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RESEARCH ARTICLE

Determinants of rural hand-pump functionality through maintenance provision in the Central African Republic

Eliza Lynn Fink[1], **Pranav Chintalapati**[1,2]*, **Adrienne Lane**[3], **Andrew Wester**[3], **Amy Javernick-Will**[1], **Karl Linden**[1]

1 Department of Civil, Environmental, and Architectural Engineering, University of Colorado Boulder, Boulder, Colorado, United States of America, **2** Department of Chemical and Biological Engineering, The University of British Columbia, Vancouver, British Columbia, Canada, **3** Water for Good Inc, Indianapolis, Indiana, United States of America

* pranav.c@ubc.ca

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Abstract

While preventive maintenance services have emerged as promising interventions to improve the continuity of water service delivery, the operational and contextual requirements for sustained functionality within maintenance models are not well understood. This paper uses data analysis to better understand factors influencing the success of rural water service delivery within the circuit rider maintenance model in fragile contexts. Incorporating operational data from a large scale circuit rider hand-pump maintenance program in the Central African Republic, mixed-effect logistic regression models were used to identify determinants of water point functionality and payment compliance. Models were informed by data from over 16,000 maintenance visits across nine years. Faster response time, proximity to urban centers, and proximity to other hand-pumps emerged as significant factors for improving water point functionality, while proximity to maintenance program headquarters, pump functionality, and frequency of maintenance visits significantly influenced payment compliance. The observed high functionality rates of hand-pumps serviced by the maintenance program indicates the potential benefits of professionalized maintenance through the circuit rider model at promoting water system reliability in fragile contexts. Despite adaptability and resilience in implementation of the circuit rider model, insecurity and conflict remain barriers to sustaining service delivery in the Central African Republic.

1. Introduction

1.1. Rural water maintenance provision

While access to safe water is a human right, water system breakdowns and the consequent extended downtimes are a public health issue that is especially prominent in rural, remote and under-resourced areas [1, 2]. In sub-Saharan Africa (SSA), one in four of hand-pumps are estimated to be non-functional at any one time [3]. High rates of non-functionality can be partly

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attributed to failures in waterpoint management, which is dominated by community based management (CBM) models that depend upon communities voluntarily adopting responsibility for infrastructure maintenance [4]. Post construction support has been identified as essential for promoting water-point functionality [5, 6]. Professionalized maintenance services are a form of post-construction support, which involve trained personnel working within clear legal and contractual frameworks with performance monitoring and transparent financing arrangements to conduct maintenance and repairs for rural water infrastructure [7]. The provision of professionalized maintenance has the potential to address some of the limitations of CBM, including limited technical resources among communities and reactive repair activities rather than preventive maintenance [4, 8–11]. There are several approaches to rural water service provision being implemented in SSA that incorporate elements of professionalized maintenance [8, 12]. The international non-governmental organization, Water for Good's [WfG] circuit rider [CR] maintenance program in the Central African Republic is one example. While approaches are expanding in SSA and show evidence of improving functionality rates [8, 12], there is a dearth of research addressing how operational strategies within these approaches impacts water system functionality or income flows. Local context [5, 13], as well as a collection of operational and contextual factors play important roles in influencing WASH service sustainability [14]. There are numerous studies that investigate predictors of hand-pump functionality in the context of CBM [5, 10, 15, 16]. However, there is limited research on factors influencing successful service delivery outcomes within maintenance arrangements in fragile contexts.

1.2. Central African Republic service area context

The CAR is considered an extremely fragile context and among the least developed countries, ranked the 6th most fragile on the Fragile States Index and 188/189 in the Human Development Index [17, 18]. Violence, political instability, and low levels of development limit government investment in infrastructure and elevate risk for water service practitioners. Water, sanitation, and hygiene (WASH) indicators in extremely fragile contexts are often more than eight times worse than in stable contexts [19]. Basic drinking water services are accessible to only 54% of the CAR's total population and 41% of the rural population [20]. About 60% of the CAR's population is rural, with a national average population density of 7.75 people per square kilometer [21]. Rurality and limited road infrastructure create logistical challenges to water service delivery. Private markets for spare parts outside of Bangui, Berbérati and other major towns are non-existent, and several areas in the CAR are still subject to active conflict and insecurity [8]. In the years through which WfG has worked in the CAR there has been ongoing unrest, with a civil war beginning in 2012. Despite limited national oversight, public sector monitoring and regulation of the water sector in the CAR, the national agency, ministry, and regional authorities are involved in water management within WfG's service area, particularly in urban and peri-urban areas [22]. The CAR government is decentralized to prefecture, sous-prefecture and commune levels, however, limited public financing restricts local governments from carrying out water sector functions [8].

