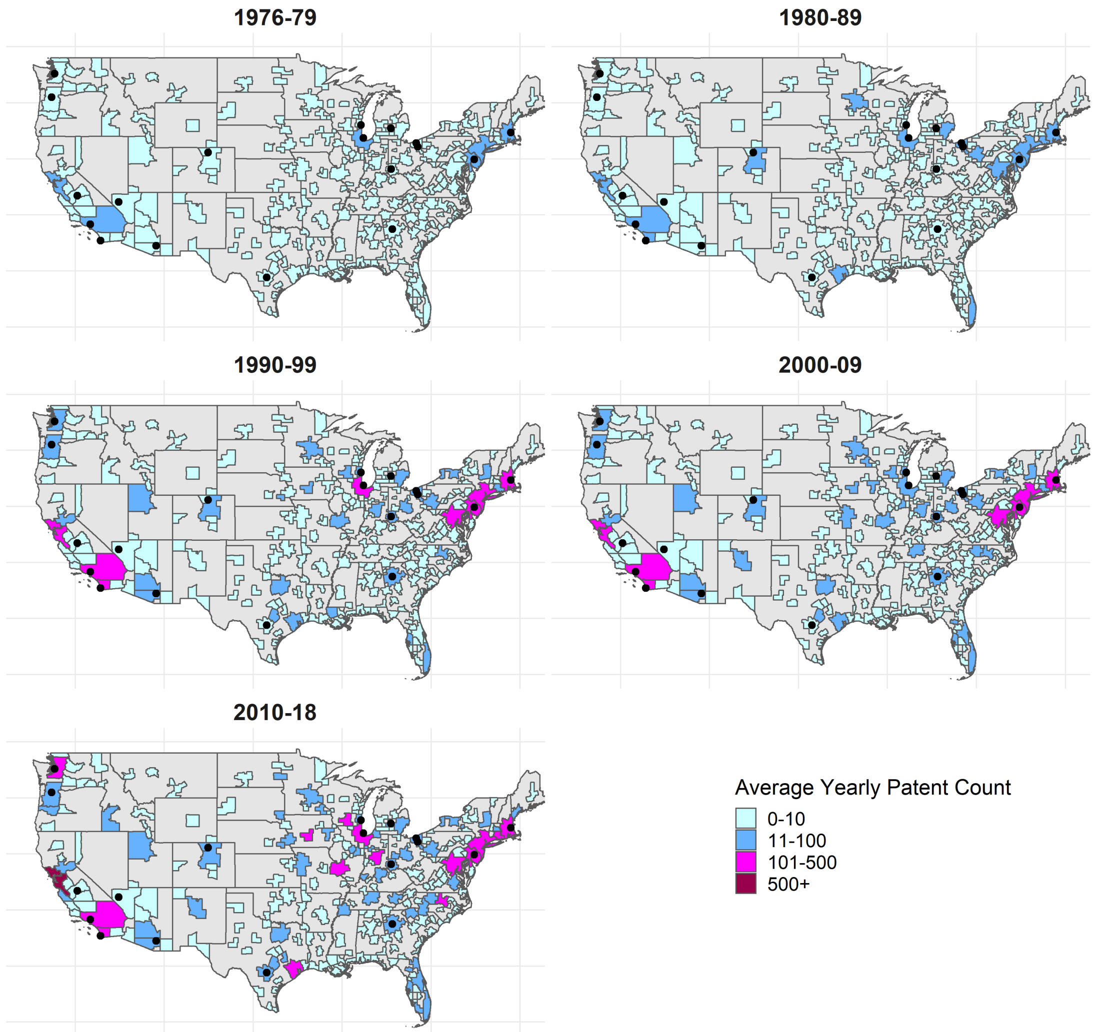
Technology clusters have been an important part of innovation policy since the mid-to-late 1990s (Porter, 2000; Braunerhjelm and Feldman, 2007; Delgado, Porter and Stern, 2014). The creation of technology clusters is intended to promote cooperation among the various stakeholders to leverage regional strengths and bridge the gap between research and ideas and successful commercialization of new products (Fieldsteel, 2013). Technology clusters are therefore largely built around industries with an already established presence and the presence of key regional stakeholders which include end-users, universities, research centers, large firms, government and other relevant institutions.

Water utilities are a key stakeholder in the water sector, responsible for the provision of water services and waste-water treatment. Many water utilities, however, are cash constrained which may limit their ability to collaborate or innovate. In particular, many innovators in the water sector aim to improve water utilities' ability to recover resources from wastewater and reduce the energy intensity of water utility operations (Daigger, 2009; Naik and Stenstrom, 2014).[28]

A key goal of water technology clusters is to mitigate some of the risk associated with the development of new technologies. Many of the water technology clusters provide funding and opportunities to test, validate, and verify new technologies, serving as a credible third-party vetting system to screen new technologies. The screening of technologies is important for two reasons.

[28] https://www.wef.org/globalassets/assets-wef/3---resources/environmmental-tech-clusters-program/clusters-leaders-meetings/water-cluster-leaders-meeting-summary-report-2017.pdf

Figure 3.1: Water-Related Patenting Activity Over Time



Note: The figure represents average patenting activity for all water-related patenting activity for each MSA by decade. Black points on the maps represent the locations of the 18 recognized water technology clusters. Black points included in all time periods to help visualize patenting activity in locations that establish a water technology cluster across time and space.

First, water-related technologies are expensive to test and scale. More importantly, development of water technologies generally require long testing and review periods because of factors such as requirements that technologies be piloted in each state as a pre-condition to commercialized nationally (e.g. Forer and Staub, 2013). Adoption of several successful technologies in the water sector have taken up to 14 years after pilot testing (O'Callaghan et al., 2018). Private venture capital funding for the development of water-related technologies is relatively scarce because of want to take on projects with shorter time horizons.

Second, end-users generally view new technologies as risky, preferring proven technologies despite the potential gains that newer technologies could offer. This risk aversion often dampens demand for new technologies and reinforces inertia. This is especially the case for water utilities as they are primarily preoccupied with continuity of service (e.g. Worm, 2018; Garrone et al., 2018). More generally, this is important as many technologies fail because they often do not address actual market needs due to a lack of end-user engagement during the development process.[29]

In 2011, the EPA established a *Water Technology Innovation Cluster Initiative* (WTICI) to jump-start innovation in the water sector by supporting the development of local water technology clusters. In this paper, reference to technology clusters specifically refers to the technology clusters that are managed as part of the WTICI.[30] The EPA's official recognition of water technology clusters represents formal and additional support to reduce barriers to innovation. As part of the initiative, for example, EPA and other federal agencies help ease regulatory hurdles and provide support for meetings, networking, planning, coordination to promote the creation of new technologies that address pressing environmental and public health challenges and encourage sustainable economic development. In 2018, the EPA transferred coordination of the water technology program to the Water Environment Federation to be managed as part of the Leaders Innovation Forum for Technology (LIFT) program, whose goal is to "establish the conditions that promote accelerated development and implementation of innovative technologies and approaches" in the water sector.[31]

A total of 18 water technology clusters across the United States are recognized by the WITCI.[32] Each of the established clusters' technology focus vary based on each regions' particular needs or strengths. These foci range from water scarcity, reuse, agriculture challenges, aging water infrastructure, and water quality. A list of the 18 existing water-related technology clusters, along with their relative foci, is provided in Appendix Table 4.1 in Appendix 4.[33] Several of the water technology clusters existed prior to WTICI. For the technology clusters that formed prior to WTICI,

[29]EPA Water Technology Innovation Cluster Leaders Meeting – March 24–26, 2014 https://19january2017snapshot.epa.gov/sites/production/files/2014-07/documents/final_march_2014_water_cluster_leaders_meeting_summary_508.pdf

[30]There is no universally accepted definition of a technology cluster (Arthurs et al., 2009). Existence of a technology clusters for various industries, including water, is measured in several ways (Wood, Harten and Gutierrez, 2018).

