CITIZEN SCIENCE:
THEORY AND PRACTICE

Becoming Infrastructure: Integrating Citizen Science into Disaster Response and Prevention

SPECIAL COLLECTION: DISASTER, INFRASTRUCTURE, AND PARTICIPATORY KNOWLEDGE

RESEARCH PAPER

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ABSTRACT

Citizen science has the potential to contribute to infrastructures for disaster prevention and response. However, sensor networks and crowdsourcing platforms do not in themselves constitute infrastructure. They become disaster infrastructure only to the extent that they are integrated into the routine practices of disaster responders. This paper examines several community-led initiatives for characterizing disasters related to air quality, to understand how citizen science becomes, or fails to become, disaster infrastructure. The integration of citizen science into disaster infrastructure is fostered by creating communities of practice that include citizen scientists and disaster responders, and actively connecting new platforms and information to pre-existing infrastructure. By deliberately undertaking these activities, practitioners can help ensure that citizen science fulfills its potential to enhance disaster infrastructure.

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On August 6, 2012, a pipe ruptured at the Chevron oil refinery in Richmond, California. A cloud of flammable gas escaped and then ignited. The resulting fire sent up a mushroom cloud of smoke that could be seen all over the northern part of the San Francisco Bay area. Chevron notified Contra Costa County officials, triggering the Community Warning System, which sounded sirens and sent alerts to county residents. Residents of Richmond, North Richmond, and San Pablo were advised to shelter in place (US Chemical Safety and Hazard Investigation Board 2015). Thousands went to the emergency room with respiratory symptoms (Bulwa and Kane 2012; Fimrite and Kane 2012; US Chemical Safety and Hazard Investigation Board 2015). Government officials, however, could not immediately offer information about what residents were exposed to. Their air monitoring did not detect elevated levels of hazardous chemicals in the air, and high levels of particulate matter did not show up in results from monitoring stations in surrounding cities (Berton, Fagan, and Ho 2012; Fimrite and Kane 2012).

In the aftermath, Chevron quickly established a new fenceline air monitoring system, and the Bay Area Air Quality Management District (BAAQMD) followed with a rule requiring such systems at all northern California refineries. While catalyzed by the fire, this expansion of air monitoring followed decades of advocacy and technological innovation by Bay area communities adjacent to oil refineries. These fenceline communities began developing community-oriented techniques for ambient air monitoring in the mid-1990s, before the term citizen science was in widespread use (Kullenberg 2015); these included real-time monitoring systems like the one Chevron installed (Ottinger 2016). Communities simultaneously called for refineries and regulatory agencies to increase their own air monitoring (e.g., Gunkelman and Bardet 2012).

The expansion of fenceline monitoring after the Chevron fire might thus be seen as case in which citizen science, and associated activism, enhanced a region's infrastructure for managing disaster: More monitoring data would presumably help ensure that the next industrial accident would be handled more effectively. On the contrary, I argue that the contributions of citizen science to disaster infrastructure are not so clear-cut. Drawing on sociological theories of infrastructure (Star and Ruhleder 1996), I posit that expanded data generated by citizen scientists may not even become part of disaster infrastructure—unless it is accepted by disaster responders and put to use in their routine practices. Whether and to what extent this happens has thus far not been a focus of research on citizen science and disaster, despite optimism about the myriad ways citizen science could enhance disaster response (e.g., Cieslik et al. 2019; Hicks et al. 2019).

In this paper, I examine several community-led initiatives for representing air quality disasters—including acute releases as well as the slow disaster of chronic exposure (Knowles 2014)—asking whether and in what ways they have become part of disaster infrastructure. My cases, encountered during two decades of ethnographic research with advocates for air monitoring in fenceline communities, include post-event air sampling near petrochemical facilities, first-person odor and incident reporting, and real-time air quality monitoring. I find that the extent to which these projects have become infrastructure varies widely. They are most likely to become part of the routines of disaster responders when new technologies are accompanied by the creation of a community of practice (Lave and Wenger 1991) that includes both citizens and responders, and when active efforts are made to create connections between existing disaster infrastructure and new data. The latter is most straightforward when new data sources are commensurate with existing standards, suggesting that groups hoping to expand the kinds of information considered in disaster response (c.f. Hicks et al. 2019) will have to not only produce data, but also take an active role in creating new standards and procedures that can direct action.

INFRASTRUCTURE AND ITS COMMUNITIES OF PRACTICE

My analysis of the contributions of citizen science to disaster infrastructure draws on Star and Ruhleder's seminal account of the nature of infrastructure (Star and Ruhleder 1996, further developed in Star 1999; Bowker and Star 1999). Infrastructure, they argue, is that which fades into the background, becoming invisible in the context of everyday use. The implication of this definition is that infrastructure can be identified only in relation to people and their activities. As Star (1999) puts it, "one person's infrastructure is another's topic, or difficulty" (p. 380). A bridge is a classic symbol of infrastructure because, for the many people that drive over it on their daily commutes, it does not require attention. It is invisibly and reliably there to enable them to get from point to point. But for the traffic engineer charged with its maintenance, the bridge is not infrastructure; it is a focal point of their work. For a cyclist or pedestrian, the bridge may be an obstacle if it lacks a shoulder or sidewalk that would allow their safe passage.

Infrastructures are shared by, and defined in their relationship to, communities of practice. A community of practice is a group of individuals engaged in a common project, who share norms, routines, and expectations about how their work is done (Lave and Wenger 1991; Wenger 2000). The structures, objects, systems, and protocols that make their routine work possible—by fading into the background and not requiring ongoing attention or reinvention—constitute infrastructure from the point of view of members of the community of practice. Indeed, although the members of a community of practice may play a variety of roles and differ in their social status, they are marked as members in part by the activity-enabling elements that they take for granted in daily practice. Infrastructure is "learned as part of membership" in a community of practice (Star and Ruhleder 1996, p. 113).