1.3. Circuit rider maintenance model

The CR maintenance model is a 'structured proactive' approach to maintenance service delivery developed specifically for rural and remote areas [8]. The model is supply driven and consists of qualified technicians who travel predetermined 'circuits' to provide regular preventive and reactive technical support to communities. The CR approach was pioneered in the United States during the 1970s and has since become a prevalent method for service delivery across

the US, Canada, Latin America, and SSA [23–26]. Established circuits allow remote areas to be routinely serviced in a relatively cost-efficient manner by minimizing the marginal cost for servicing additional communities. While there is limited research on the effectiveness of CR maintenance approaches in low-resource contexts, previous studies have found that CR models can reduce the time to repair breakdowns relative to ad-hoc servicing [27], and had positive outcome for communities as a low cost drinking water delivery intervention [24]. Although preventive maintenance services have potential to mitigate financial, environmental, and technical disadvantages experienced by some communities [10], there is still variation in levels of functionality within maintenance models that demands further analysis to improve understanding.

1.4. Water for good

1.4.1. Organizational history. WfG is a non-governmental organization operating a large-scale CR maintenance program in the CAR. WfG has drilled 958 new wells and is the largest maintenance service provider in the CAR, maintaining over 1800 hand-pumps, which serve an estimated 800,000 people [28]. The WfG head office is located in Indiana, USA with field offices in Berbérati and Bangui. CAR. WfG offices and the locations of all water points installed or serviced by WfG between 2012 and 2020 are show in Fig 1[a] and 1[b] displays the total number of maintenance visits, pumps maintained, and new well installations by year.

The original WfG CR program consisted of four teams of two technicians, each team with a predetermined truck route, which took up to three weeks to complete. Although the maintenance model remained broadly consistent between 2012 and 2017, geographic scope and total number of communities serviced varied with organizational growth, insecurity, and funding restraints. Fig 1[b] demonstrates the organization's growth through expansion of coverage through well installations and maintenance services. Each hand-pump enrolled in the program was intended to be visited twice annually, however, in application there was wide variance in frequency and time between maintenance servicing.

1.4.2. Alternative maintenance modalities. In 2017 and 2018, WfG introduced alternative motorcycle based maintenance models adapted for urban and peri-urban areas. The Rapid Response (RR) program served 63 hand-pumps that were supplemental to the beleaguered

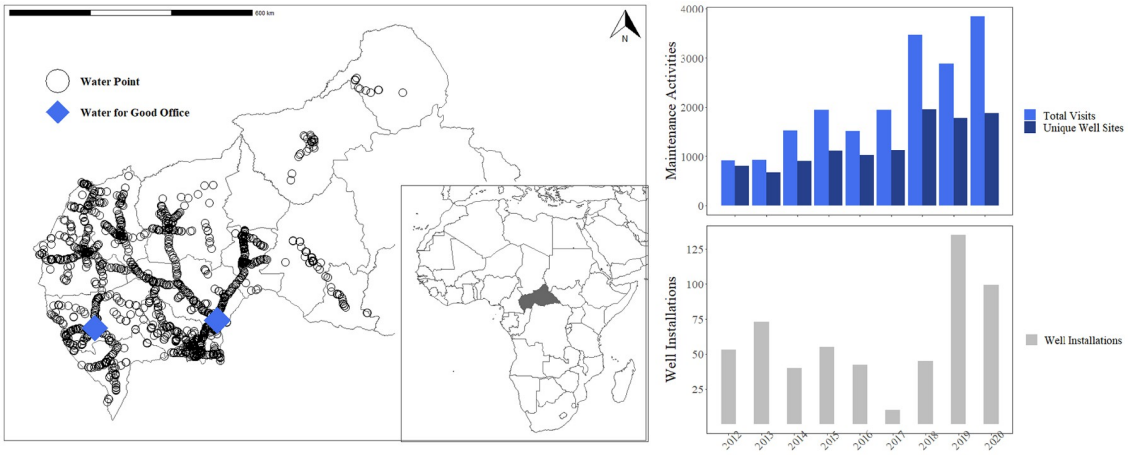

Fig 1. [a] Locations of water points serviced by WfG across the CAR (map created with data from OCHA Central African Republic [29] and Natural Earth [30]); [b] Number of maintenance visits, unique wells maintained, and new well installations by year.