[31]http://cweawaternews.org/lift-program-expands-with-water-technology-innovation-clusters/

[32]The location of each cluster is geocoded then assigned to the MSA in which is located.

[33]https://www.wef.org/resources/water-technology-innovation-clusters/innovation-clusters-map/

I use 2011, the start of the initiative, as the first year.

3.4 Additional Data

The main goal of this study is to examine the relationship between scarcity and water-related technological innovative activity. It is therefore important to control for other drivers of innovative activity unrelated to scarcity. Additional data is collected at the MSA level to capture attributes at a regional scale that may affect the level of water-related innovation and innovative activity, more generally.

3.4.1 Toxic Release Inventory.

Water Quality is measured using data from the Toxic Release Inventory (TRI) from 1986-2017, which is maintained by the EPA.[34] The program requires facilities in various industries which manufacture, process, or use significant amounts of toxic chemicals, to report annually on storage, use, and releases of these chemicals, including information on the medium in which the substance is released (e.g. air, water, landfill). An advantage of these data is that firms are not fined for the content of their reports. Firms are find for not reporting information. This minimizes concern over incentives for misreporting.[35]

The main purpose of the data compiled by TRI is to provide information about industrial management of potentially dangerous chemicals to inform the public, help communities plan for potential chemical emergencies, and assist local governments in accessing information on possible exposures. A count of the number of chemicals released that are known carcinogens is used to capture the effect of informal regulation on innovative activity. Given that the program was established in 1987, these measures do not exist prior to 1987. These measures are set to 0 in years before the program was established to reflect the fact that this type of informal regulatory pressure was non-existent.

[34]Congress created the Toxic Release Inventory (TRI) in 1986 under Section 313 of the Emergency Planning and Community Right-to-Know Act (EPCRA) in response to a deadly chemical release at a chemical plant in West Virginia in 1985. https://www.epa.gov/toxics-release-inventory-tri-program/tri-basic-data-files-calendar-years-1987-2017

[35]Other potential data sources on water pollution include federal data repositories: Storet Legacy, Modern Storet, and the National Water Information System (NWIS). Though these sources are valuable sources of water quality information, they suffer from several issues. First, they are not easily accessible by the public. Second, locations of stations are not exogenous. Lastly, the timing of the readings themselves are highly endogenous.

3.4.2 Census Data

Decennial censuses from 1970–2010 are used to collect data on education to proxy for the availability of a skilled workforce, measured as the proportion of the population with a college degree or higher. Data for years in between collection are linearly interpolated.[36] Yearly population estimates for MSAs are obtained from the Complete Economic and Demographic Data Source (CEDDS). Using these data, a measure of population growth is constructed to capture development pressures that may put strain on existing water supply.

3.4.3 Municipal Financial Records

The state of the existing water-related infrastructure may affect both firm location as well as firm investment in water-related technologies. Municipal spending on water-related infrastructure is measured using data from the 1967-2015 Annual Survey of State and Local Government Finances. These data include reports for annual capital and total expenditures for waste-water, solid waste management, and natural resources for each local government. These annual estimates are averaged at the MSA level and linearly interpolated for missing years.

4 Estimation

I adopt a "treated-within-the-treated" approach, extending the difference-in-difference framework to evaluate both the impact of establishing a Water Technology Cluster on water-related patenting activity in addition to changes in patenting activity following the incidence of drought. This approach makes use of variation in both the timing and geographic location in the incidence of droughts and the recognition of water technology clusters to explain differences in patenting water-related patenting activity.

In this setup, MSAs that experience drought are considered exposed to a "water scarcity treatment." Following the event study literature, I capture the dynamic effects of a drought shock in MSA i, using indicator variables. Let d_i denote a year in which MSA i experiences a drought shock; $t - d_i$ therefore represents the number of years elapsed since a drought shock, i.e. "relative time" (Borusyak and Jaravel, 2017; Schmidheiny and Siegloch, 2019). Indicator variables for each

[36]Data collected from IPUMS NHGIS (Manson et al., 2017) and Longitudinal Tract Data Base (Logan, Xu and Stults, 2014)

year following a drought shock can be expressed as $\sum_{\tau=1}^{\infty} \mathbb{1}\{t-d_i=\tau\}$, where $\tau=1$ represents the first year following a drought shock and $\tau=\infty$ is the maximum lag possible given the data. Pre-trends (i.e. $\tau \leq 0$) are not included because the incidence of a drought episode is considered to be as-good-as-randomly assigned.[37]

Additionally, MSAs in which a water technology cluster is established are considered to have received a "policy treatment." These MSAs are treated at various times and, once treated, remain treated thereafter. Specifically, the policy treatment is defined as, $T_{it} \in [0,1]$, where $T_{it}=0$ if MSA i has not established a Water Technology Cluster by year t and $T_{it}=1$ if it has. MSAs that never establish a Water Technology Cluster are included in the analysis as control locations. An interaction term, $\sum_{\tau=1}^{\infty} \mathbb{1}\{t-d_i=\tau\}T_{it}$ is included to capture the dynamic effect of a drought shock that occurs in MSAs with an established water technology cluster. The basic modeling approach is given by (5):

$$P_{it} = \sum_{j}^{J_i}\sum_{\tau=1}^{\infty}\gamma_\tau \mathbb{1}\{t-d_{ij}=\tau\} + \beta T_{it} + \sum_{j}^{J_i}\sum_{\tau=1}^{\infty}\theta_\tau \mathbb{1}\{t-d_{ij}=\tau\}T_{it} + \delta X_{it} + \eta_i + \epsilon_{it} \tag{5}$$

where i indexes MSAs, t indexes calendar years, and j indexes drought events. MSA fixed effects, η_i, are included to capture time-invariant characteristics that vary by MSA. Specifically, η_i would account for the general propensity to generate water-related patents and capture factors that account for these differences, such as institutions, regulatory environments, the presence of water resources, or differences in knowledge stocks that would affect the level of patenting across MSAs. Standard errors are adjusted for both heteroscedasticity and autocorrelation due to potential persistence of drought shocks that would be captured by ϵ_{it}. I estimate this equation separately for each technology type (All, Conservation, Supply, Water-Quality) to account for heterogeneous effects across the broad range of activities that droughts affect.

The coefficient γ_τ represents patenting activity in years following droughts in MSAs without a water technology cluster and the coefficient θ_τ any additional patenting activity that occurs in MSAs with an established technology cluster. Identifying the the effect of a drought shock on patenting activity depends on the assumption that an innovator files for a patent in the same location that they experience drought, i.e. they do not move locations between when drought

[37]Droughts are usually predicted up to a month in advance. In certain rare instances, droughts are predicted up to a year in advance (Huang et al., 2014).

occurred and when patent is filed.[38]

