Modeling on-site wastewater treatment system performance fragility to hydroclimate stressors

Laura E. Kohler, JoAnn Silverstein and Balaji Rajagopalan

ABSTRACT

Increasing variability of climate-related factors, especially precipitation and temperature, poses special risks to on-site wastewater treatment systems (OWTS), which depend on subsurface saturation conditions for treatment and dispersion of wastewater. We assess OWTS *fragility* – the degree to which a system loses functionality – as a step to characterizing the resilience of residential wastewater treatment systems. We used the frequency and indexed severity of OWTS failures and resulting repairs to quantify fragility as a function of hydroclimate variables, including precipitation, temperature and stream flow. The frequency of each category of repair (minor, moderate and major) for 225 OWTS obtained from Boulder County public health records was modeled as a function of climate factors using a generalized linear model with a Poisson distribution link function. The results show that prolonged precipitation patterns, with monthly rainfall >10.16 cm, influence OWTS fragility, and complete loss of OWTS functionality, requiring replacement, is impacted by high temperatures, frequency of wetter-than-normal months, and the magnitude of peak stream flow in the watershed. Weather-related covariates explained 70% of the variability in OWTS major repair data between 1979 and 2006. These results indicate that fragility arising from climate factors, and associated costs to owners, environmental and health impacts, should be considered in planning, design and operation of OWTS.

Key words | on-site wastewater treatment systems, resilience, septic systems, weather effects

Laura E. Kohler (corresponding author)
JoAnn Silverstein
Balaji Rajagopalan
Civil, Environmental, and Architectural Engineering,
University of Colorado,
428 UCB,
Boulder,
CO 80309,
USA
E-mail: *laura.kohler@colorado.edu*

Balaji Rajagopalan
Cooperative Institute for Research in Environmental Sciences,
University of Colorado,
428 UCB,
Boulder,
CO 80309,
USA

INTRODUCTION

Increasing climate variability and related weather patterns threaten both the physical and functional integrity of infrastructure including wastewater collection and treatment systems. Subsurface components of these systems are particularly vulnerable to flooding and soil saturation conditions. Clogging and loss of percolation in the soil treatment unit (STU) of on-site wastewater treatment systems (OWTS) have been identified as a major factor determining OWTS performance (McKinley & Siegrist 2011). In a survey of 45 local OWTS regulatory agencies in California, 96% reported using effluent surfacing in the STU as an indicator of malfunction; the secondary effect of STU failure, sewage backup, was used by 84% of the agencies (California Wastewater Training and Research Center & USEPA 2003). Moreover, delays in recovery from failures pose risks to the public and environment through prolonged exposure to wastewater constituents through direct contact with released wastewater, groundwater and drinking water supplies. During Hurricane Sandy, for instance, 11 billion gallons of untreated and partially treated sewage flowed into rivers, bays, canals, and in some cases city streets, a consequence of record storm-surge flooding (Kenward *et al.* 2013). However, less attention has been paid to weather-related damage to OWTS although those systems serve 25% of the US population and 10–40% of the population in Sandy-affected states (EPA 2002). While the association is widely acknowledged (Amador *et al.* 2014), no quantitative analysis of the relationship between weather and OWTS failure exists (Amador *et al.* 2014; UNICEF & GWP 2014; Morales *et al.* 2015, 2016).

Use of OWTS is increasing beyond its rural origins, with over 30% of new developments served by on-site technologies (EPA 2002). Outside of the USA, on-site technology is leveraged to provide sanitation services in communities that either currently use unimproved facilities or have no access to safe disposal of fecal waste (WHO & UNICEF

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2015). Even under normal environmental conditions, the failure rate of OWTS is significant – as high as 50% in some regions of the USA. More variable precipitation (both rainfall and snow equivalents) and flooding events heighten the risk of failure of sanitation systems dependent on underground storage tanks and subsurface discharge through unsaturated soil (Kirtman *et al.* 2013). Therefore assessment of the response of OWTS to weather-related variables should be an important component to planning and design of these systems. To enable informed decisions, we consider the link between OWTS performance and weather patterns in a resilience framework.

Bruneau *et al.* (2003) characterizes resilience as determined by four system properties: robustness, rapidity, redundancy, and resourcefulness. While all four properties affect resilience, system vulnerability to external stressors and the degree a system loses functionality can directly affect the time and resources required to recover performance. Therefore, we focus on *fragility* – the difference between 100% of the expected level of OWTS performance and robustness, which is the level of performance after a significant perturbation (Figure 1). McDougall (2009) further breaks down fragility into *design* and *natural fragility*. Natural fragility describes the distribution of infrastructure system performance outcomes, i.e. failure frequency and the degree of failure, when operations are outside of conditions assumed by the engineer; design fragility of OWTS has been the object of a number of studies (e.g. McKinley & Siegrist 2011). Kohler *et al.* (2016a, 2016b) have studied OWTS fragility related to maintenance and regulatory factors. Natural fragility reflects performance reliability under real world conditions, compared to reliability under purely designed conditions (McDougall 2009). We hypothesize that OWTS natural fragility, expressed as the frequency distribution of failure events, is associated with weather patterns, especially those that affect soil saturation and clogging conditions in the STU. The integrity of underground septic tanks also is subject to groundwater conditions via infiltration and cracking resulting from soil pressure changes.