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Table 1. WfG service modalities.

	Approach	Pumps Serviced (2019)	Transportation Mode	Service Area	Payment Structure
Standard Circuit Rider	Structured Proactive	1487	Truck	Rural, Full WfG service area excluding alternative programs	Flat per-visit rate
Rapid Response	Responsive	63	Motorcycle	Urban areas not connected to municipal water supply. Berbérati.	Per visit, based on repair cost
Hybrid Motorcycle	Structured Proactive and Responsive	248	Motorcycle	Urban and peri-urban with high water point density. Bangui and Berbérati.	Flat per-visit rate

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municipal water supply, with a call-in number provided for mechanics to respond to breakdowns. The Hybrid Motorcycle (HM) program was piloted to supplement the truck based CR teams in areas with high water point density and designed to blend the structured preventive approach of CR with the improved responsiveness of the RR program. Both RR and HM programs were intended to improve frequency of visits compared to the traditional CR model and used motorcycles instead of trucks. The use of motorcycles reduces transportation costs but limits the number of spare parts and tools that teams can carry, constraining repair capacity. Table 1 summarizes the fundamental difference between maintenance modalities.

1.4.3. Finances. WfG financially supports all aspects of the service delivery model, with the maintenance program accounting for approximately 12.7% of the organization's total expenses [31]. The majority of WfG's funding comes from grants and contributions, with a portion of income from program revenue in the form of community payments [32]. Payment compliance has not been a priority for WfG, as there are few community socialization activities regarding payment and infrequent sanctions for non-payment. Prior to the civil war, all communities serviced by WfG had contracts and were charged a service fee. During years of peak conflict maintenance activities continued but expectations for payment were suspended, though a few communities continued to pay. As the region stabilized, mechanics resumed messaging for payment, however a majority of hand pumps for communities who did not pay were still serviced. Mechanic discretion determines if pumps were serviced for non-compliant communities. If communities were perceived as unable to pay by mechanics, pumps would still be serviced. If mechanics perceived that communities were able but unwilling to pay, they reserved the right to not perform maintenance services. In 2020, these visits, in which maintenance services were not performed, began being indicated in data collection as "monitoring". Mechanics salaries are not contingent on collecting community payments. Payment compliance by communities is less than 50%, and in 2020 community payments covered approximately 4.9% of total maintenance expenses. Fig 2 shows the scale of maintenance program revenue and expenses relative to total WfG organizational financial flows in 2020. The scale of maintenance program revenue relative to total WfG income flow illustrates the degree of donor dependency in this maintenance model, with less than 5% of maintenance program expenses covered by income from community payments. For the traditional CR and HM service modalities, communities were charged a flat rate [20,000 Central African CFA, or approximately $34 USD, applying a June 2016 exchange rate] per visit for maintenance services. Fees for the RR program were based on actual costs of repair which on average is higher than the flat rate.

Reliable rural water service delivery requires a functioning system including institutional arrangements, policies, financing, and regulation. This system is essential for establishing an enabling environment that makes sustainable maintenance service possible [33]. Instability and the associated limited government capacity in the CAR currently constrain water service