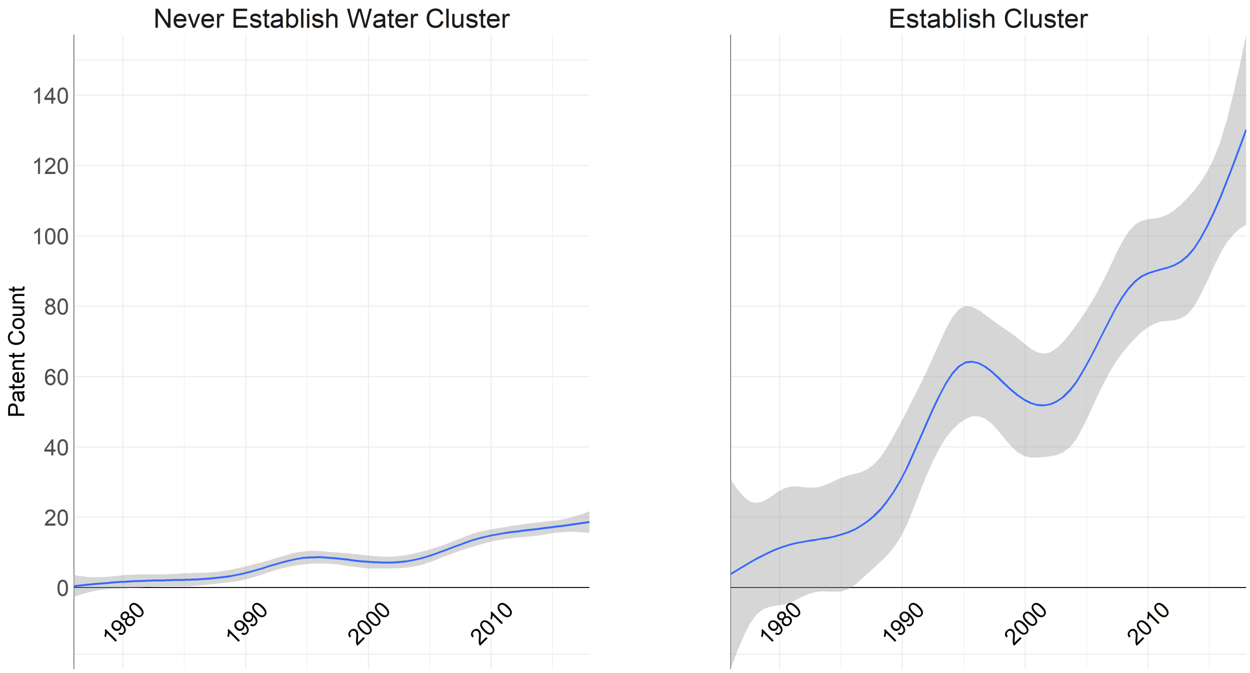
The vector X_{it} represents time-varying observed covariates to controls for factors may affect water-related patenting activity. First, I control for local innovative activity using a measure of per capita patenting activity unrelated to water as proxy for the general propensity to patent in each year t and MSA i. Second, I control for regulatory pressure to create new water-related technologies unrelated to scarcity using a count of the number of chemicals released that are known carcinogens. Lastly, I control for temporal variations in patenting incentives for water-specific technologies using the number of successful U.S. applications in year t in non-MSA areas, including those filed by foreign corporations (Jaffe and Palmer, 1997). I also include US census region-specific linear time trends to capture long-term patenting trends due to differences in climate and regional institutions.

The coefficient, β, captures the mean change in patenting activity observed pre- and post-establishment of a water technology cluster. Causal interpretation of β requires that the establishment of a water technology cluster be uncorrelated with water-related patenting activity. A priori, there is reason to be concerned that the location of a technology clusters is not random because its establishment is a result of local initiatives. The policy treatment, T_{it}, may therefore be endogenous as MSAs select into treatment. Simply comparing locations with that establish a water technology cluster to those that do not is not sufficient because locations in which a cluster was created may be systematically different than those where one was not created. More importantly, these differences might due to unobserved characteristics that would also be systematically correlated with the outcome of interest (i.e. water-related patenting activity). These unobserved characteristics will be subsumed in ϵ_{it}. As shown in Figure 4.2, patenting trends in MSAs that eventually establish a water technology cluster are significantly different from MSAs that have not established a cluster.

In the main specification, I account for the potential endogeneity of the policy treatment using a parametric control function approach motivated by Heckman (1978) extensively used in the literature (Semykina and Wooldridge, 2010; Papke and Wooldridge, 2008; Imbens and Wooldridge, 2009; Semykina and Wooldridge, 2010; Fernández-Val and Vella, 2011; Wooldridge, 2015; Kawatkar et al., 2018). As a robustness check, I also estimate the effect of water technology clusters using a Baysian Structural Time-Series approach in Appendix 6. This alternative approach constructs a

[38] This is a common assumption made in literature on innovation.

Figure 4.2: Water-Related Patenting Activity in MSAs that do and do not Establish a Water Technology Cluster



Note: The solid lines represent average patenting activity. The shaded region represents the associated 95% confidence interval.

synthetic control using untreated MSAs. The results from this alternative approach are consistent with the results presented in this section.

The parametric control function approach approach is implemented in two stages. In the first stage, a selection equation is specified and estimated using a Probit regression at each cross-section, year t, to obtain estimates of time variant unobserved heterogeneity that explains the selection into treatment. These estimates are then used to construct the Inverse Mills Ratio, $\hat{\lambda_{it}}$. The control function is then included as a regressor in the outcome equation to purge ϵ_{it} of the factors that led to selection. This approach is inherently an instrumental variable method. The first stage is specified as follows:

$$P(T_i = 1|z_{it}) = \phi(z_{it}\delta_t + \bar{z}_i\xi_t) \tag{6}$$

where z_{it} are instrumental variables and $\bar{z}_i$ are time means of these instruments.[39] The set of

[39]Binary instrumental variables are not time-meaned.

Table 4.3: Control Function Exclusion Restrictions

Variable	**Description**	**Data Source**
	Time-Invariant Factors	
EPA office	Distance to the nearest regional EPA office	EPA
CEE	MSA with a Civil and Environmental Engineering Dept.	SR
	Time-Varying Factors	
Previous drought episodes	the total number of drought episodes that a MSA experienced from 1930 through time $t-1$	NOAA
WaterExp	Expenditure on operation, maintenance, and construction of public water supply systems	ASSLGF
SewExp	Expenditure on provision, maintenance, and operation of sanitary and storm sewer systems and sewage disposal and treatment facilities	ASSLGF

Notes: EPA- Environmental Protection Agency; SR- Shanghai Ranking; NOAA-National Oceanic and Atmospheric Administration; ASSLGF - Annual Survey of State and Local Governments

exclusion restrictions used in the first stage consist of factors related to water-specific concerns and the RIS literature. These variables are summarized in Table 4.3 and discussed in Appendix 2.

In the second stage, the $\hat{\lambda_{it}}$ is included as an additional explanatory variable to control for selection bias.[40] MSA fixed effects are replaced with time means of the instruments to purge the idiosyncratic error term of the factors that led to selection in addition to including the constructed control function as an additional explanatory variable. The resulting error term in the new outcome equation is theoretically orthogonal to the explanatory variables.[41] The second stage is specified as follows:

$$P_{it} = \sum_{j}^{J_i} \sum_{\tau=1}^{\infty} \gamma_\tau \mathbb{1}\{t - d_{ij} = \tau\} + \beta T_{it} + \sum_{j}^{J_i} \sum_{\tau=1}^{\infty} \theta_\tau \mathbb{1}\{t - d_{ij} = \tau\} T_{it} + \delta X_{it} + \hat{\lambda_{it}} + \bar{z}_i + \epsilon_{it} \qquad (7)$$