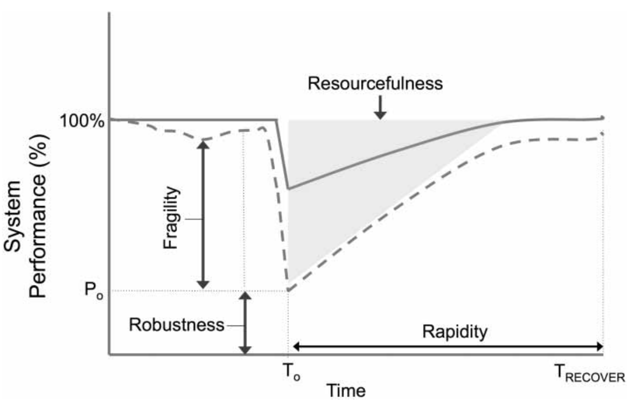

Figure 1 | Conceptual framework for resilience measurement (adapted from Bonstrom & Corotis (2014)).

We use documented OWTS repairs in Boulder County, Colorado, USA, ranked in a severity index, as the measure of OWTS failure. A generalized linear model (GLM) regression method is then used to evaluate the association of natural fragility, hereinafter shortened to *fragility*, with local temperature, rainfall and stream flow conditions over a range of time scales.

METHODS

Data

Repair permit data were collected for 225 OWTS in the Boulder–St Vrain Creek watershed in northeastern Colorado, maintained by the Boulder County Public Health Department. The geographic distribution of the OWTS sample is shown in Figure 2. The sample represents an overall OWTS population of 14,300 and encompasses the full range of topographic and demographic characteristics of Boulder County. Only OWTS with County-approved permits meeting design regulations were included in the sample, although approximately one-third of the Boulder County OWTS, typically older systems, are not permitted. Thus all of the sample OWTS met regulations regarding minimum distance to the water table (at the time of installation), set backs from surface waters, area, and soil percolation conditions (Boulder County 2014).

Variable definition

Dependent variable

The frequency of repairs over the period of record from 1979 to 2015 is the fragility measure. While not all repairs are associated with a complete failure and associated visible contaminant release, the frequency and the severity of repairs provide a measure of decrease in system performance.

Each documented repair is classified into minor, moderate, and major categories, based on a rating system used by the Boulder County Public Health (BCPH) Department (Kohler *et al.* 2016a, 2016b) and recorded for the 225

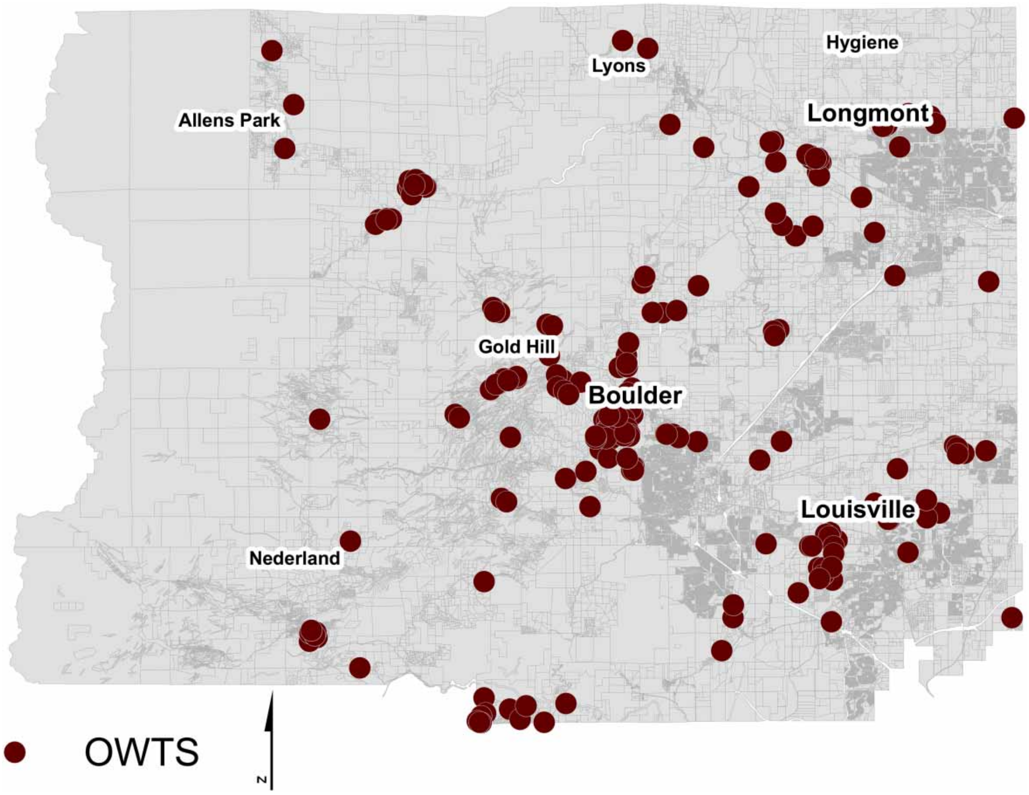

Figure 2 | Geographic distribution of OWTS in Boulder County, Colorado. Communities west of Boulder are located in the foothills with more-sloped terrains, highest elevation ~2,500 m, whereas communities to the east are in the high plains, elevation ~1,500 m. Elevation change occurs over a distance of approximately 50 km.