In the context of their uses by communities of practice, infrastructures appear seamless. Yet they comprise multiple, heterogeneous elements, entangled and embedded with each other in such a way that it is hard to tell where one ends and the next begins (Star and Ruhleder 1996). Among these elements, importantly, are standards that allow different systems to function smoothly together, and category systems that help attach meaning to information (Bowker and Star 1999). Infrastructure has "reach or scope" in that it can be useful at different times or in different places, without having to be reinvented or reassembled in each new situation (Star and Ruhleder 1996, p. 113). Infrastructures can and do change, but they do so incrementally, always building on what Star and Ruhleder (1996) call the "installed base" of standards, categories, practices, algorithms, and material objects already taken for granted in routine practice.

DISASTER INFRASTRUCTURE

Building on Star and Ruhleder's theory of infrastructure, I define disaster infrastructure as the interconnected resources that enable routine responses to disaster or the risk of disaster by communities of practice charged with mitigating the disaster's harms. The Community Warning System activated in response to the Chevron refinery fire in Richmond is one example: Emergency responders use it to classify the severity of accidents, and based on the CWS Level, determine what steps should be taken, e.g., evacuation versus shelter-in-place. Sensor networks could also constitute part of a disaster infrastructure, but—following Star and Ruhleder's account—only if those involved in disaster management and response have shared routines for integrating sensor data seamlessly into their decisions and activities. If disaster managers struggle to remember where to find sensor data or argue over how to interpret it, sensor networks are (to paraphrase Star) topic or difficulty, not infrastructure.

Questions of how disaster infrastructure is created, comes to be taken for granted, and changes with the introduction of new technologies, have received relatively little explicit attention in disaster studies. Many disaster researchers have framed disaster management and disaster risk reduction as a problem of governance. Reviewing the literature on disaster governance, Tierney (2012) calls attention to the need for civil society organization, private corporations, and diverse agencies at many levels of government to coordinate their activities, and for mechanisms such as norms, standards, and best practices to facilitate collective action among diverse entities. Effective disaster governance, in other words, depends on robust infrastructures shared by cross-sector communities of practice. Yet the governance lens glosses over the specifics of these infrastructures, including how they are constituted in tandem with communities of practice. A focus on disaster infrastructure can thus enrich a disaster governance framework but is not reducible to it.

Disaster studies has also advanced an understanding that not every disaster is a fast-moving, acute event like an earthquake or explosion. Slow disasters, such as climate change or the global asthma epidemic, create ongoing harms and chronic states of emergency (Knowles 2014; Kenner 2018). Further, slow disasters and fast emergencies are inextricably linked; for example, the slow disaster of deferred maintenance of industrial systems can lead to explosions such as the 2012 Chevron fire (US Chemical Safety and Hazard Investigation Board 2015). Disaster infrastructures thus need to be analyzed not only in terms of how they function across phases of disaster—risk reduction, response, and recovery—but also in terms of how they help to manage disasters in their acute and chronic aspects.

CITIZEN SCIENCE AND DISASTER

Citizen science has the potential to play a role in improving disaster response, prevention, and management. Review articles document hundreds of disaster-related citizen science projects worldwide, representing varying kinds of citizen involvement, hazards, and research methods (e.g., Chari et al. 2019; Hicks et al. 2019; Paul et al. 2017). While many disaster citizen science projects focus on collecting and making available information during an emergency, citizen science is also argued to be useful in preventing and recovering from disasters (Hicks et al. 2019; Cieslik et al. 2019). Citizen science is hypothesized to be able to play an important role in characterizing and mitigating slow disaster, such as worsening seasonal environmental conditions or chronic exposures to pollution (e.g., Cieslik et al. 2019; Mah 2017).

One well-acknowledged challenge for citizen science and citizen sensing is whether, and under what conditions, it will be taken up by policy makers. Authors writing about the problem of policy uptake tend to focus on questions related to the validity of data and methods of quality assurance (e.g., Suman 2000). In contrast, a focus on citizen science as potential disaster infrastructure forces us to ask not whether disaster responders accept citizen-generated data, but whether they incorporate it into their routines and come to take it for granted. Acceptance of citizen science data as valid and legitimate may be necessary for disaster responders (and policy makers more generally) to incorporate it into their routines, but it is not sufficient to establish citizen science data as infrastructure.

Published accounts of disaster-related citizen science seldom offer insight into how, or whether, these projects become infrastructure for disaster responders. In many cases, studies of disaster citizen science report on the establishment of a new initiative, either in the wake of or in anticipation of disaster (e.g., McCormick 2012; Liu et al. 2011). These reports may not be followed up by subsequent studies of how new data or technologies were taken up by disaster responders, or how they functioned later, in other disasters. McCormick (2012), for example, shows how a crowdsourcing platform called the iWitness Pollution Map generated a new diversity of data about the impacts of the 2010 Gulf oil spill and suggests its potential for informing disaster response and catalyzing social movements. But to know whether the platform has become infrastructure, we would need to know how it was used in response to chemical spills later in the decade.

Safecast, a citizen-led radiation monitoring initiative founded in Japan after the Fukushima nuclear disaster in 2011, is one of the few disaster citizen science projects that has received sustained attention from researchers (e.g., Hemmi and Graham 2014; Brown et al. 2016; Hultquist and Cervone 2018; Polleri 2019). Nonetheless, it remains hard to determine whether it is becoming infrastructural, in the sense of being likely to inform the actions of emergency responders in the event of another large-scale nuclear disaster. In contrast, research on the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) shows its citizen-collected precipitation data becoming part of disaster infrastructure through its use in National Weather Service (NWS) daily precipitation maps, in flood predictions by river forecasters, and in project planning by the Army Corps of Engineers (Bowser and Shanley 2013).

Although CoCoRaHS has not been studied through an infrastructure lens, Reges et al's (2016) history of the project alludes to characteristics of the project that likely contributed to its becoming infrastructure. Citizen science data integrated easily with the installed base because volunteers measured quantities that were already used by weather forecasters. One forecaster furthered this integration by creating software to make CoCoRaHS data available to forecasting offices in real time. In addition, citizen volunteers were encouraged to become part of forecasters' communities of practice by attending scientific conferences and by pursuing research questions.