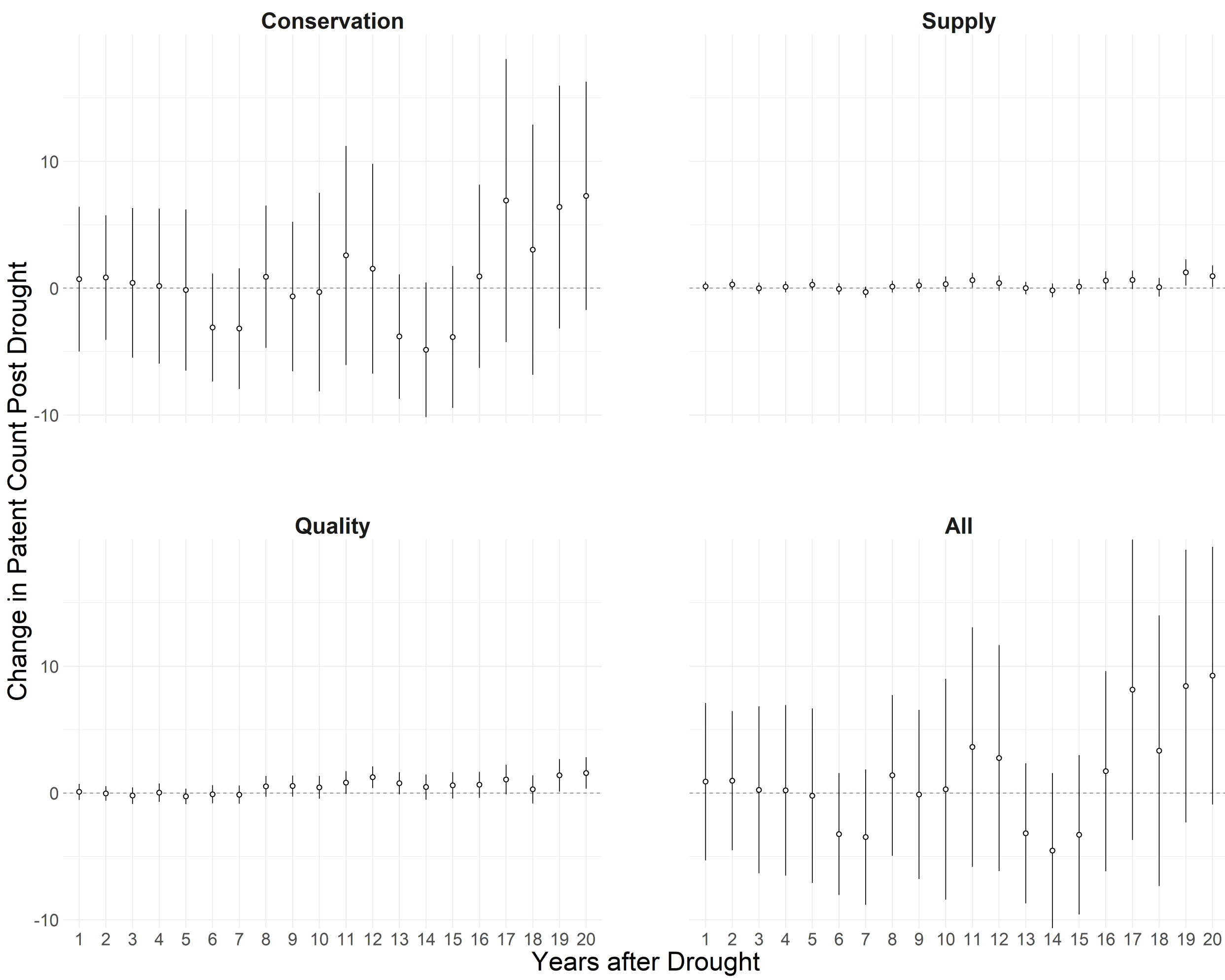
The results of estimating (7) are shown graphically in Figure 4.3 through Figure 4.5 for various subsets of the coefficients of interest. The full numerical results are given in Appendix

[40]This approach is the basis for Heckman two-step estimator for endogeneity.

[41]This was first proposed by (Mundlak, 1978) and (Chamberlain, 1979). In the absence of selection bias, the transformation produces the same results as a fixed effects approach (Semykina and Wooldridge, 2010).

Table 1.4. Starting with patenting activity following the incidence of drought, the results suggest no evidence that water-scarcity shocks induce more innovation. As shown in Figure 4.3, the magnitude of the lagged coefficients, $\sum_{\tau}^{\infty} \gamma_{\tau}$, are relatively small and insignificant from zero, especially for supply and pollution abatement technologies.

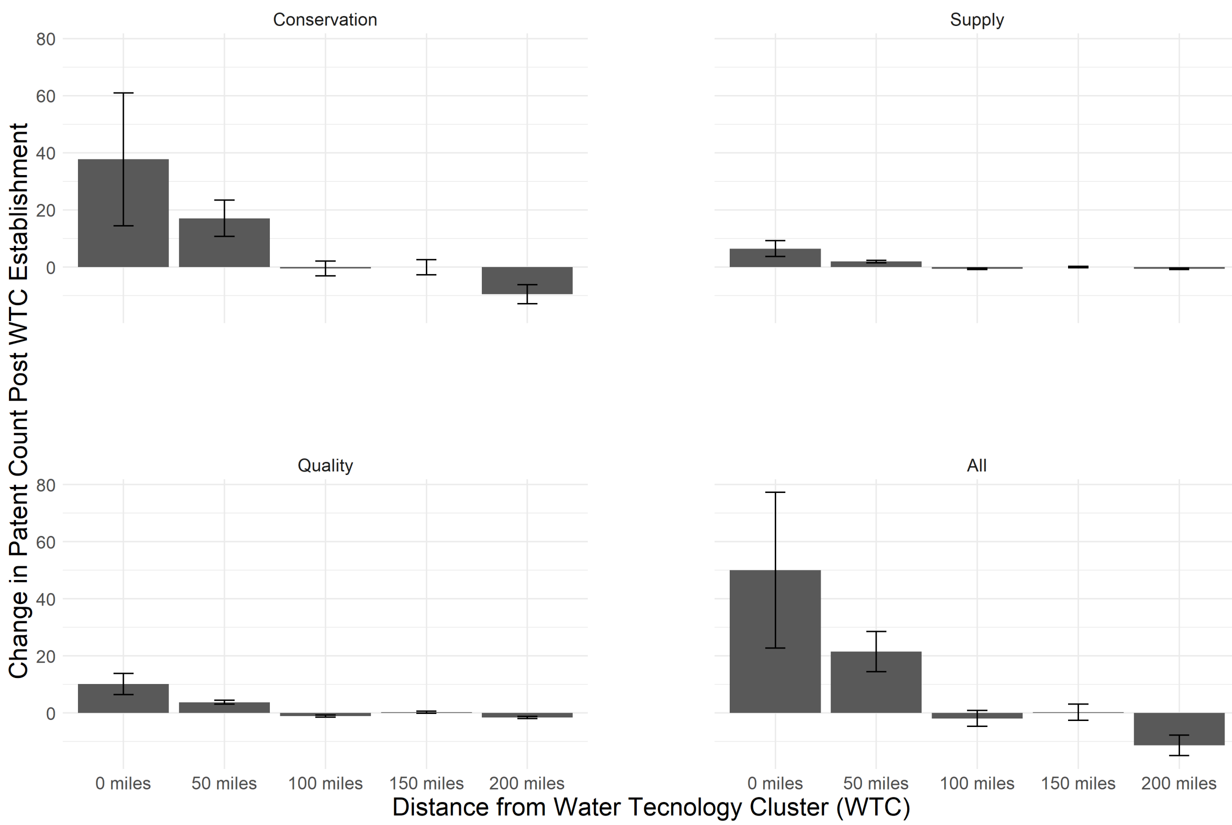
Figure 4.3: Patenting Activity after Drought



Note: Coefficients represent the change in patent counts at each lag following the occurrence of a drought shock.

With respect to the impact of water technology clusters, the results indicate that establishing a water technology cluster that receives formal recognition by the EPA increases patenting activity. In Figure 4.5, this effect is represented in the 0mi column. The effect is strongest for water conservation technologies, with an approximate increase of 41 patents per year. Smaller increases are observed for water supply and water quality technologies, with increases in average patent count of approximately 7 and 11 respectively. I also find evidence of spillover effects for MSAs within a 50mi radius of a treated MSA (i.e. MSA with a water technology cluster). I find that MSAs further than 50mi do not significantly increase patenting activity. Moreover, I find evidence that MSAs further between 150-200mi of a treated MSA may decrease patenting activity. One potential explanation for this is that innovators that would have filed for patents in these locations filed for them in the treated MSA instead.