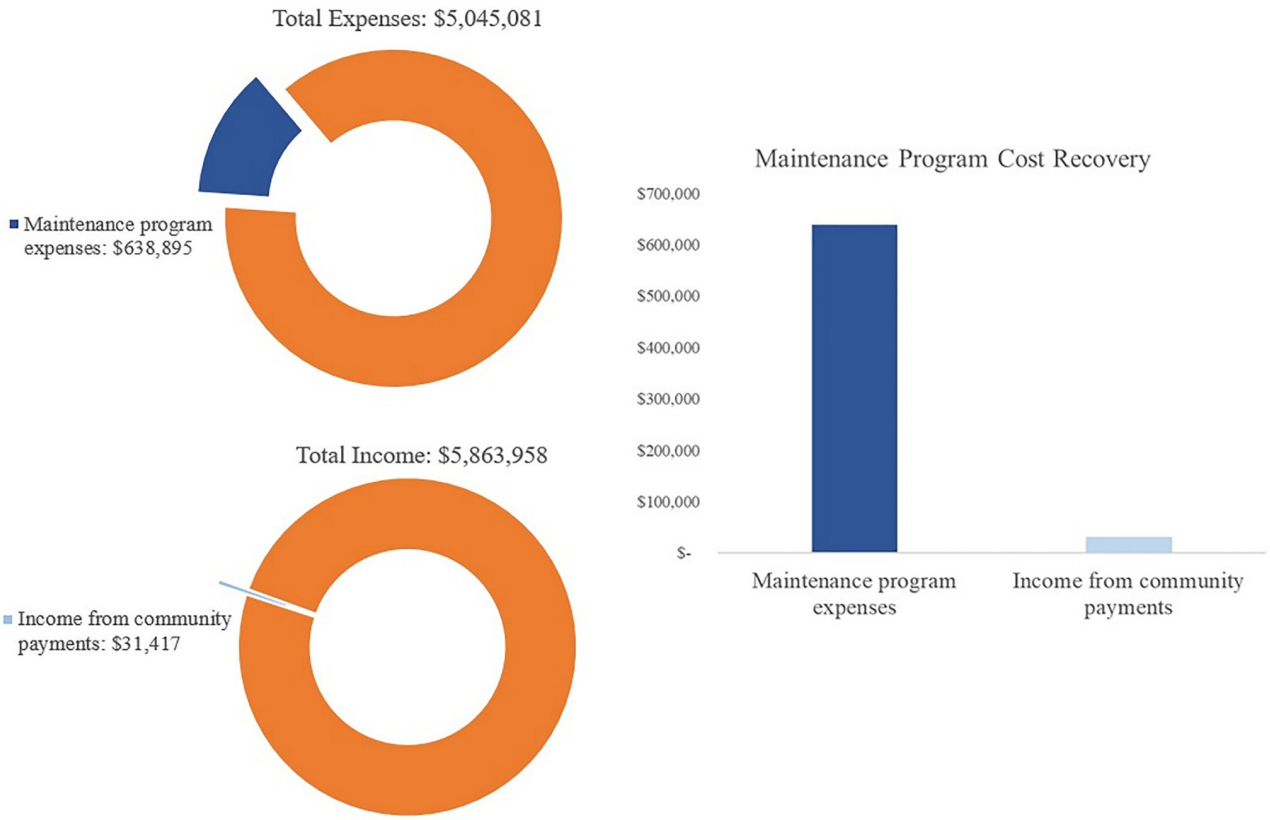

Fig 2. In 2020 revenue from community payment represented less than one percent of total WfG income and covered 4.9% of maintenance program expenses.

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delivery from being improved at a systemic-level. Given the fragile context, WfG currently focuses on expanding coverage by supplementing CBM with elements of professionalized maintenance and hand-pump installations, rather than being a fully professionalized maintenance service that benefits from institutional and policy frameworks established within the local government. WfG's model relies on CBM for a several basic activities and can be classified as *Community Based Management Plus* [11, 34].

1.5. Study objectives

Through a longitudinal analysis of service delivery outcomes of WfG's maintenance program, this study aims to address gaps in the literature for rural water sustainability both within fragile contexts and maintenance models. This research considers data collected by WfG maintenance technicians between 2012 and 2020 to provide insight into how operational and contextual factors, such as the time between maintenance visits and local water point density, have historically affected the success of service delivery outcomes. The effects of RR and HM alternative maintenance modalities on outcomes compared to the traditional CR model are analyzed to build understanding about operational decisions and potential for service expansion. Success for service delivery sustainability outcomes is considered both through hand-pump functionality and community payment compliance metrics. Data on payment compliance is considered to gain information about community valuation of service delivery and to inform on how to socialize the idea of paying for water, an important consideration for long term

sustainability [35, 36]. Mixed-effect logistic regression models are applied to identify determinants of water point functionality and community payment compliance within WfG's maintenance program to provide insight into how various factors shape the success of service delivery for hand-pump maintenance in fragile contexts.

2. Methods

2.1. Data collection

Data used in this study were drawn from a comprehensive record of WfG's maintenance activities between 2012 and 2020. Data was collected for WfG's monitoring, evaluation, research and learning purposes and not specifically for this study. WfG operates as a maintenance service provider in the CAR and collects performance data through a partnership MOU with the CAR Ministry of Hydraulics and a convention with the Ministry of Planning. As part of compliance with this convention, WfG submits an Annual Work Plan and Annual Report of activities each year.