OWTS in the sample. A minor repair is any repair to the septic tank or lateral pipes. Moderate repairs refer to replacement of the STU. Failure of both the septic tank and STU constitutes a major repair often requiring replacement of the entire system. The dependent variable, *annual repairs*, is the annual sample frequency of each type of repair. The distribution of each type of repair serves as an indicator of fragility for the sample population. Failures associated with minor and moderate repairs exhibit partial losses of function and lower degrees of fragility, whereas major repairs result from a near complete loss of performance, representing the highest degree of fragility. Similar to Kohler *et al.* (2016a, 2016b), the sample consists of only permitted OWTS to control for compliance with siting, design, and installation criteria set by the County.

Figure 3 shows the distribution of each category of repair over the period of record from 1979 to 2015, indicating an increased repair frequency starting in 2007. Between 2007 and 2008, BCPH reformed their practices regulating OWTS installation, permitting and maintenance. The county initiated the EPA Septic Smart program with a goal to inspect and approve permits for all OWTS in the County by December 31, 2023. More important, in 2008, the County adopted a new regulation, enforcing professional system assessments, and required repairs at the time of any property sale (Septic Smart Program 2015). Based on information from the County, we resolved that the rise in repairs after 2007, apparent in Figure 3, reflects increased frequency of reporting after the County's initiative to permit systems and add a regulation. The association of this factor with repair severity was determined earlier (Kohler *et al.* 2016a, 2016b). Thus for fragility modeling we use data until 2006, removing the period of the trend that is mainly a result of policy actions and not climate related.

Independent variables

Both temperature and precipitation, where precipitation is defined as both rainfall and snow, have recognized effects on OWTS performance. Temperature extremes can affect biological activity, flow and mixing within the primary treatment unit (septic tank or vault) and treatment processes in the biomat of the STU. For example, when temperatures are less than 5 °C the bacterial removal rate of *Escherichia*

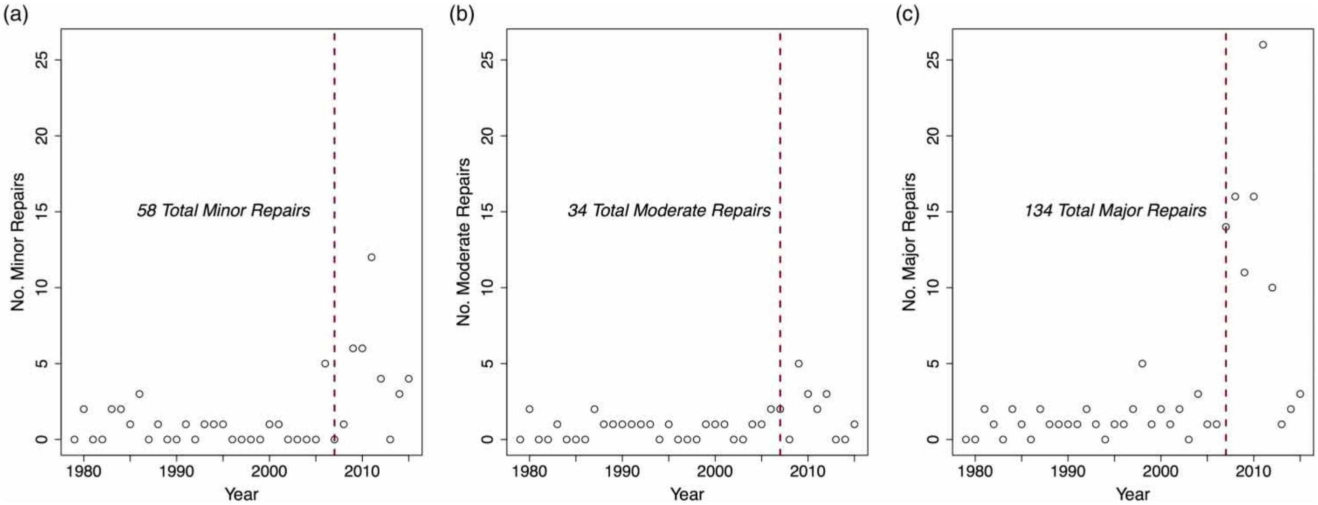

Figure 3 | Frequency distribution of minor (a), moderate (b), and major (c) repairs from 1979 to 2015. The dashed vertical line indicates the introduction of Septic Smart and a new inspection regulation in 2007. Consequently, this study focuses on the frequency of each class of repair in each year from 1979 to 2006.

coli in the STU has been estimated at less than 20%, whereas temperatures closer to 20 °C have three times the removal rate (Morales *et al.* 2015). Additionally, Luostarinen *et al.* (2005, 2007) confirm that low temperature extremes inhibit upflow anaerobic sludge blanket septic tanks in removing suspended solids and dissolved organic material.

Precipitation can have a physical and therefore visible impact from excess hydraulic loading during high rainfall and snowmelt events above the level set out in design criteria for the STU. Groundwater infiltration and inflow through inadequately sealed covers can cause septic tank overflows, resulting in STU clogging as well as physical damage to the STU (Morales *et al.* 2015). A Google search for ‘rainfall effects on septic systems’ returned 335,000 results, confirming the impact of rainfall and snowmelt on septic system function. These websites primarily provide instructions to homeowners on how to diagnose, mitigate and recover from heavy rainfall events. FloHawks Plumbing & Septic, Inc., for instance, posted on the implications of high intensity rainfall and snowmelt events, cautioning homeowners about septic system use after such events as well as providing practical measures to mitigate long term system damage, such as conserving water and limiting usage during events and diverting rain flows from the STU (FloHawks Plumbing & Septic 2015). Less visible impacts include the reduction of vertical separation distances between the OWTS and water table as well as increased transport of nutrients and pathogens through soil.