Literature on disaster citizen science shows that citizen-generated data can become part of disaster infrastructure, but it does not do so automatically. Questions remain about the factors that determine whether citizen science initiatives will become part of disaster infrastructure, and the processes through which they do. Community-led projects for characterizing air quality in fenceline communities can offer insight into these questions.

DISASTER INFRASTRUCTURE FOR AIR QUALITY

Air quality disasters occur when sudden surges in air pollution cause fatalities or illness. These are often associated with industrial chemical releases, such as the 1984 methyl isocyanate leak at a Union Carbide facility in Bhopal, India (Fortun 2001). Industrial emissions can also combine with atmospheric conditions to cause air quality emergencies, as in the case of the 1948 Donora Smog, where a temperature inversion trapped polluted air at ground level in a steel town outside of Pittsburgh, Pennsylvania, killing 20 people (Jacobs et al. 2018). Dangerous air quality can be a secondary consequence of other major disasters, including the September 11, 2001 attack on the World Trade Center (Landrigan et al. 2004) and the 2020 California wildfires (Stark 2020b).

Air quality is also a site of slow disaster. Chronic exposure to air pollution is an ongoing danger to communities on industrial fencelines, near transportation hubs, in FEMA trailers, and otherwise on the "frontlines" of environmental degradation (e.g., Ottinger 2013; Ahlers 2016; Shapiro, Zakariya, and Roberts 2017). Unbreathable environments and a warming world are resulting in an asthma epidemic (Kenner 2018), and poor air quality is being shown to make people more vulnerable to COVID-19 (Ali and Islam 2020). In fenceline communities, breathtaking but subacute chemical releases blur the line between air quality emergencies and slow disaster: environmental regulators tend to regard these smaller incidents as anomalous, whereas exposed residents see them as symptomatic of the systemic danger posed by petrochemical facilities (Ottinger 2009).

Disaster infrastructures for air quality entail the resources and routines used by emergency responders for dealing with acute releases, and by environmental regulators charged with the management of air quality under "normal" conditions. In the United States (U.S.), emergency response for chemical releases is usually coordinated at the local level, resulting in infrastructures that vary from place to place. Communities of practice include public officials, especially from the fire department, and representatives of industrial facilities, who manage emergencies on their own sites and offer mutual aid to other nearby facilities. Emergency response routines include mechanisms for informing the public about what is happening and how to stay safe, such as sirens, phone calls, and text messages. Disaster infrastructure also entails resources to enable responders to decide when and what to communicate to the public: sensors, classification schemes that distinguish moderately dangerous situations from truly catastrophic ones, and boilerplate language about safety precautions (e.g., "shelter in place").

U.S. infrastructures pertaining to the slow disaster of air quality are coordinated at the national level through the Environmental Protection Agency (EPA), with some variation between state and regional agencies. Together, environmental regulatory agencies have created a national network of air quality monitors, measuring six criteria pollutants (particulate matter [PM], ozone, nitrogen dioxide, sulfur dioxide, carbon monoxide, and lead), and possibly a few others such as total volatile organic compounds and benzene, on a coordinated schedule using standardized methods. Data from criteria pollutant measurements are used to calculate a standardized Air Quality Index (AQI), which ranks air quality on a scale of 1 to 500, giving ranges for six descriptive, color-coded categories from "good" to "unhealthy" to "hazardous." Agencies supply for their publics both the current AQI and AQI forecasts, as well as warnings and guidelines for occasions when the AQI is predicted to exceed a certain threshold. These infrastructures for slow disaster—that is, the management of routine air quality—overlap significantly with the infrastructures of emergency response. The same monitors that produce data inputs for the AQI, for example, are likely to be referred to in the event of a chemical spill.

THE CITIZEN SCIENCE OF AIR QUALITY

Infrastructures for emergency response and routine air quality management have been regular targets of criticism by environmental justice (EJ) activists. In the aftermath of acute chemical releases, residents of fenceline communities often question whether enough information was communicated quickly enough, and whether advice to shelter in place or evacuate was protective enough—or, conversely, unnecessarily alarming. They frequently ask what was in the air and often discover a paucity of relevant information. The routine management of air pollution as a slow disaster is perhaps the most criticized. EJ activists have for decades complained that agency monitoring stations are not located near enough to the most vulnerable communities, and that they monitor far too few of the pollutants to which some communities—particularly those near petrochemical plants—may be exposed.

Over time, agencies have incrementally improved their infrastructures in response to these criticisms. The EPA's 2015 refinery rule requires benzene monitoring around the circumference of all U.S. oil refineries, for example. Simultaneously, fenceline communities and their allies have been developing their own strategies for collecting data about air quality. The earliest of these were developed in response to a disaster: a 16-day leak from a refinery in Rodeo, California in 1994 that sickened many workers and residents of two neighboring towns (Slater 1995). In the aftermath, residents and their allies developed the Fenceline, a suite of sophisticated real-time air monitors that measured concentrations of toxic gases at the border of the refinery (Ottinger 2016). They also created the bucket, an inexpensive, easy-to-use device with which residents can take samples for laboratory analysis, generating high-resolution "snapshots" of the toxic gases in the air during petrochemical releases (Kullenberg 2015; Ottinger 2010). Both innovations had far-reaching impacts. The bucket came to be used by fenceline communities all over the world (O'Rourke and Macey 2003). The Fenceline became a model for the extensive monitoring that refineries could and should be doing, and it informed the fenceline monitoring programs launched in the Bay area after the 2012 Chevron Richmond refinery fire.

Advances in technology in the first decade of the 2000s, combined with EJ activists' growing experience with buckets and (to a lesser extent) real-time monitors, led some to envision even more distributed, more accessible monitoring strategies that took advantage of ordinary people's five senses. The first platform to collect experiential data about air quality (and other environmental impacts) after petrochemical releases was the Louisiana Bucket Brigade's iWitness Pollution Map, launched immediately following the 2010 BP oil spill in the Gulf of Mexico (McCormick 2012). It allowed for open-ended reports via multiple channels (e.g., phone, e-mail, SMS). A similar reporting system, the IVAN program, soon followed for a handful of EJ communities in California (Jatkar and London 2015). In Pittsburgh, Pennsylvania, engineers at Carnegie Mellon University's CREATE Lab wanted to collect residents' sensory experiences in a way that allowed for aggregation and comparison. They created an app that asked users to rate what they were smelling on a scale of 1 to 5, and created easy visuals to show how bad air quality had been on any given day, based on user reports (Hsu et al. 2020).