Information was recorded by WfG technicians who completed reports on-site during each maintenance visit using the digital data collection platform, iFormBuilder (https://www.zerionsoftware.com/iformbuilder). The electronic reporting included the unique well identifier, time-stamped GPS data, photo verification, spare parts used, pump functionality status, and other site-specific information. Data includes records from visits to hand-pumps that are officially enrolled in the WfG maintenance program, as well as those that are effectively non-participating for either community management or technical reasons. WfG technicians continued to monitor non-participating pumps for a variety of reasons, including providing an up to date asset inventory of hand-pumps in the CAR. All observed visits were included in modeling because records did not disaggregate between 'participating' and 'non-participating' well locations until 2020, where 75.3% of pumps visited were participating.

High Resolution Population Density maps were used to calculate population within a one kilometer radius of each well [37]. The original data set represented the population of the CAR in 2018, and was adjusted for growth using World Bank estimates, assuming spatially uniform growth [38]. Detailed information on the sources of data used in models, including modifications of raw data, is included in S1 Text.

Data was provided for 18,938 maintenance visits, of which 16,399 were used in the final modeling stage. There were 3552 instances of breakdowns across all visits, and 3066 of these observations were included in final models. Visit observations with missing data, such as missing well location or functionality status were excluded from the study. The first maintenance visit for each pump in the records was excluded from models to allow the number of days and functionality status from the previous visit to be included as modeling covariates.

2.2. Statistical models

Mixed effect logistic regression models were used to identify and quantify the influence of factors that impact the success of WfG's maintenance outcomes. The three binary outcome variables analyzed were:

1. *Pump working*, which reported the hand-pump's functionality status upon the arrival of mechanics
2. *Pump fixed*, which, conditional on breakdown occurrence, reported the hand-pump's functionality upon the departure of mechanics (after maintenance services were performed)

3. *Payment*, which reported presence of community payment to mechanics at the time of maintenance visit

Details as to how variables are defined are included in S1 Text. Three mixed effect logistic regression models were created to model the mean probability of success for each outcome variable from a range of predictor variables. These are referred to herein as Model 1, 2, and 3, corresponding to their respective outcome variables. Models were run using the lme4 package in R [39]. Outcome variables from maintenance records were coded into binary responses for each visit. Success for outcome 1 was defined as water being available from a pump at the arrival of mechanics Success for outcome 2 was defined as water being available from the pump at departure of mechanics, given the pump was non-functional upon arrival. Success for outcome 3 was defined as the presence of payment from the community to the mechanics at the time of visit, regardless of amount.

When considered across all pumps from 2012 to 2020, outcome variable 1 [pump working on arrival] represents the success of the maintenance program at preventing pump breakdown between visits. This encompasses the effectiveness of the CR preventive maintenance activities and community capacity to repair minor damages between WfG servicing. Aggregated across the data set, success for outcome variable 2 (pump fixed) indicates effectiveness of reactive maintenance and decreased severity of breakdowns. Together, outcomes 1 and 2 are indicative of functionality and success of water system maintenance service delivery across WfG's service area, with higher success rates resulting in higher water system uptime for communities. Although payment compliance is not a primary goal for WfG, whose focus is to increase coverage, the payment outcome provides insight on socialization of paying for water and the relationships between payment and functionality. Furthermore, payment compliance reflects community valuation of maintenance services and may play a role in reinforcing technician motivation. Predictor variables that emerged as statistically significant with odds ratios (OR) greater than one were interpreted to have a positive effect on the outcome variable, variables with ORs less than one were interpreted as having a negative effect on the outcome variable.

The well identification number for each pump was included as a random intercept in the models to account for the clustered nature of the data due to repeated measurements of individual pumps across time [40]. Models 1 and 3 included 2210 unique wells and Model 2 included 1270. Covariates in the model included both predictor variables and control variables. Predictor variables were selected based on relevance to hypothesis testing, and were consistent with factors considered in literature on rural water sustainability in varying contexts [5, 6, 15, 16, 41], or were identified as factors of interest by WfG management. A summary of literature informing variable selection, and details on variable calculations and data sources are available in S1 Text. In models 1 and 2, the pump type and whether the visits were indicated as "monitoring" visits by WfG staff were included as control variables. Control variables do not have associated hypotheses and were included to improve model accuracy and account for potential confounding factors. All covariates in the final models were tested for multiple collinearities using variance inflation factor scoring and determined to be sufficiently independent. Descriptive data for outcomes and categorical covariates are included in Table 2. Descriptive statistics for continuous covariates are included in Table 3. A summary of variables included in each model is provided in Table A in S1 Text. Hypothesized conceptual relationships between covariables are visualized in Fig A and described in Table A in S2 Text.