Annual temperature and precipitation profiles for the study location were obtained from the National Climatic Data Center of NOAA (NCDC 2015). The number of months with precipitation totals over 10.16 cm (4.0 inches) was selected to represent prolonged wetter-than-average soil conditions with the associated effects on OWTS failure described earlier. As a reference, in Boulder County April and May are typically the wettest months with precipitation totals of 6.22 cm (2.45 inches) and 7.75 cm (3.05 inches), respectively, from 1948 to 2005 (Desert Research Institute 2005). Monthly rainfall totals over 10.16 cm have occurred only 43 times in a 38-year period (a less than 10% probability of occurrence). The frequency of days with precipitation over 1.2 cm were included to capture the effects due to severe single rainstorm events that occur over a shorter period of time and impact the system through surface runoff.

Annual peak stream flow is selected as another independent variable based on its contribution to shallow groundwater levels through interflow (data from USGS gage 06730500). Annual peak stream flow is considered a proxy for increased groundwater levels which can influence the performance of OWTS reliant on buried storage tanks and subsurface discharge through unsaturated soil. While the interaction mechanisms between groundwater and surface water are complex, hydrographs are commonly used to estimate groundwater recharge either directly or using water balance models (Mau & Winter 1997; Sophocleous 2002; Yeh *et al.* 2007). Stream flow, being an integrator of precipitation, soil moisture and watershed response, is an excellent indicator for subsurface conditions.

Table 1 lists each variable. The variables coded with ‘_S’ are recorded from April to October to capture rainfall precipitation versus the annual total, which includes snow equivalents.

Table 1 | Annual frequency and severity of precipitation and temperature independent variables

	Code	Explanation
Frequency of temperature extremes	DT90	No. of days per year with maximum temperature greater than or equal to 32 °C (90 °F)
	DT00	No. of days per year with minimum temperature less than or equal to −18 °C (0 °F)
Frequency and magnitude of precipitation	DP05_S	No. of days per year with precipitation greater than or equal to 1.2 cm (0.5 in) (Apr–Oct)
	TPCP	Total annual precipitation in centimetres (inches)
	MR40_S	No. of months per year with monthly precipitation totals above 10.16 cm (4.0 inches) (Apr–Oct)
Surface/groundwater flows	PEAK_FL	Annual peak flow in m^3/s (cubic feet per second)

Model development

We propose to use a GLM to model the fragility, i.e. response repair frequency, Y, as a function of hydroclimate variables identified above. GLMs are finding wide application due to their flexibility in modeling non-Gaussian features and ease of implementation – such as for space–time weather generation (Verdin *et al.* 2015), wastewater quality modeling and resiliency (Weirich *et al.* 2015), and recently to OWTS repair magnitude (Kohler *et al.* 2016a, 2016b).

As the time of introduction of Septic Smart and the inspection regulation are known, we break the time series data into two regions – pre- and post-Septic Smart, as mentioned above. Assuming the repair reporting requirements were constant before 2007, we consider the occurrence of OWTS repairs in each year from 1979 to 2006 for all 225 systems; the response variable Y for all 225 systems is, consequently, an annual count of repairs in a certain class.

In the GLM, the response variable, Y, is allowed to be a realization from any distribution in the exponential family.

$$Y \sim G(\boldsymbol{\theta}) \tag{1}$$

where G is any exponential type distribution and $\boldsymbol{\theta}$ is the set of parameters that define G. Assuming a Poisson distribution reduces the GLM to a Poisson regression model with parameter μ (McCullagh & Nelder 1989). The canonical link function for the Poisson distribution, the log link, is as follows:

$$Log(\mu) = \alpha + \boldsymbol{\beta X} \tag{2}$$

where μ is the expected value of Y, $E(Y)$. The log of μ is a linear function of the explanatory variable(s), $\boldsymbol{X}$, and a random component α. Consequently, μ is the product of the exponential functions of α and the product(s) $\boldsymbol{\beta X}$.

$$\mu = e^{\alpha+\boldsymbol{\beta X}} = e^{\alpha} e^{\boldsymbol{\beta X}} \tag{3}$$

The residuals are defined as:

$$\epsilon = Y - E(Y) \tag{4}$$

where ϵ is the set of model residuals. These are assumed to be normally distributed and uncorrelated as with a standard linear regression (McCullagh & Nelder 1989). $E(Y)$ is the expected value of the Y determined from the model.

The Akaike Information Criterion (AIC) selects a best model by considering all the possible subsets of the independent variables from the fit model. We have applied GLM models for all potential combinations of the variables shown in Table 1. The best performing model was selected using both a forward and backward fitting procedure, known as a stepwise comparision that selects the best fit by minimizing AIC. AIC minimizes the log-likelihood with a penalty for the number of model parameters (Akaike 1974).

RESULTS AND DISCUSSION

It can be seen from Table 2 that the expected number of repairs in a given year in each category is modulated by a combination of precipitation, temperature and precipitation-related attributes, namely the frequency of extreme temperatures (days over 32 °C), incidences of wet months (months with rainfall totals over 10.16 cm) and the magnitude of peak flows in Boulder Creek. Table 2 highlights the significant variables at 90% for each category of repair.