The Smell Pittsburgh app has become Smell My City as the CREATE Lab has gained new partners who want to deploy it in other cities. Among them have been Air Watch Bay Area, a platform that curates data from refineries' fenceline monitoring systems and deploys first-hand reporting technologies to enable residents to annotate the data with their own observations.

Finally, the 2010s saw an increase in the availability of low-cost, real-time monitors. Fenceline monitors like those installed in Richmond and Rodeo cost tens of thousands of dollars and require experts to operate them. In contrast, new, commercially available monitors produce a similar amount of data (one set of readings every few minutes) and cost only a few hundred dollars. There remains a gap, in that no low-cost monitor measures the individual toxic gases, such as benzene and hydrogen sulfide, that the fenceline monitors do, and that are of particular concern to communities adjacent to petrochemical facilities. Nonetheless, one low-cost, real-time monitor has become especially popular, even among fenceline communities: the PurpleAir monitor for particulate matter (Peters 2020). PurpleAir monitors belonging to individual users form a giant network through the company's website, which offers access to data from around the world.

Buckets, reporting platforms, and real-time monitors share an important characteristic of infrastructure: they reach across space and time. In contrast to time-delimited studies of air quality or exposure assessments in a particular EJ community, they are designed for routine use and for deployment without reinvention when something out-of-the-ordinary happens. But infrastructures exist in relation to particular uses and communities of practice. Whether these strategies for representing air quality can be considered disaster infrastructure in particular depends on whether they are integrated into the routine practices of emergency responders and air quality regulators.

METHODOLOGY

To examine how citizen sensing becomes part of disaster infrastructure, I draw on my long-term ethnography of community-led air monitoring in communities adjacent to petrochemical facilities. Since 2001, I have been a participant-observer at EJ organizations with a focus on community air monitoring, including Communities for a Better Environment, Global Community Monitor, and the Louisiana Bucket Brigade. I have spent time in Louisiana and California fenceline communities and have conducted interviews with pioneers and active users of buckets, fenceline monitoring systems, and the iWitness Pollution Map. In 2016, I initiated the participatory design project that resulted in Air Watch Bay Area (AWBA), and continue to collaborate with residents of Bay area fenceline communities and the CREATE Lab on its development. In the process, I have witnessed the evolution of the Smell My City app. My discussion of the IVAN network relies on Jatkar and London's (2015) study and interactions with one IVAN task force member.

Regulators, refinery representatives, and other disaster responders have rarely been willing to be interviewed for my research. To glean insights into the routines of disaster responders, I have followed initiatives by regulatory agencies to enhance industrial safety, promote air monitoring in fenceline communities, and/or incorporate citizen science; I have observed responses to a number of industrial incidents in Louisiana and northern California; and I have spoken with residents about how they have interacted with refinery and public officials around disaster response and prevention.

In the absence of first-hand access to disaster responders' communities of practice, my research cannot state conclusively to what extent community-led monitoring has been integrated into the routines of disaster responders; it may be becoming infrastructural in ways that are not yet visible to outsiders. My research can, however, identify factors that contribute to citizen science becoming part of disaster infrastructure and to point to obstacles that prevent community-led sensing from informing the routines of disaster responders. My research also demonstrates the sort of analysis necessary to determine whether citizen sensing can truly be considered disaster infrastructure.

FINDINGS

Community-led strategies for representing air quality fall into three broad categories—event sampling with buckets; first-person reporting on a variety of platforms; and real-time monitoring with fenceline monitoring systems and PurpleAir monitors. Each stands in different relation to pre-existing disaster infrastructure, and their incorporation into disaster infrastructure has varied widely.

EVENT SAMPLING

Buckets equip fenceline community residents to take air samples following a chemical release. Samples, collected over a period of a few minutes, are analyzed by a laboratory to determine chemical concentrations, and results are returned after a number of days. Taking a bucket sample is thus a way of responding to disaster, but bucket results can seldom inform emergency management directly. Instead, they can identify chronic or recurrent air quality issues, or a pattern of releases that constitutes a systemic danger in the minds of residents (Ottinger 2009).

Bucket sampling directly replicates a practice used by industrial facilities and government agencies. They respond to releases by taking an air sample in a stainless steel canister, the contents of which are analyzed using the same laboratory procedures as bucket samples (Ottinger 2010). Disaster responders use these data to troubleshoot: to identify the source of an odor or release, for example.

Buckets potentially expand and improve the practice of event sampling. Emergency responders, especially those from government agencies, have to travel to the site of a release to take a sample, whereas residents who are already on site can respond immediately. However, disaster responders have not embraced the use of buckets. Early in the device's history, Contra Costa County, California, officials worried that residents would put themselves in harm's way by going outdoors during a release to take a sample. This concern resurfaces periodically as an argument against involving citizens in event sampling.

When communities do take bucket samples, it is standard practice for regulatory agencies and industrial facilities to follow them up with their own monitoring—either canister samples or mobile monitoring. Only when they can corroborate residents' results is further action taken. In this sense, bucket sampling merely helps create pressure on disaster responders to initiate a response to a smell or incident, following their normal procedures. The actual sampling by citizens is not incorporated into those procedures in a meaningful way.

There have been exceptions. Organizers shared with me the story of one case, in Hamilton County, Ohio, where public officials became convinced enough that residents had a legitimate concern about an industrial facility that they equipped residents to take canister samples. In this case, residents were enlisted into the routines of responders, and their data were taken seriously.

Despite occasional inclusion in the management of industrial accidents, event sampling by fenceline communities has not been incorporated into routines for managing the slow disaster of petrochemical exposures. Residents see bucket data as representing the chronic dangers of petrochemical pollution; however, environmental regulators are adamant that short-term, ad hoc event samples cannot contribute to a systematic understanding of exposures or public health impacts. Bucket sampling, as a result, has not become part of the infrastructure of air quality assessment or environmental enforcement.