2.3. Sensitivity analysis

For each of outcome variable, four sensitivity analyses were conducted to validate robustness of model findings: 1) excluding outliers 2) applying only a subset of pumps that were identified

Table 2. Descriptive data for outcomes and categorical variables.

Outcome		n	%
Pump Working			
	TRUE	13332	81%
	FALSE	3066	19%
Pump Fixed			
	TRUE	1477	48%
	FALSE	1589	52%
Community Payment			
	TRUE	2407	15%
	FALSE	13991	85%
Models 1 and 3			
Visits		16398	
Water points		2210	
Variable		n	%
Fixed at Previous Visit			
	TRUE	14829	90%
	FALSE	1569	10%
Pump Type			
	HPV 60	308	2%
	HPV 100	11175	68%
	India Mark	401	2%
	Hydro India	4251	26%
	Moino	127	1%
	Other	136	1%
Hybrid Motorcycle			
	TRUE	1187	7%
	FALSE	15211	93%
Rapid Response			
	TRUE	494	3%
	FALSE	15904	97%
Monitoring			
	TRUE	867	5%
	FALSE	15531	95%
Model 2			
Visits		3066	
Water Points		1270	
Variable		n	%
Pump Type			
	HPV 60	2014	66%
	HPV 100	100	3%
	India Mark	674	22%
	Hydro India	99	3%
	Moino	82	3%
	Other	97	3%
Hybrid Motorcycle			
	TRUE	190	6%
	FALSE	2876	94%
Rapid Response			

(*Continued*)

Table 2. (Continued)

	TRUE	70	2%
	FALSE	2996	98%
Monitoring			
	TRUE	253	8%
	FALSE	2813	92%

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as "participating" in 2020 3) with a random intercept accounting for geographic clustering at the prefecture level and 4) with a random intercept accounting for geographic clustering at the sous-prefecture level. Outliers were identified using Mahalanobis distance for all continuous variables [42]. In the sub-analysis of participating pumps, because data on delineation between participating and non-participating water points is only available for year 2020, all wells marked as participating in this year were assumed to be participating between 2012 and 2020.

3. Results and discussion

Model results for predictor variables are included in Table 4, and full results including control variable effects and sensitivity analysis are available in S3 Text. A diagram visualizing relationships between variables and outcomes supported by results is available in supplementary information Fig B in S2 Text.

3.1. Improving functionality

Overall, water point functionality from WfG's maintenance visit observations appear to be higher than the reported 75% functionality spot functionality that literature suggests is typical across SSA [3], with 81.2% of WfG visits between 2012 and 2020 reporting pumps working on arrival and 89.1% reporting functioning after maintenance services. These functionality levels account for all WfG visits, including both officially enrolled and non-participating hand-pumps. In 2020 when disaggregated data is available, the sub-set of participating pumps had 27.8 percentage points higher functionality on arrival than non-participating locations, with 97.2% of observations of participating pumps functional after maintenance services compared to 69.4% for non-participating pumps. Although delineation of pump participation status

Table 3. Summary statistics for continuous variables.

Variable	Units	Mean	SD	Min	Max
Models 1 and 3. n = 16398					
Time Since Last Maintenance Visit	days	243.9	231.6	0.0	2884.0
Distance to Nearest WfG Office	km	121.0	86.5	0.0	693.7
Distance to Nearest Urban Center	km	50.6	40.8	0.7	336.0
Number of People in 1km of Well	people	3326.6	4593.6	0.0	40794.6
Average Distance to Nearest 5 Water for Good Wells	km	3.3	3.9	0.2	79.6
Model 2. n = 3066					
Time Since Last Maintenance Visit	days	281.3	313.6	0.0	2838.0
Distance to Nearest WfG Office	km	113.5	74.4	0.0	356.8
Distance to Nearest Urban Center	km	52.0	38.1	1.0	156.5
Number of People in 1km of Well	people	3357.7	5006.5	0.0	40794.6
Average Distance to Nearest 5 Water for Good Wells	km	3.9	4.6	0.2	40.3

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Table 4. Model results on determinants for functionality upon arrival, functionality after maintenance service given breakdown, and payment compliance.