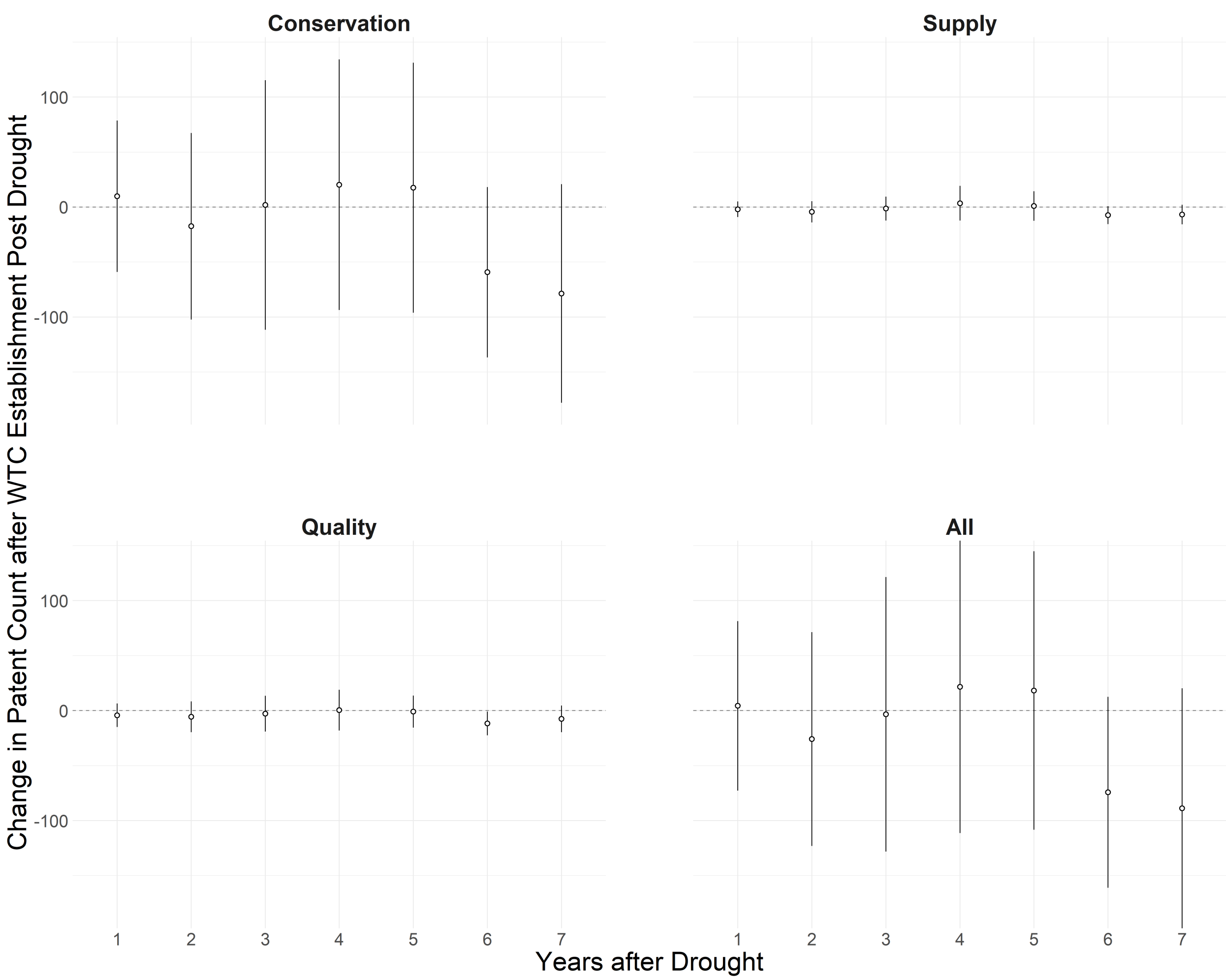
Figure 4.4: Effect of Water Technology Cluster on Patenting Activity



Note: The 0mi column is the additional patenting activity that occurs in MSAs with an established technology cluster. Subsequent columns represent the change in patenting activity for MSAs within the specified radius of a water technology cluster.

As shown in Figure 4.4, results also indicate that droughts do not induce more innovation MSAs with water technology clusters. The magnitude of the lagged coefficients for the effect of drought in MSAs with water technology clusters, $\sum_{\tau}^{\infty} \theta_{\tau}$, are not significantly different from zero.

Figure 4.5: Patenting Activity after Drought in MSA with Water Technology Cluster



Note: Coefficients represent the change in patent counts at each lag following the occurrence of a drought shock in MSAs with an established water technology cluster.

5 Conclusion

In this paper, I focus on technological innovation in water sector because of the long-standing perception that water-related innovative activity is lagging. I study the inventive phase of water-related innovation to shed light on whether innovators react to water scarcity, focusing on the timing of the inventions, as opposed to characteristics of the inventions themselves. Specifically, I estimate the extent to which water scarcity motivates innovators to create new water-related technologies, using the incidence of drought as exogenous water scarcity shocks.

In general, findings indicate that patenting activity does not increase following water scarcity shocks. This finding is important as droughts are expected to become more severe.[42] Several explanations exist for why this may be the case. First, it is possible that the droughts observed during the sample period were not considered to be serious 'scarcity signals.'

Second, the uncertainty in the incidences of drought may influence preferences for investmenting in new technologies. Previous research has shown that people tend to overweigh the likelihood of the most favorable outcomes and are consequently less likely to invest or demand technologies (Bernedo and Ferraro, 2017). Similarly, empirical evidence also suggests that government insurance programs that insure against crop losses due to extreme heat (e.g. subsidized crop insurance program) may potentially distort inventivies to create or adopt technologies in the agricultural sector (Annan and Schlenker, 2015).

Third, it is also possible that technologies already in existence are being increasingly adopted following instances of drought. Taking this perspective, adoption of already existing technologies may be considered "innovative" as it would be addressing an issue in a way that is new for that location as water issues intersect strongly with local concerns and solutions are contingent on local conditions. This study points to the need to better understand the adoption behavior of water-related technologies in the context of scarcity.

Lastly, it is also the case that extreme droughts create conditions that may inhibit innovative activity. For instance, extreme water scarcity can lead to or exacerbate other natural disasters (e.g. wildfires, floods, sinkholes) or lead to social unrest (Westerling et al., 2003; Ichoku et al., 2016; Hand, Thompson and Calkin, 2016; Scasta, Weir and Stambaugh, 2016).[43] These secondary effects

[42] With few exceptions, most droughts have not lasted that long as the period under study happens to be one of the wettest periods within the last 500 years (Pederson et al. 2015).

[43] In California, wildfire related-damages in 2018 totaled over $2.5 billion. Land subsidence can occur as ground

may draw resources away from innovating on water-related issues.

With respect to water technology clusters, I find that the establishment of water technology clusters increases local patenting activity as well as activity in nearby locations. I find no evidence, however, that innovators operating in the context of a water technology cluster increase innovative activity after experiencing a drought. The most likely reason for this finding is that there are too few years of post-drought data to be able to detect a different response. Further research is needed to understand this finding. This finding would support the notion that there are significant barriers to innovation that technology clusters address. Though further work is needed to investigate the attributes of water clusters that specifically enable them to promote innovative activity, this study also points to the need to evaluate policies that leverage market forces to promote water-related innovation.

dries which can rupture pipelines buried within, causing costly repairs and wasted water. While the occurrence of wildfires is not solely driven by drought conditions, the number of wildfire incidents and the extent of their associated damaged have increased in part due to changing climate (Hand, Thompson and Calkin, 2016).