FIRST-PERSON REPORTING

Platforms like the iWitness Pollution Map, the IVAN program, Air Watch Bay Area (AWBA), and Smell My City (SMC) all create the possibility for users to contribute sensory data about air quality—such as odor reports and flare sightings—to disaster response. They aggregate reports from many users, crowdsourcing information that could be useful to identifying or responding to an emergency. They also create an archive of reports that could document slow disaster and potentially suggest points of intervention.

Like buckets, these platforms partially reproduce the installed base of disaster responders. Most jurisdictions provide a means for citizens to report chemical odors or other air quality concerns. For example, in Louisiana, where the iWitness Pollution Map originated, the Louisiana Department of Environmental Quality has a web form and phone numbers through which one can report an incident or file an environmental citizen complaint. In other places, like Contra Costa County, California, where AWBA operates, one can report an incident to the county as well as to BAAQMD.

Government agencies have not taken steps to incorporate information from community-created reporting apps into their pre-existing platforms. Jatkar and London (2015) raise this explicitly as a problem for the IVAN program, and their report suggests that there would be benefits to linking IVAN reports with the CalEPA's reporting system, as long as communities could maintain control of their reporting systems. They also document regulators' reluctance to support reporting systems controlled by community and nonprofit groups. We met with similar resistance from BAAQMD to first-person reporting in Air Watch Bay Area, to the point where AWBA working group members decided to include language on their site reminding users to also report their observations to the agency. The CREATE Lab, too, has found Pittsburgh's air quality agency, the Allegheny County Health Department (ACHD), unreceptive to offers to convey Smell Pittsburgh reports directly to its online reporting.

The challenge of integrating first-person reporting platforms with the installed base of regulatory reporting systems is one barrier to their becoming infrastructure. But even if the technologies were integrated, disaster responders would have to determine how to cope with the new data within their existing routines and protocols for dealing with citizens' reports. If a regulatory agency is obliged to follow up on every report that it receives—as one CREATE Lab staff member suspects the ACHD is—then an app like Smell My City that generates a large number of reports presents a problem. It puts responders in the position of either being chronically backlogged or having to create new procedures for choosing a subset of reports to follow up on. Routines for follow-up also seemed to be at stake in our conversations with BAAQMD about AWBA reporting. BAAQMD staff trusted their reporting form to provide the right information for the agency to be able to respond; they seem concerned that reports coming in through other sources would either lack important context, or not make it to them in a timely manner.

These issues of follow-up are dealt with explicitly in the IVAN program. Each community that hosts an IVAN online reporting platform also has a Task Force, consisting of representatives of EJ organizations, other community organizations, and staff from government agencies. Each task force meets monthly to decide together how to follow up on reports, and to make sure that issues that have come up through the reports are resolved (Jatkar and London 2015). In the process, Task Force members learn the routines, expectations, and categories of disaster responders' communities of practice:

> Environmental justice advocates and community leaders learn what kind of information is most useful to public agencies in order to investigate the environmental problems reported.... Additionally, community partners involved with IVAN better recognize the range of public agencies and the issues they handle (Jatkar and London 2015, p. 5).

By learning other aspects of disaster infrastructure—such as what information regulators can act on and how hazards are classified as falling under the jurisdiction of one public agency or another—community members and EJ activists are able to build bridges between the IVAN reporting system and the installed base of disaster infrastructure. Despite the lack of technological integration between IVAN and regulatory reporting systems, then, IVAN networks could well be considered part of the infrastructure for responding to the slow disaster of chronic chemical hazards, precisely because their data have meaning for communities of practice—the Task Forces—dedicated to managing and preventing disaster.

REAL-TIME MONITORING

Real-time monitors use optical techniques to determine concentrations of pollutants in the ambient air without ever taking a sample or involving a laboratory. They run continuously, generating a new reading or set of readings every one to five minutes, depending on the monitor and its configuration. Results are reported immediately to a website, app, or both. Residents of fenceline communities, and other areas where real-time monitors are installed, can view fluctuations in pollution as they happen, and they will often check on the monitoring data when they observe a problem with air quality, like a chemical smell or a smoky haze. Real-time fenceline monitors, installed by oil refineries in Northern California, primarily measure toxic gases such as benzene and hydrogen sulfide. PurpleAir monitors measure particulate matter and are installed on individual homes.

Unlike event sampling and first-person reporting, real-time monitoring supplements rather than duplicates the installed base of disaster infrastructure. Neither environmental regulators nor agencies responsible for emergency response typically conduct continuous monitoring for individual toxic gases. If they monitor for these pollutants at all, they take 24-hour canister samples to yield long-term averages. Twenty-four hour samples are also the norm for regulatory monitoring of particulate matter, although the EPA has been experimenting with continuous particulate monitoring technology, as in its Village Green project. In addition to providing information about fluctuations in air quality, real-time monitoring fills spatial gaps. Fenceline monitoring is targeted to areas that regulatory monitoring tends to avoid, and the inexpensive PurpleAir monitors enable fine-grained coverage of areas in between official monitoring stations.

Continuous monitors face the challenge of becoming relevant to practices of emergency response and air quality management. The Valero refinery in Benicia, California has one of the newest fenceline monitoring systems in the area, installed in 2018 to meet a new regulatory requirement. When asked how its data would be used in emergency response, Benicia's fire chief said that high readings from the monitors would not automatically trigger a community warning, but the data would be taken into account along with other information. His lack of specificity suggests not only that a high degree of judgment is required of emergency responders reacting to a crisis, as one would expect, but also that standard operating procedures for dealing with fenceline data may have yet to emerge.