Given the log link function, a unit change in x has a multiplicative effect on μ (Agresti 2007). For ease of

Table 2 | Significant model coefficients

	Minor			**Moderate**			**Major**		
R^2	**0.38**			**0.53**			**0.70**		
	α	e^{α}	p	α	e^{α}	p	α	e^{α}	p
Intercept	−1.862	0.155	0.008	−0.932	0.394	0.074			
	β	e^{β}	p	β	e^{β}	p	β	e^{β}	p
DT90	0.047	1.048	0.007						
DT00									
TPCP									
DP05_S									
MR40_S							0.527	1.694	0.025
PEAK_FL				0.001	1.001	0.056	−0.001	0.999	0.022

R^2 is a statistical measure of how close the data are to the fitted regression and p indicates the level of significance of each independent variable in describing the Poisson parameter, μ. p-values less that 0.01 indicate variables that are significant at 90%

interpretation we included e^{β} in Table 2. Where $e^{\beta} > 1$, the variable increases the expectation of Y, and where $e^{\beta} < 1$, it decreases the expectation. If e^{β} is close or equal to 1, this means that the expected outcome is not related to the covariate, x.

For instance, for minor repairs, a unit increase in the number of days with temperatures exceeding 32 °C increases the expectation or mean number of repairs in a given year by a factor of 1.048. Therefore, the expectation of minor OWTS function losses can be described as:

$$\mu_{\text{minor}} = e^{-1.862} * e^{0.047 x_{\text{DT90}}} \quad (5)$$

High temperatures have been found to increase digestion during warmer months due to 'spring turnover' increasing both the amount of solids accumulation in the tank as well as the amount that leaves the tank due to interrupted settling (D'Amato 2008). While solids increase in warmer temperatures, settling and solids removal decrease often due to gas eruption during increased digestion (D'Amato 2008). Water-demanding activities, which often increase seasonally, can overwhelm septic tanks and increase the amount of solids entering the STU (Crites & Tchobanoglous 1998). Temperature extremes may not directly affect the integrity of the primary treatment unit; however, the physical consequences of temperature on septic tank processes, leading to clogging and/or solids overflow, often require maintenance services (D'Amato 2008). Furthermore, service providers typically assess the integrity of the system upon their visit, which may explain the correlation between minor repairs and temperature in that more damage is identified during these periods – tank and/or sewer damages that would have potentially gone unnoticed.

Moderate loss of performance seems to be associated with one variable, peak stream flow (PEAK_FL), which is an indicator of surface and subsurface moisture conditions through interflow. The GLM expectation of moderate function losses is:

$$\mu_{\text{moderate}} = e^{-0.932} * e^{0.001 * \text{PEAK\_FL}} \quad (6)$$

The influence of flow on moderate fragility is relatively small. Since e^{β} is nearly 1, this indicates that, in fact, the covariate has little influence on the expected number of moderate repairs in a year. Only when the peak flow is substantially high would we see an effect on expected repair. This is a reasonable relationship, given that the highest flows would influence the groundwater table level and in turn compromise performance of the STU. Surface runoff related to a high annual peak flow event may also influence the performance of the secondary treatment unit. This relationship is illustrated in Figure 4(b).

The highest degree of fragility – represented by major repairs – is associated with two variables, the occurrence of wet months, MR40_S, and PEAK_FL. The variables describe the expected number of major repairs in each year as:

$$\mu_{\text{major}} = e^{0.527 * \text{MR40\_S}} * e^{-0.001 * \text{PEAK\_FL}} \quad (7)$$