		Confidence Interval		
Variable	**OR**	**2.50%**	**97.50%**	**p-value**
Model 1. Pump functionality upon arrival				
Time Since Last Maintenance Visit (days)	1.00	1.00	1.00	<0.001
Hybrid Motorcycle Program	1.28	1.04	1.58	0.022
Rapid Response Program	1.00	0.70	1.41	0.990
Distance to Nearest WfG Office (km)	1.00	1.00	1.00	<0.001
Distance to Nearest Urban Center (km)	1.00	0.99	1.00	<0.001
Number of People in 1km Radius of Well	1.00	1.00	1.00	0.372
Average Distance to Nearest Five WfG Wells	0.96	0.95	0.98	<0.001
Model 2. Pump fixed given breakdown				
Time Since Last Maintenance Visit (days)	1.00	1.00	1.00	<0.001
Hybrid Motorcycle Program	0.96	0.63	1.48	0.862
Rapid Response Program	0.57	0.29	1.12	0.103
Payment Received by Maintenance Team	16.04	9.73	26.43	<0.001
Distance to Nearest WfG Office (km)	1.00	1.00	1.00	0.049
Distance to Nearest Urban Center (km)	1.00	0.99	1.00	0.156
Number of People in 1km Radius of Well	1.00	1.00	1.00	0.161
Average Distance to Nearest Five WfG Wells	1.00	0.97	1.02	0.812
Model 3. Payment of maintenance team				
Functionality at Last Maintenance Visit	1.21	0.96	1.53	0.102
Time Since Last Maintenance Visit (Days)	1.00	1.00	1.00	<0.001
Hybrid Motorcycle Program	0.25	0.19	0.35	<0.001
Rapid Response Program	0.25	0.19	0.35	<0.001
Pump Working on Arrival of Maintenance Team	0.69	0.59	0.80	<0.001
Pump Fixed on the Departure of Maintenance Team	10.80	7.28	16.03	<0.001
Distance to Nearest WfG Office (km)	1.00	1.00	1.00	0.003
Distance to Nearest Urban Center (km)	1.00	1.00	1.00	0.509
Number of People in 1km Radius of Well	1.00	1.00	1.00	<0.001
Avg. Distance to Nearest Five WfG Wells (km)	1.01	0.99	1.03	0.488

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could not be included in the primary analysis, some of the variance in functionality attributable to enrollment could have been captured in models through the well identification number random intercept and the fixed payment effect, as mechanics were unlikely to receive payment from non-participating communities. In a sensitivity analysis including only pumps that are participating in 2020, assuming these water points were participating throughout the study time frame, model results generally supported those found from the whole data set and are included in Tables G-I in S3 Text. Table 5 summarizes key differences in data between the

Table 5. Differences in data for subset of pumps participating in 2020.

	All Visits		Participating Subset	
Total Wells	2210		1511	
Total Visits	16398		12297	
	n	%	n	%
Working on Arrival	13332	81%	10343	84%
Working on Departure	14644	89%	11471	93%
Payment	2407	15%	2111	17%

https://doi.org/10.1371/journal.pwat.0000024.t005

subset of pumps participating in 2020 and the full data set, indicating higher proportions of functionality on arrival, functionality on departure, and payment compliance for the subset of participating pumps.

Since data are based on observations during visits, information on when breakdown occurred is unavailable and therefore downtime estimates cannot be accurately determined. Instead, data can be considered as spot functionality observations at the time of visits. While reliable data for downtime is unavailable, considering maintenance visits as spot functionality observations suggest that the maintenance programs are effective at reducing breakdowns relative to SSA regional estimates. However, due to extreme fragility and low levels of development, the CAR is not representative of the SSA region at large [17, 18]. While water system functionality rates in conflict zones and least developed countries have not been studied extensively as a sub-set of SSA, WASH indicators suggest that functionality rates in more remote and conflict affected areas are lower than regional averages [19].