Designers of the Fenceline at the refinery in Rodeo took pains to integrate its data with emergency response routines from the time it was first installed. The 1996 memorandum of understanding detailing the technical specifications of the first-of-its-kind monitoring system includes a provision for establishing alarm levels "which could trigger the use of the various elements of the community warning system" (CWS). The refinery, county, and community groups were all involved in setting those levels. Twenty-five years later, a small group of dedicated residents continues to meet quarterly with refinery officials and county representatives to oversee the Fenceline, and this group has been instrumental in reinforcing the connections between monitoring data and the CWS. After a 2012 hydrogen sulfide release that sickened numerous residents, they lowered the alarm level to better correspond to the concentrations being reported by the Fenceline when widespread health effects occurred. Subsequently, residents on the committee used the alarm levels to call the refinery out for its failure to report consequential releases to the county so that the CWS could be triggered.

In this case, real-time monitoring data is being integrated with disaster infrastructures in large part through the inclusion of residents in a community of practice with disaster responders from government and industry, around the operations of the Fenceline. This approach, which has not been replicated in other communities with fenceline monitoring systems, has its limitations. Alerts are not automated; it remains up to refinery personnel to notice and act on Fenceline readings. The fact that residents need to continue to pressure them to do so suggests that they have not fully routinized their use of real-time data. Further, the Fenceline has become (partially) infrastructural only in the context of emergency response to industrial releases. There have not been comparable inroads into making fenceline monitoring data relevant to the management of slow disaster—that is, the routines of non-emergency environmental protection and enforcement. This is partly because slow disaster infrastructures do not include ambient air standards for most of the pollutants measured by fenceline monitors. For fenceline data to be incorporated into air quality protection, some accepted means for contextualizing them would also have to be built into the infrastructure.

PurpleAir measurements of particulate matter (PM) are more obviously relevant to disaster infrastructures. PM concentrations are regulated by the U.S. Clean Air Act; they are reflected in the Air Quality Index; and their adverse health effects are widely acknowledged. The relevance of PM data, the widespread popularity of PurpleAir monitors, and the EPA's growing interest in citizen science (National Advisory Council for Environmental Policy and Technology 2016) may be among the reasons that environmental regulators have made active efforts to incorporate PurpleAir data into air quality infrastructures.

Even before PurpleAir launched in 2015, the EPA's Office of Research and Development was assessing the quality and reliability of low-cost air sensors. The connection between these efforts and the EPA's installed base was made explicit in a presentation by EPA staff member Kristen Benedict to a July 2015 "Community Air Monitoring Training" event. Benedict stressed the fundamental incommensurability between one-minute readings, like those generated by many low-cost particulate monitors, and the AQI, which was designed for longer averaging times. She then described work her group had been doing to give meaning to short-term data, using statistical methods to predict whether a high one-minute reading could indicate a health concern over a longer period. Although her study was still in progress, this work aimed at integrating new, citizen-oriented monitoring into the EPA's air monitoring and health messaging infrastructures.

More recently, EPA staff has focused specifically on how to understand and incorporate PurpleAir data. Researchers from the agency, with local agency partners, conducted a study that co-located PurpleAir and regulatory monitors at a variety of sites across the U.S. and compared their data (Johnson and Holder et al. 2020). Ultimately, they developed a correction equation that could be applied to PurpleAir data (Johnson and Frederick et al. 2020). With the development of the correction factor, the EPA began to include PurpleAir data in its AirNow platform as part of a Smoke and Fire Map launched during the 2020 wildfire season (Stark 2020a). Color-coding PurpleAir data according to AQI categories, the Smoke and Fire Map grafts PurpleAir monitors onto the installed base. More than other citizen-led representations of air quality, the low-cost PM monitors are becoming infrastructure.

CONCLUSION: INTEGRATING CITIZEN SCIENCE INTO DISASTER INFRASTRUCTURE

There has been significant optimism that citizen science of many sorts can make important contributions to disaster infrastructure. My research on community-led efforts to generate new data about air quality—representing both chemical releases and the slow disaster of toxic exposures—complicates this hope. Monitoring systems, sensor networks, and crowdsourcing platforms do not in themselves constitute infrastructure. To earn that status, they need to become a taken-for-granted part of the shared routines of a community of practice. To be considered disaster infrastructure in particular, community-led air monitoring projects would need to be part of the routines of communities of practice charged with responding to air quality emergencies, managing air pollution, or both.

The research presented here shows that few projects initiated by fenceline communities have become fully part of the disaster infrastructure surrounding air quality. Event sampling with buckets and most first-person reporting platforms have remained detached from disaster response routines, informing regulators and emergency responders in only marginal or ad hoc ways. The IVAN network and fenceline monitoring have been partially integrated into disaster infrastructure. In both cases, their success has been underpinned by the conscious creation of a community of practice that includes residents and disaster authorities; moreover, these communities of practice have been engaged in the ongoing work of setting standards for what should be responded to, and how. PurpleAir monitors have been most thoroughly integrated into disaster infrastructure, largely because EPA scientists have worked to render them compatible with the installed base, which includes regulatory monitors, AirNow, and the AQI.

More importantly, this research demonstrates that incorporating citizen science into disaster infrastructure takes thoughtful, deliberate work. Disaster responders need to engage with citizen scientists. Those looking to create new sensor networks or crowdsourcing platforms as part of disaster infrastructure should simultaneously be creating expanded, heterogeneous communities of practice for disaster response, similar to the IVAN Task Forces. The information created by citizen scientists is unlikely to be mobilized by disaster responders in the absence of a mutual understanding of how it will inform action, and the development of routines for putting it into service. Building bridges between the installed base and new sources of information is also essential.

This work is most straightforward when new data are commensurate with existing standards. PurpleAir monitors, for example, required only a correlation equation to be folded into the EPA's apparatus for measuring particulate matter and communicating health risks. Citizen science strategies that involve the creation of new categories of data—for example, Smell My City's smell rating scale or the Fenceline's one-minute readings of ambient concentrations of air toxins—will necessitate the development of new standards for distinguishing normal conditions from worrisome ones, and new courses of action for responding to the latter. Communities who initiate monitoring from outside established disaster infrastructures can push for these bridges to be built, as the Fenceline's early proponents did when they established the expectation that fenceline monitoring data would be linked to community warning system alert levels. Ultimately, though, they depend on the recognition and participation of officials with the authority to prevent or manage disasters.