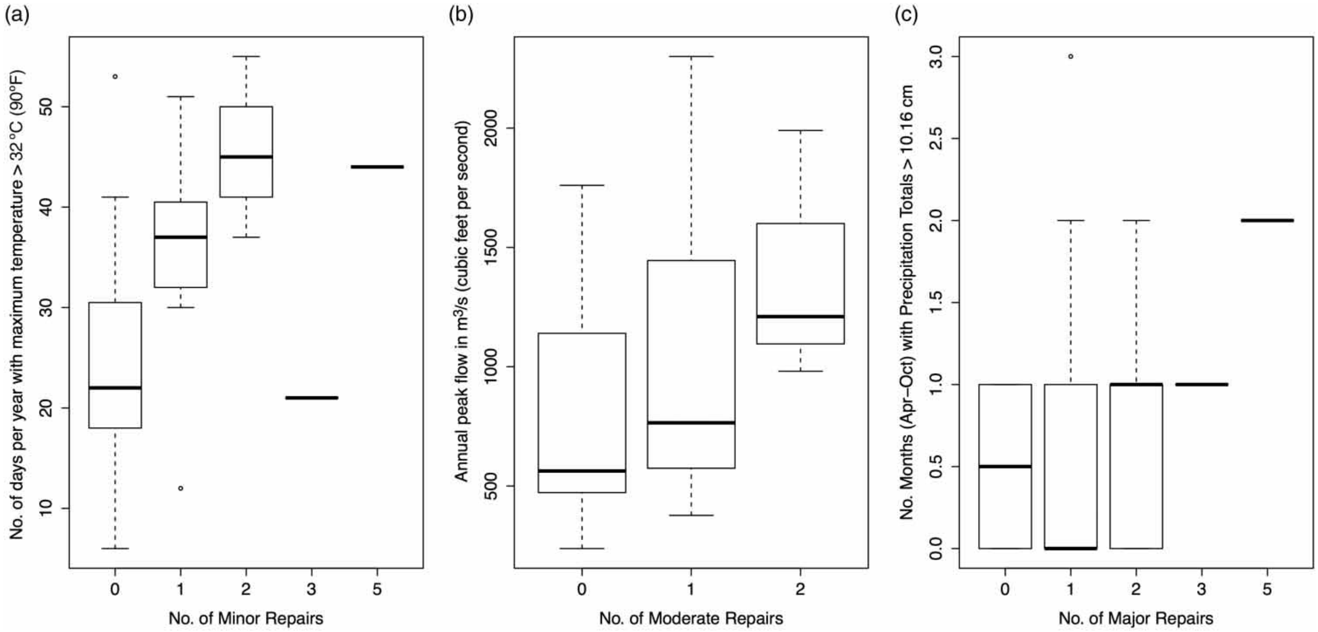

Figure 4 | Dependency of observed repair frequency on significant hydroclimate variables. (a) Minor repair frequency related to the number of days over 32 °C in a year. (b) Moderate repair frequency given increased annual peak flow. (c) Major repair frequency related to number of months in a year with totals over 10.16 cm.

A unit increase in the number of months with rainfall exceeding 10.16 cm increases the mean number of repairs in a given year by $1.694 = \exp(0.527)$, where a unit increase in the peak flow of Boulder Creek dampens the expected repair frequency by a factor of $0.999 = \exp(-0.0001)$, indicating that peak flow has little effect on the expected mean number of repairs. In extremely wet months, saturated soil conditions impact infiltration of septic tank effluent.

Figure 4 illustrates the relationships between the covariates identified as having the strongest influence on the frequency of each class of repair in a given year and the observed frequency of each repair type. The frequency of each repair type increases as the covariate increases, supporting the coefficient estimates output by the GLM analysis.

Figure 5(a) specifically shows the total precipitation each month from 1979 to 2006 and the 10.16-cm threshold. The most significant association of OWTS fragility and weather was with systems requiring major repairs, typically equivalent to replacement, and suggests that OWTS are especially vulnerable to an extended period (month) of higher than normal precipitation. Figure 5(b) is a time series of the observed major repairs representing the near complete loss of OWTS performance in each year and the expected major repairs predicted by the GLM. In years with at least 1 month where rain exceeded 10.16 cm, OWTS failures occur also at a higher frequency. Over the 27-year period, considering only April to October for rainfall events, 23 months (of 189 months) surpassed 10.16 cm. Figure 4 shows that OWTS fragility is associated with frequency of high rainfall months (e.g. 1995 was a wet year and high monthly rainfall conditions account for three of the five reported OWTS failures that year.

Figure 6 has the observed number of each class of repair (x-axis) versus the predicted number (y-axis). The dashed line indicates perfect agreement between the observed and the model calculated values. The GLM model of expected repair frequency, μ, in each category as a function of weather-related covariates accounts for approximately 38%, 53% and 70% of the variability in the number of minor, moderate and major repairs, respectively, from 1979 to 2006.

While hydroclimate-related variables capture a significant portion of the variability of repairs year to year, other variables such as OWTS user-operational variables identified previously by Kohler *et al.* (2016a, 2016b) also influence the observed variability. Researchers have suggested advanced design strategies for mitigating climate-related vulnerability such as elevated or 'mound' systems and replacement of native soil with engineered materials in STUs (California Wastewater Training and Research Center & USEPA 2003; Miles *et al.* 2014). We did not distinguish between design characteristics of the OWTS in the sample, although these also may account for