Appendices

Appendix 1 Innovation Results

Appendix Table 1.4: Main Results

	Water-Related Technologies			
	All	Conservation	Supply	Quality
Cluster in MSA	53.739***	40.851***	6.664***	10.698***
	(14.235)	(12.141)	(1.437)	(1.911)
Carcinogens (lbs)	1.083***	0.756***	0.128***	0.284***
	(0.091)	(0.080)	(0.011)	(0.017)
Patenting activity in MSA	29.923***	27.449***	1.176***	1.913***
	(5.549)	(5.106)	(0.275)	(0.388)
Water patenting foreign	0.005***	0.004***	0.0004***	0.0004***
	(0.001)	(0.001)	(0.0001)	(0.0001)
Control fun	−16.972***	−14.985***	−0.509**	−1.944***
	(3.778)	(3.579)	(0.218)	(0.383)
CEE	14.678***	10.205**	2.159***	3.716***
	(4.830)	(4.498)	(0.330)	(0.526)
MSA-EPA dist	−0.00001	−0.00000	−0.00000***	−0.00000*
	(0.00001)	(0.00001)	(0.00000)	(0.00000)
Northest	−3.351	−3.002	−0.278*	−0.312
	(2.119)	(1.927)	(0.145)	(0.247)
Midwest	4.609	3.216	0.568*	1.059**
	(4.213)	(3.786)	(0.301)	(0.425)
South	−6.731***	−6.003***	−0.365***	−0.617***
	(1.591)	(1.402)	(0.130)	(0.208)
Constant	30.382***	27.121***	0.033	3.694***
	(9.564)	(8.983)	(0.603)	(1.051)

Note: Effect of water technology cluster limited to the MSA in which it is located. Time means of the instruments omitted. HAC standard errors are reported.

Appendix 2 Control Function Exclusion Restrictions

In this section, I discuss the choice of exclusion restrictions used in the selection equation and the rationale behind the identification assumption (i.e., why the variables impact selection but not the main equation of interest).

Distance to the nearest regional EPA Office

Water technology clusters that are part of the Water Technology Cluster Initiative acquire recognition from the EPA. Consistent with the regional economic framework adopted in this paper, I posit that proximity to a regional EPA office would presumably be correlated with the location of a water technology cluster. Moreover, proximity to a regional EPA office would only be associated with water-related patenting activity through it's association with water technology clusters.

Presence of a Civil and Environmental Engineering Department

Universities are a key industry-related institution in the innovative process, creating, diffusin, and deploying new knowledge in economically useful ways (Feldman et al., 2002). The location of universities Civil Engineering programs is used as a proxy for universities that focus on water-related issues. A list of these universities, provided in Appendix Appendix 5, is obtained from Shanghai Ranking and geocoded. Of the 200 universities listed, 48 were in the United States.

Drought history

Water technology clusters may differ in the nature of the technologies they work on, depending on the region's particular needs and strengths. I control for the propensity to work on water scarcity issues by controlling for each location's propensity to experience drought using the total number of drought episodes from 1930 through time $t-1$.

Expenditure on water and sewer infrastructure

Water innovators are interested in key aspects of water utility operations, most notably water treatment. For instance, water treatment is energy intensive. Additionally, waste-water contains valuable materials that can be extracted and re-purposed (Monteith et al., 2008). Water utilities in their capacity to finance (construct, maintain, operate) facilities necessary for those purposes due to limited resources.[44] I proxy for water utility's capacity to collaborate using MSA-level on expenditures for facility operation, maintenance, and construction.

[44] https://www.wef.org/globalassets/assets-wef/3—resources/environmmental-tech-clusters-program/clusters-leaders-meetings/water-cluster-leaders-meeting-summary-report-2017.pdf

Appendix 3 Patent Codes

In this section, I provide the lists of IPC and CPC codes for water-related technologies in Tables Appendix Table 3.1, Appendix Table 3.2, and Appendix Table 3.3 from Haščič and Migotto (2015). I supplement this list for desalination technologies using codes identified by van der Vegt et al. (2011). The main advantage of using these codes to identify particular types of innovations is that they are heavily reliant on the detailed knowledge of patent examiners (Haščič and Migotto, 2015; van der Vegt et al., 2011). Furthermore, this approach is useful as it captures many of the recent water-related technologies that have been driven by advances in digital technologies that has cross-over applications in the water sector. Alternative approaches to identifying patents involves the use of keywords (e.g. Ajami, Thompson and Victor, 2014). Using keywords, however, can be a costly strategy as the search outcome will be highly sensitive to the set of keywords used. This method would likely underestimate of innovation in the water sector.

Appendix Table 3.1: IPC and CPC Codes for Technologies Aimed at Water Pollution Abatement

Category	***IPC Codes***	***Description***
Water and Waste Water Treatment	B63J4	Arrangements of installations for treating water or sewage
	C02F	Treatment of water, waste water, sewage, or sludge
	C09K3/32	Methods for treating liquid pollutants
	E03C1/12	Plumbing installations for waste water
	E03F	Sewers-cesspools
Fertilizer from wastewater	C05F 7/00	Fertilizers from water, sewage sludge, sea slime, ooze or similar masses
Oil Spill Cleanup Related	E02B15/04-10	Devices for cleaning the surface of open water from oil or like floating materials by separating or removing these materials
	B63B35/32	Vessels adapted for collecting pollution from open water
	C09K 3/32	Materials for treating liquid pollutants, e.g. oil, gasoline, or fat

Appendix Table 3.2: IPC and CPC Codes for Technologies Aimed at Water Supply Augmentation

Category	***IPC Codes***	***Description***
Water Collection	E03B 5	Use of pumping plants
	E03B 3/06-26	Ways to collect drinking water or tap water from underground
	E03B 9	Methods for drawing off water
	E03B 3/04, 28-38	Ways to collect drinking water or tap water from surface water
	E03B 3/03	Ways to collect drinking water or tap water from rainwater
	E03B 3/02	Vessels for collecting or storing rainwater for use in household
	E03B 3/00, E03B 3/40	Ways to collect drinking water or tap water from surface water, underground, or rainwater
Water Storage	E03B 11	Arrangements or adaptations of tanks for water supply
Desalination	B01D	Physical or chemical processes or apparatus in general: separation
	F24J	Production or use of heat not otherwise provided
	F03G	Spring, weight, inertia, or like motors; mechanical-power-producing devices or mechanisms, not otherwise provided for or using energy sources not otherwise provided for
	F01K	Steam engine plants; steam accumulators; engine plants not otherwise provided for; engines using special working fluids or cycles
	H01L	Semiconductor devices; electric solid-state devices not otherwise provided for
	A01G	Horticulture; cultivation of vegetables, flowers, rice, fruit, vines, hops, or seaweed; forestry; watering
	F03D	Wind motors
	F04B	Positive displacement machines for liquid pumps
	F03B	Machines or engines for liquids
	B63B	Ships or other waterborne vessels; equipment for shipping

Appendix Table 3.3: IPC and CPC Codes for Technologies Aimed at Water Conservation

Category	***Codes***	***Description***
Indoor water conservation	F16K21/06-12	Self-closing valves, i.e. closing automatically after operation, either retarded or immediately after opening
	F16K 21/16-20	Self-closing valves, i.e. closing automatically after operation, closing after a predetermined quantity of fluid has been delivered
	F16L 55/07	Arrangement or mounting of devices, e.g. valves for venting or aerating or draining
	E03C 1/084	Jet regulators with aerating means
	E03D 3/12	Flushing devices discharging variable quantities of water
	E03D 1/14	Cisterns discharging variable quantities of water
	A47K 11/12	Urinals without flushing
	A47K 11/02	Dry closets
	E03D13/007	Waterless or low-flush urinals
	E03D5/016	Special constructions of flushing devices with recirculation of bowl-cleaning fluid
	E03B1/041	Greywater supply systems
	Y02B 40/46	Optimization of water quantity (for dishwashers)
	Y02B 40/56	Optimization of water quantity (for washing machines)
Irrigation	A01G 25/02	Watering arrangements located above the soil which makes use of perforated pipe-lines or pip-lines with dispensing fittings, e.g. for drip irrigation

Continued on next page

Appendix Table 3.3 – *Continued from previous page*

Category	***Codes***	***Description***
	A01G 25/06	Watering arrangements making use of perforated pipe-lines located in the soil
	A01G 25/16	Control of watering
	C12N15/8273	Mutation or genetic engineering: DNA or RNA, concerning genetic engineering, vectors, e.g. plasmids, or their isolation, preparation or purification for drought, cold, salt resistance
Power Production	F01K 23/08-10	Combustion heat from one cycle heating the fluid in another
	F01D 11	Non-positive displacement machines or engines, e.g. steam turbines/Preventing or minimizing internal leakage of working fluid
Water Distribution	F17D5/02 & E03	Pipe-line systems/Preventing, monitoring, or locating loss
	F16L55/16 & E03	Devices for covering leaks in pipes or hoses
	G01M 3/08, G01M 3/14, G01M 3/18, G01M 3/22, G01M 3/28 & E03	Investigating fluid tightness of structures, by detecting the presence of fluid at leaking point

Appendix 4 Water Technology Clusters Locations and Establishment Dates

Sources: Picou (2014).