To say that citizen science—especially community-led, social movement–based citizen science—struggles to become part of disaster infrastructure is by no means to denigrate its importance for communities plagued by air pollution. In some fenceline communities, bucket air samplers have become integral to the routines of organizing for industrial safety and tougher environmental rules. Smell Pittsburgh has attracted a thriving, engaged group of users and raised public awareness of air quality issues. And the iWitness Pollution Map brought regulatory scrutiny to chemical releases from the IMTT petrochemical storage facility in St. Rose, Louisiana in 2014—after a community activist thrust printouts of 375 first-person reports into the hands of then-EPA Administrator Gina McCarthy. Nonetheless, these community-led efforts have the potential for even greater impact if regulators, emergency responders, community members, and their allies are deliberate about integrating them into disaster infrastructure.

ETHICS AND CONSENT

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The author has no competing interests to declare.

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REFERENCES

Ahlers, CD. 2016. Race, ethnicity, and air pollution: New directions in environmental justice. *Environmental Law*, 46(4): 713–758.

Ali, N and **Islam, F.** 2020. The effects of air pollution on COVID-19 mortality and infection: A review on recent evidence. *Frontiers in Public Health*, 8: 580057. DOI: https://doi.org/10.3389/fpubh.2020.580057

Berton, J, Fagan, K and **Ho, V.** 2012. Blasts, flares hit refinery; East Bay residents told to stay inside as thick smoke spews into sky from Chevron plant. *San Francisco Chronicle*. August 7.

Bowker, GC and **Star, SL.** 1999. *Sorting things out: Classification and its consequences*. Cambridge, MA: The MIT Press. DOI: https://doi.org/10.7551/mitpress/6352.001.0001

Bowser, A and **Shanley, L.** 2013. *New visions in citizen science*. Washington, DC: Woodrow Wilson International Center for Scholars.

Brown, A, Franken, P, Bonner, S, Dolezal, N and **Moross, J.** 2016. Safecast: Succesful citizen-science monitoring for radiation measurement and communication after fukushima. *Society for Radiological Protection*, 36: S82–S101. DOI: https://doi.org/10.1088/0952-4746/36/2/S82

Bulwa, D and **Kane, W.** 2012. Refinery smoke blew past air monitors. *SFGate*. August 29.

Chari, R, Sayers, ELP, Amiri, S, Leinhos, M, Kotzias, V, Madrigano, J, Thomas, EV, Carbone, EG and **Uscher-Pines, L.** 2019. Enhancing community preparedness: An inventory and analysis of disaster citizen science activities. *BMC Public Health*, 19: 1356. DOI: https://doi.org/10.1186/s12889-019-7689-x

Cieslik, K, Shakya, P, Uprety, M, Dewulf, A, Russell, C, Clark, J, Dhital, MR and **Dhakal, A.** 2019. Building resilience to chronic landslide hazard through citizen science. *Frontiers in Earth Science*, 7: 278. DOI: https://doi.org/10.3389/feart.2019.00278

Fimrite, P and **Kane, W.** 2012. Richmond air quality safe, analysis says. *San Francisco Chronicle*. August 8.

Fortun, K. 2001. *Advocacy after Bhopal: Environmentalism, disaster, new global orders*. Chicago: University of Chicago Press. DOI: https://doi.org/10.7208/chicago/9780226257181.001.0001

Gunkelman, J and **Bardet, M.** 2012. Residents have a right to know what is in the air. *SFGate*. August 21. [https://www.sfgate.com/opinion/openforum/article/Residents-have-right-to-know-what-is-in-the-air-3802444.php, January 28, 2021].

Hemmi, A and **Graham, I.** 2014. Hacker science versus closed science: Building environmental monitoring infrastructure. *Information, Communication, and Society*, 17(7): 830–842. DOI: https://doi.org/10.1080/1369118X.2013.848918

Hicks, A, Barclay, J, Chilvers, J, Armijos, MT, Oven, K, Simmons, P and **Haklay, M.** 2019. Global mapping of citizen science projects for disaster risk reduction. *Frontiers in Earth Science*, 7: 226. DOI: https://doi.org/10.3389/feart.2019.00226

Hsu, Y-C, Cross, J, Dille, P, Tasota, M, Dias, B, Sargent, R, Huang, T-H and **Nourbakhsh, I.** 2020. Smell Pittsburgh: Engaging community citizen science for air quality. *ACM Transactions on Interactive Intelligent Systems*, 10(4). DOI: https://doi.org/10.1145/3369397

Hultquist, C and **Cervone, G.** 2018. Citizen monitoring during hazards: Validation of Fukushima radiation measurements. *GeoJournal*, 83: 189–206. DOI: https://doi.org/10.1007/s10708-017-9767-x

Jacobs, ET, Burgess, JL and **Abbott, MB.** 2018. The Donora smog revisited: 70 years after the event that inspired the Clean Air Act. *American Journal of Public Health*, 108(S2): S85–S88. DOI: https://doi.org/10.2105/AJPH.2017.304219

Jatkar, S and **London, JK.** 2015. *From testimony to transformation: The Identifying Violations Affecting Neighborhoods (IVAN) program in California*. Davis, CA: UC Davis Center for Regional Change.

Johnson, K, Frederick, S, Holder, A and **Clements, A.** 2020. Air Sensors: PurpleAir, AirNow Fire and Smoke Map, and their use internationally. U.S. State Department Embassy Fellows Program Monthly Virtual Meeting, Durham, NC, December 03, 2020

Johnson, K, Holder, A, Frederick, S, Hagler, G and **Clements, A.** 2020. PurpleAir PM2.5 performance across the U.S.#2. Meeting between ORD, OAR/AirNow, and USFS, Research Triangle Park, NC, February 3. [https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=CEMM&dirEntryId=348236, March 16, 2021].

Kenner, A. 2018. *Breathtaking: Asthma care in a time of climate change*. Minneapolis: University of Minnesota Press. DOI: https://doi.org/10.5749/j.ctv69ssz2

Knowles, S. 2014. Learning from disaster? The history of technology and the future of disaster research. *Technology and Culture*, 55(4): 773–784. DOI: https://doi.org/10.1353/tech.2014.0110

Kullenberg, C. 2015. Citizen science as resistance: Crossing the boundary between reference and representation. *Journal of Resistance Studies*, 1(1): 50–76.