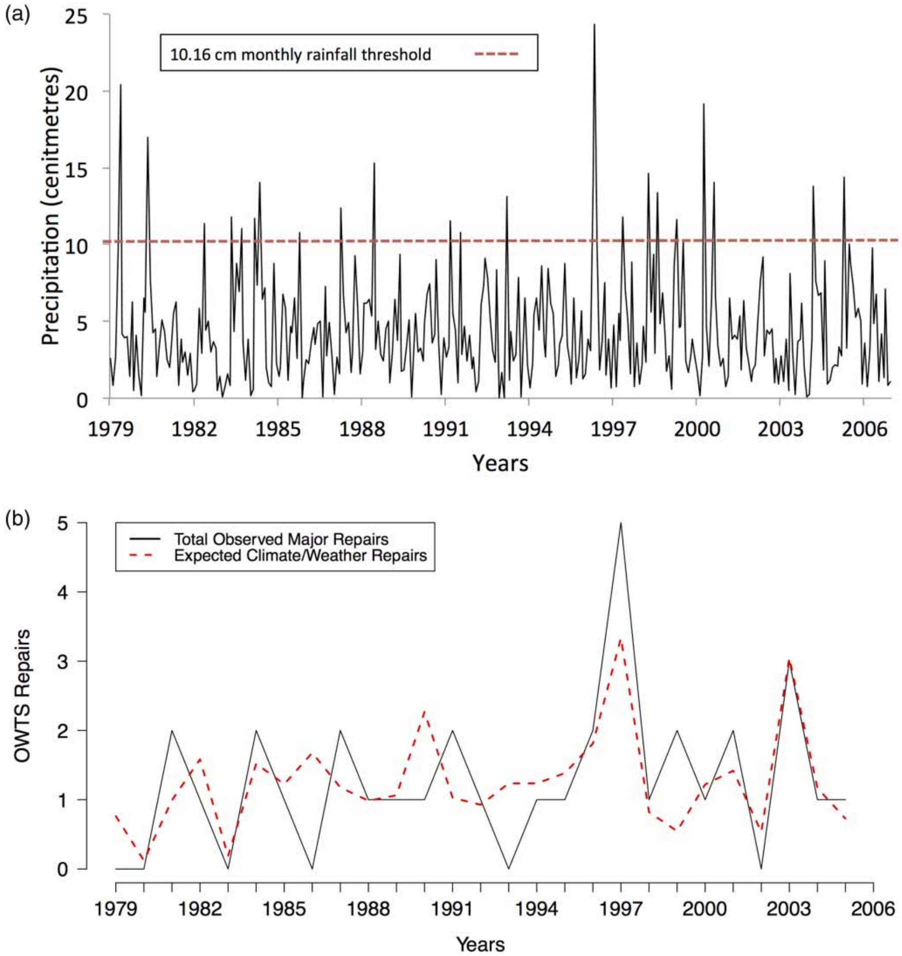

Figure 5 | Monthly rainfall totals from 1979 to 2006 (a). Observed major repairs over that same period and expected repairs as determined by the GLM, indicating major fragility (b).

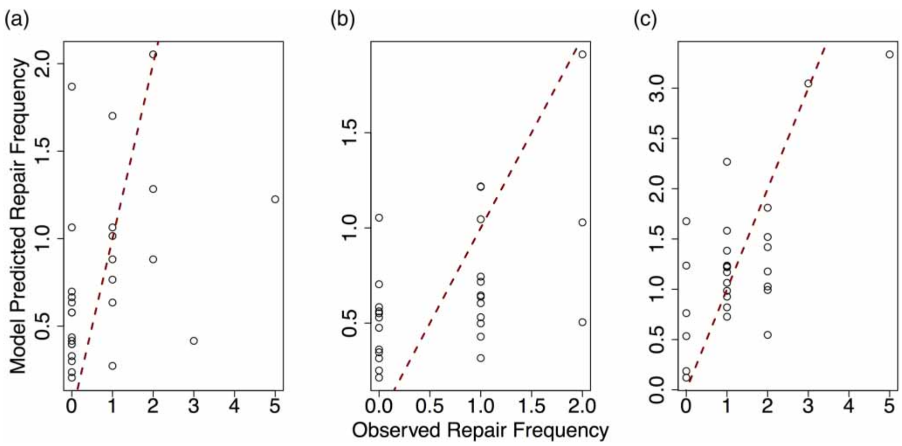

Figure 6 | Observed versus predicted plots for the minor (a), moderate (b) and major (c) repairs (fragility) models.

a portion of the observed variability in sample fragility, especially in relationship to moderate repairs. The GLM results suggest that weather exerts a significant influence on OWTS fragility, measured as the degree to which a system loses function, represented by increasing magnitude of required repairs and replacement.

CONCLUSION

A statistical method based on GLM was developed for modeling the effect of hydroclimate on the degree of OWTS fragility over a period of uniform regulation of OWTS systems in Boulder County, Colorado, from 1979 to 2006. The relationship between the frequency of minor, moderate, and major repairs and high temperature and precipitation was evaluated using a GLM where a Poisson distribution represented the number of repairs in a given year. The results suggest that variability in the frequency of OWTS repairs and replacements each year can be attributed, in part, to weather; particularly, uncharacteristically wet months with rainfall over 10.16 cm and annual peak stream flow correlate with the frequency of major repairs in each year. The principal outcome of this study is a validated foundation for the relationship between OWTS performance/failure and weather variability, with implications for siting, design and vulnerability assessment.

REFERENCES

Agresti, A. 2007 *An Introduction to Categorical Data Analysis*, 2nd edn. John Wiley, Hoboken, NJ, USA.

Akaike, H. 1974 A new look at the statistical model identification. *IEEE Transactions on Automatic Control* **19** (6), 716–723.

Amador, J., Loomis, G. & Kalen, D. 2014 Soil-based onsite wastewater treatment and the challenges of climate change. In: *Paper presented at Soil Science Society of America: Innovation in Soil-based Onsite Wastewater Treatment in Albuquerque*, *NM*, April 7–8, 2014.

Bonstrom, H. & Corotis, R. 2014 First-order reliability approach to quantify and improve building portfolio resilience. *Journal of Structural Engineering* **142** (8), C4014001-1.

Boulder County 2014 *Onsite Wastewater Treatment System (OWTS) Regulations*. Boulder County, CO, USA.

Bruneau, M., Chang, S., Eguchi, R., Lee, G., O'Rourke, T., Reinhorn, A., Shinozuka, M., Tierney, K., Wallace, W. & von Winterfelt, D. 2003 A framework to quantitatively assess and enhance the seismic resilience of communities. *Earthquake Spectra* **19** (4), 733–752.

California Wastewater Training and Research Center & USEPA Region 9. 2003 *Status Report: Onsite Wastewater Treatment Systems in California*. Available from: http://www.swrcb.ca.gov/water_issues/programs/owts/docs/stat_rpt0803.pdf (accessed 9 July 2016).

Crites, R. & Tchobanoglous, G. 1998 *Small and Decentralized Wastewater Management Systems*. WCB McGraw-Hill, USA Boston, USA.

D'Amato, V. 2008 *Factors Affecting the Performance of Primary Treatment in Decentralized Wastewater Systems*. Water Environment Research Foundation, Alexandria, VA, USA and IWA Publishing, London, UK.