Appendix Table 4.1: Water Technology Clusters Supported by *Water Technology Cluster Initiative*

Cluster Name	Location	Year Est.	Focus
	MIDWEST		
Current	Chicago, IL	2016	Technology testing
Michigan Water Technology Initiative	Lansing, MI	2009	Technology testing
Cleveland Water Alliance	Cleveland, OH	2014	Technology testing
Confluence Water Technology Innovation Cluster	Cincinnati, OH	2010	Treatment
Akron Global Water Alliance	Akron, OH	2014	Treatment
The Water Council	Milwaukee, WI	2007	Technology testing
	NORTHEAST		
NorthEast Water Innovation Network	Boston, MA	2011	Technology testing
Water Technology Innovation Ecosystem	Philadelphia, PA	2011	Treatment
	SOUTH		
Accelerate H20	San Antonio, TX	2010	Water and energy
H2OTECH	Atlanta, GA	2015	Human health
	WEST		
University of Arizona Water & Energy Sustainable Technology Center	Tucson, AZ	2013	Technology testing
Maritime Alliance*	San Diego, CA	2007	Maritime technology
Los Angeles Cleantech Incubator	Burbank, CA	2011	
BlueTech Valley	Fresno, CA	2011	Commercialization services, technology testing
Colorado Water Innovation Cluster	Fort Collins, CO	2010	Agriculture, efficiency, water filtration
WaterStart	Las Vegas, NV	2012	Conservation, storage, treatment
Oregon Water Tech Innovators	Portland, OR	2014	Storage, treatment, stormwater management
PureBlue	Seattle, WA	2016	

Source: Water Environment Federation (n.d.). Maritime Alliance was formerly known as TMA BlueTech.

Appendix Table 4.2: Other Water Technology Clusters Not Supported by *Water Technology Cluster Initiative*

Cluster	**Location**	**Year Est.**	**Focus**
NorTech	Cleveland, OH	2011	Technology testing
Louisiana Water Network		2015	
Global Water Alliance (GWA)	Philadelphia, PA	2006	Safe drinking water and sanitation/hygiene services
Pittsburg Water Economy Network	Pittsburg, PA	2012	Industrial Water Retention and Storage, Water Reuse and Treatment
Surge Accelator*	Houston, TX	2011	Energy efficiency, oil and gas
Urban Clean Water Technology Zone	Tacoma, WA	2014	Stormwater treatment

Surge Accelator filed for bankruptcy in 2016.

Appendix 5 Engineering Departments with a Water Specialization

Appendix Table 5.1: List of US Universities with Environmental Engineering Department with a Water Specialization

Texas A&M University	University of North Carolina at Chapel Hill
University of California, Davis	Columbia University
University of Illinois at Urbana-Champaign	Georgia Institute of Technology
University of California, Berkeley	North Carolina State University - Raleigh
Colorado School of Mines	Portland State University
Stanford University	University of California, Riverside
University of Colorado at Boulder	University of Iowa
Oregon State University	Yale University
University of California, Irvine	Florida International University
Pennsylvania State University - University Park	Johns Hopkins University
Colorado State University	University of Connecticut
Duke University	University of Massachusetts Amherst
California Institute of Technology	University of Michigan-Ann Arbor
Cornell University	University of Nevada-Las Vegas
Princeton University	University of Utah
University of Florida	University of California, Los Angeles
University of Washington	University of California, Santa Barbara
Virginia Polytechnic Institute and State University	Arizona State University
Massachusetts Institute of Technology (MIT)	The Ohio State University - Columbus
Michigan State University	Utah State University
Purdue University - West Lafayette	University of Idaho
University of Maryland, College Park	University of Oklahoma - Norman
University of Minnesota, Twin Cities	University of Arizona
University of Nebraska - Lincoln	The University of Texas at Austin

Appendix 6 Robustness Check: Effect of Water Technology Clusters on Innovative Activity

In this section, I use a Bayesian Structural Time-Series (BSTS) approach is used as an alternative method to quantify the causal impact of water technology clusters on patenting activity (a robustness check on the estimates presented in Section 4). The BSTS approach consists of constructing counterfactuals, referred to as synthetic controls, to represent the scenario where no technology cluster was established. The synthetic control is constructed using using a matching algorithm that identifies a pool of MSAs without clusters with similar patenting trends to MSAs that establish clusters prior to treatment. The difference between post-treatment predictions for the synthetic control and the observed outcomes observed for the treated MSAs is considered the impact of establishing a water technology cluster.

The BSTS approach is implemented in three steps (Brodersen et al., 2015; Schmitt et al., 2018).[45] First, Each MSA $i \in 1, ..., N$ with a water technology cluster is matched with a set of control MSA's $C_k = c_k, k \in 1, ..., K$ that does not have a cluster. The set of control MSAs are chosen based on the similarities in patenting activity prior to the establishment of the water technology cluster. In the second step, predicted levels of innovation for the synthetic control are subtracted from the observed levels of innovation in the treated MSAs to obtain a measure of increased patenting levels due to the water technology cluster for each treated MSA i in each post-intervention year, s.

$$\phi_{is}^{(\tau)} = y_{is} - \tilde{y}_{is}^{(\tau)} \tag{8}$$

The cumulative impact of water technology clusters in each treated MSA i is then calculated as the sum of the impact in post-intervention years.

[45]The methodology was developed to assess the the impact of marketing campaigns. The BSTS methodology was implemented using the R package *CausalImpact* provided by Google (Brodersen et al., 2015) via the *MarketMatching* wrapper written to simplify implementation. "CausalImpact 1.2.1, Brodersen et al., Annals of Applied Statistics (2015). http://google.github.io/CausalImpact/"