Landrigan, PL, Lioy, PJ, Thurston, G, Berkowitz, G, Chen, LC, Chillrud, SN, Gavett, SH, Georgopoulos, PG, Geyh, AS, Levin, S, Perera, F, Rappaport, SM, Small, C and **NIEHS Trade Center Working Group.** 2004. Health and environmental consequences of the world trade center disaster. *Environmental Health Perspectives*, 112(6): 731–739. DOI: https://doi.org/10.1289/ehp.6702

Lave, J and **Wenger, E.** 1991. *Situated learning: Legitimate peripheral participation*. Cambridge: Cambridge University Press. DOI: https://doi.org/10.1017/CBO9780511815355

Liu, Y, Priyawongwisal, P, Handa, S, Yu, L, Xu, Y and **Samuel, A.** 2011. Going beyond citizen data collection with Mapster: A mobile+cloud real-time citizen science experiment. *IEEE Seventh International Conference on e-Science Workshops*, Stockholm, Sweden. DOI: https://doi.org/10.1109/eScienceW.2011.23

Mah, A. 2017. Environmental justice in the age of big data: Challenging toxic blind spots of voice, speed, and expertise. *Environmental Sociology*, 3(2): 122–133. DOI: https://doi.org/10.1080/23251042.2016.1220849

McCormick, S. 2012. After the cap: Risk assessment, citizen science, and disaster recovery. *Ecology and Society*, 17(4): 31. DOI: https://doi.org/10.5751/ES-05263-170431

National Advisory Council for Environmental Policy and Technology. 2016. *Environmental protection belongs to the public: A vision for citizen science at EPA*.

O'Rourke, D and **Macey, GP.** 2003. Community environmental policing: Assessing new strategies of public participation in environmental regulation. *Journal of Policy Analysis and Management*, 22(3): 383–414. DOI: https://doi.org/10.1002/pam.10138

Ottinger, G. 2009. Epistemic fencelines: Air monitoring instruments and expert-resident boundaries. *Spontaneous Generations*, 3(1): 55–67. DOI: https://doi.org/10.4245/sponge.v3i1.6115

Ottinger, G. 2010. Buckets of resistance: Standards and the effectiveness of citizen science. *Science, Technology, and Human Values*, 35(2): 244–270. DOI: https://doi.org/10.1177/0162243909337121

Ottinger, G. 2013. *Refining expertise: How responsible engineers subvert environmental justice challenges*. New York: New York University Press. DOI: https://doi.org/10.18574/nyu/9780814762370.001.0001

Ottinger, G. 2016. Citizen Engineers at the Fenceline. *Issues in Science and Technology*, 32(2): 72–78.

Paul, JD, Buytaert, W, Allen, S, Ballesteros-Cánovas, Bhusal, J, Cieslik, K, Clark, J, Dugar, S, Hannah, DM, Stoffel, M, Dewulf, A, Dhital, MR, Liu, W, Nayaval, JL, Neupane, B, Shiller, A, Smith, PJ and **Supper, R.** 2017. Citizen science for hydrological risk reduction and resilience building. *WIREs Water*, 5(1): e1262. DOI: https://doi.org/10.1002/wat2.1262

Peters, A. 2020. How this small sensor startup became essential to helping California deal with toxic wildfire smoke. *Fast Company*. August 27. [https://www.fastcompany.com/90543956/how-this-small-sensor-startup-became-essential-to-helping-california-deal-with-toxic-wildfire-smoke#:~:text=Dybwad%2C%20based%20in%20Salt%20Lake,gravel%20mine%20nearly%20every%20day, September 23, 2020].

Polleri, M. 2019. Conflictual collaboration: Citizen science and the governance of radioactive contamination after the Fukushima nuclear disaster. *American Ethnologist*, 46(2): 214–226. DOI: https://doi.org/10.1111/amet.12763

Reges, HW, Doesken, N, Turner, J, Newman, N, Bergantino, A and **Schwalbe, Z.** 2016. CoCoRaHS: The evolution and accomplishments of a volunteer rain gauge network. *Bulletin of the American Meteorological Society*, 97(10): 1831–1846. DOI: https://doi.org/10.1175/BAMS-D-14-00213.1

Shapiro, N, Zakariya, N and **Roberts, JA.** 2017. A wary alliance: From enumerating the environment to inviting apprehension. *Engaging Science, Technology, and Society*, 3: 575–602. DOI: https://doi.org/10.17351/ests2017.133

Slater, D. 1995. Something scary in the air. *East Bay Express*, 1: 10–22. September 22.

Star, SL and **Ruhleder, K.** 1996. Steps towards an ecology of infrastructure. *Information Systems Research*, 7(1): 111–134. DOI: https://doi.org/10.1287/isre.7.1.111

Stark, K. 2020a. Making sense of Purple Air vs AirNow, and a new map to rule them all. *KQED*. September 4. [https://www.kqed.org/science/1969271/making-sense-of-purple-air-vs-airnow-and-a-new-map-to-rule-them-all, January 25, 2021].

Stark, K. 2020b. Smoke from California's record wildfires is its own disaster. *KQED*. September 22. [https://www.kqed.org/science/1969739/smoke-from-californias-record-wildfires-is-its-own-disaster, March 3, 2021].

Suman, AB. 2020. *Sensing the risk: A case for integrating citizen sensing into risk governance*. Open Press TiU.

Tierney, K. 2012. Disaster governance: Social, political, and economic dimensions. *Annual Review of Environment and Resources*, 37: 341–63. DOI: https://doi.org/10.1146/annurev-environ-020911-095618

US Chemical Safety and Hazard Investigation Board. 2015. *Final investigation report: Chevron Richmond refinery pipe rupture and fire*. Report No. 2012-03-I-CA.

Wenger, E. 2000. *Communities of practice: Learning, meaning, and identity*. Cambridge: Cambridge University Press.

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