Desert Research Institute 2005 *Boulder Monthly Climate Summary*. Period of Record: 8/1/1948 to 12/31/2005. Available from: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?coboul (accessed 22 February 2016).

EPA 2002 *Onsite Wastewater Treatement Manual*. US EPA.

FloHawks Plumbing & Septic, Inc. 2015 *Rainy Season is Here. How do Storms Impact your Septic System?* Available from: http://www.flohawks.com/blog/rainy-season-is-here-how-do-storms-impact-your-septic-system/ (accessed 11 July 2016).

Kenward, A., Yawitz, D. & Raja, U. 2013 *Sewage Overflows from Hurricane Sandy*. Climate Central, Princeton, NJ, USA. Available from: http://www.climatecentral.org/pdfs/Sewage.pdf (accessed 5 January 2016).

Kirtman, B., Power, S. B., Adedoyin, J. A., Boer, G. J., Bojariu, R., Camilloni, I., Doblas-Reyes, F. J., Fiore, A. M., Kimoto, M., Meehl, G. A., Prather, M., Sarr, A., Schär, C., Sutton, R., van Oldenborgh, G. J., Vecchi, G. & Wang, H. J. 2013 Near-term climate change: projections and predictability. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (T. F. Stocker *et al.* eds). Cambridge University Press, Cambridge, UK.

Kohler, L., Silverstein, J. & Rajagopalan, B. 2016a Predicting life cycle failures of on-site wastewater treatment systems using generalized additive models. *Environmental Engineering Science* **33** (2), 112–124.

Kohler, L., Silverstein, J. & Rajagopalan, B. 2016b Risk-cost estimation of on-site wastewater treatment system failures using extreme value analysis. *Water Environment Research*. doi: 10.2175/106143016X14609975747289.

Luostarinen, S. & Rintala, J. 2005 Anaerobic on-site treatment of black water and dairy parlour wastewater in UASB-septic tanks at low temperatures. *Water Research* **39** (2–3), 436–448.

Luostarinen, S., Sanders, W., Kujawa-Roeleveld, K. & Zeeman, G. 2007 Effect of temperature on anaerobic treatment of black water in UASB-septic systems. *Bioresource Technology* **98** (5), 980–986.

Mau, D. P. & Winter, T. C. 1997 Estimating ground-water recharge from stream flow hydrographs for a small mountain watershed in a temperate humid climate, New Hampshire, USA. *Ground Water* **35** (2), 291–304.

McCullagh, P. & Nelder, J. 1989 *Generalized Linear Models*, 2nd edn. Springer-Science + Business Media, Buena Vista.

McDougall, A. 2009 Fragility: the next wave in critical infrastructure protection. *Journal of Strategic Security* **2** (2), 91–98. doi: http://dx.doi.org/10.5038/1944-0472.2.2.4. Available from: http://scholarcommons.usf.edu/jss/vol2/iss2/4.

McKinley, J. W. & Siegrist, R. L. 2011 Soil clogging genesis in soil treatment units used for onsite wastewater reclamation: a review. *Critical Reviews in Environmental Science and Technology* **41**, 2186–2209.

Miles, R. J., Borchelt, G. & Casaletto, D. 2014 Treatment of drip dispersed effluent in imported soils. *Conference Proceedings of the Soil Science Society of America*, *Albuquerque, NM*, *USA*.

Morales, I., Amador, J. & Boving, T. 2015 Bacteria transport in a soil-based wastewater treatment system under simulated operational and climate change conditions. *Journal of Environmental Quality* **44** (5), 1459–1472.

Morales, I., Cooper, J., Amador, J. A. & Boving, T. B. 2016 Modeling itrogen losses in conventional and advanced soil-based onsite wastewater treatment systems under current and changing climate conditions. *PLoS ONE* **11** (6), e0158292. doi:10.1371/journal.pone.0158292.

NCDC (National Climatic Data Center) 2015 *Annual Climatological Summary of NCDC Summary of the Month Dataset (DSI-3220)*. Available from: https://gis.ncdc.noaa.gov/geoportal/catalog/search/resource/details.page?id=gov.noaa.ncdc:C00040 (accessed 4 December 2015).

Septic Smart Program 2015 *SepticSmart Program*. Boulder County Colorado, Available from: http://www.bouldercounty.org/env/water/pages/septicsmartindex.aspx.

Sophocleous, M. 2002 Interactions between groundwater and surface water: the state of the science. *Hydrogeology Journal* **10**, 52–67.

UNICEF & Global Water Partnership (GWP) 2014 *WASH Climate Resilient Development: Technical Brief*.

Verdin, A., Rajagopalan, B., Kleiber, W. & Katz, R. 2015 Coupled stochastic weather generation using spatial and generalized linear models. *Stochastic Environmental Research and Risk* **29**, 347–356.

Weirich, S., Silverstein, J. & Rajagopalan, B. 2015 Resilience of secondary wastewater treatment plants: prior performance is predictive of future process failure and recovery time. *Environmental Engineering Science* **32** (3), 222–231.

WHO & UNICEF 2015 *25 Years Progress on Sanitation and Drinking Water: 2015 Update and MDG Progress*. WHO, Geneva and UNICEF, New York.

Yeh, H., Lee, C., Chen, J. & Chen, W. 2007 Estimation of groundwater recharge using water balance model. *Water Resources* **34** (2), 153–162.

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