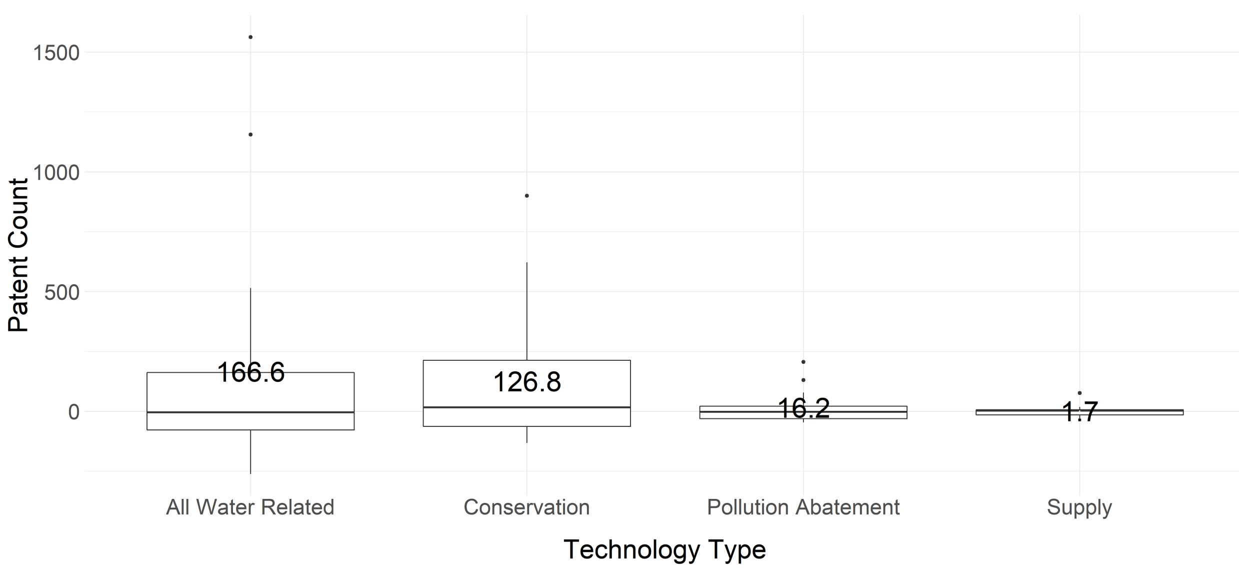
$$\phi_i^{(\tau)} = \sum_{s=1}^{T} \phi_{is}^{(\tau)} \quad (9)$$

The average impact of water technology clusters is the average of these effects across treated MSAs:

$$\bar{\phi}^{(\tau)} = \sum_{i=1}^{N} \frac{\phi_i^{(\tau)}}{N} \quad (10)$$

As in Section 4, the impact of water technology clusters is estimated using a 0mi, 50mi and 100mi radii. Results for the average effect of water technology clusters on patenting activity, $\bar{\phi}^{(\tau)}$, by technology type are provided in Figures Appendix Figure 6.1- Appendix Figure 6.3. In Figure Appendix Figure 6.1, the effect of water technology clusters is limited to the MSA in which it is located. The results indicate that the establishment of water technology clusters, on average, has no effect on patenting activity.

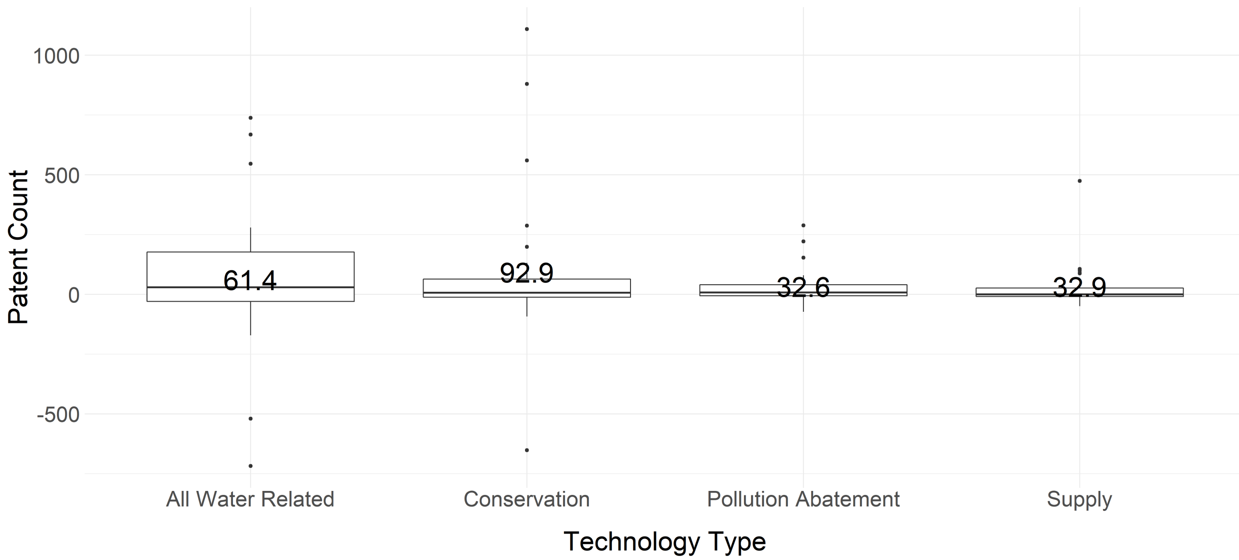
Appendix Figure 6.1: Impact of Water Technology Clusters on Patenting Activity



Note: The boxplot shows the average effect of water technology clusters on patenting activity by technology type. Effect of technology cluster limited to the MSA in which it is located.

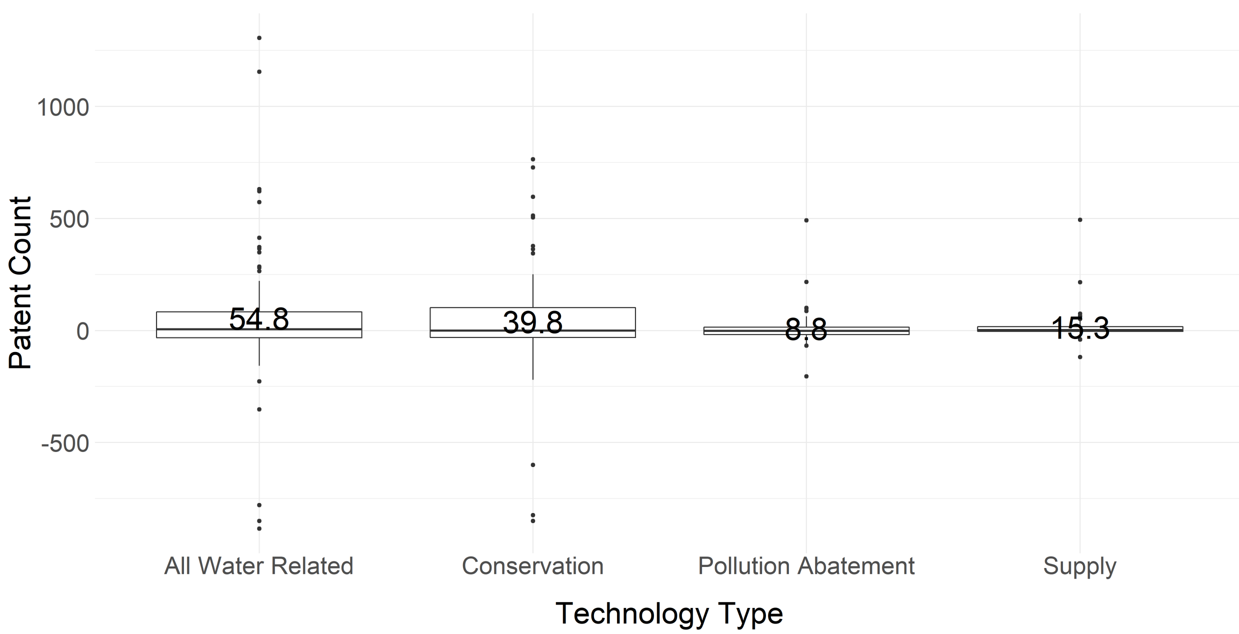
Figure Appendix Figure 6.2, the effect of water technology clusters is extended to MSAs within a 50mi radius of a water technology cluster. The results indicate that the establishment of water technology clusters, on average, increases patenting activity for technologies that augment water supply and those that abate water pollution.

Appendix Figure 6.2: Impact of Water Technology Clusters on Patenting Activity: 50mi radius



Note: The boxplot shows the average effect of water technology clusters on patenting activity by technology type. Effect of technology cluster extented to MSAs within a 50mi radius. The algorithm could not find adequate matches for three MSAs.

Appendix Figure 6.3: Impact of Water Technology Clusters on Patenting Activity: 100mi radius



Note: The boxplot shows the average effect of water technology clusters on patenting activity by technology type. Effect of technology cluster extented to MSAs within a 100mi radius. The algorithm could not find adequate matches for three MSAs.

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