Although the median time between maintenance visits in the data was six months, aligning with WfG's goals to visit pumps biannually, there was a wide variance in the time since previous maintenance visits. Insecurity frequently constrained the geographic scope of WfG operations, resulting in the longest reported gap being almost eight years. In model results, decreasing the time between visits correlated with improved functionality outcomes at both the arrival of technicians and after maintenance services. The reported OR for a change in one day between maintenance visits is effectively equal to 1. However, as time between visits increases, the relationship becomes more practically significant. For increased time of 90 days, models indicate that odds of functionality on arrival decreases by a factor of 0.94 (95% CI: (0.93–0.96)) and odds of a broken pump being fixed decreases by a factor of 0.92 (95% CI: (0.88–0.96)). This suggests that while small changes in time between visits are insignificant, long gaps in service, such as those observed when maintenance to a region was constrained by insecurity, reduce the probability of functionality on arrival and of successful repair. This observed correlation highlights the value of proactive preventive maintenance and supports that investing in increased frequency of maintenance visits and improved response times could contribute to preventing and reducing the severity of hand-pump breakdowns. The marginal effects of decreasing the time between maintenance visits on all three model outcome variables can be visualized in Fig 3.

In addition to the length of time between visits, geographic characteristics influenced functionality outcomes. Models included in the sensitivity analysis indicated that geographic

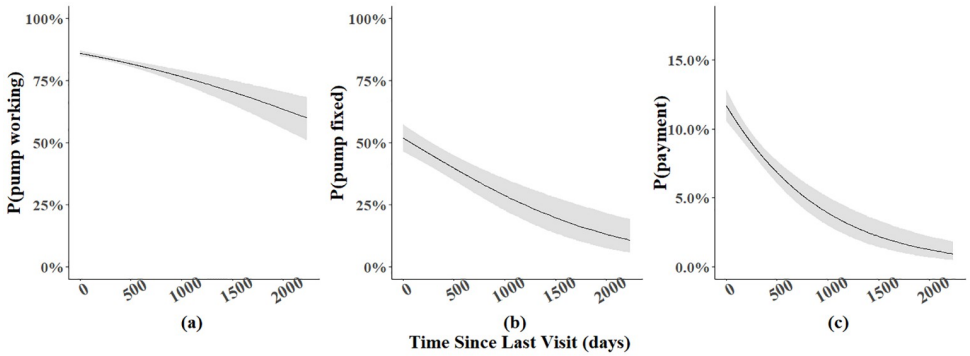

Fig 3. Marginal effects from model results show declining probability of (a) pump working with increased time between visits in Model 1; (b) pump fixed after maintenance service with increased time between visits in Model 2; (c) payment compliance with increased time between visits [43].

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clustering, considered at both the prefecture and sous-prefecture administrative levels accounts for some variation in observed outcomes. Prefecture and sous-prefecture were found to be highly colinear with distance to urban center and distance to WfG office metrics using variance inflation factor scoring. However, including random effects for geographic clustering generally did not impact the interpretation of determinants of functionality outcomes.

Increased distance to urban centers correlated with decreased odds of success for functionality on arrival (OR 20 km change in distance: 0.92, 95% CI: (0.88, 0.96)). However, the effect of proximity to urban centers did not emerge as significant in sensitivity analysis accounting for only pumps participating in 2020. The distance to urban center serves as a proxy for the remoteness, suggesting that improved accessibility contributes to higher functionality. In the CAR, inaccessibility for remote locations is compounded by insecurity issues. Underlying mechanisms behind the observed relationship between 'distance to urban center' and functionality outcomes could be attributed to components of accessibility, including better road conditions, improved availability of spare parts, and reduced insecurity that can all contribute to community or mechanic capacity to perform repairs and routine maintenance. The effect of proximity to WfG offices shows a counterintuitive correlation with functionality outcomes, with the odds of success increasing as the distance to an office increase. This observation could be the result of confounding effects not controlled for in the model. The correlation between Average Distance to Nearest 5 WfG Wells and the functioning on arrival outcome (OR 1 km unit: 0.96, 95% CI: (0.95, 0.98)) suggests that higher pump density corresponds to reduced breakdowns. A possible explanation for this observation is that accessibility to nearby pumps for users reduces wear and tear on a particular pump, decreasing breakdown frequency. Increased pump density can also improve operational effectiveness by decreasing the marginal cost in travel expenses for mechanics to service each additional pump. These findings support that investment in hand-pump infrastructure throughout CAR could have synergistic impacts on long term maintenance outcomes.

In the primary model, participation in the HM program correlates with higher odds of functionality on arrival (OR = 1.28 95% CI: (1.04, 1.58)). However, this did not emerge as significant in sensitivity analysis accounting for geographic clustering or including only participating pumps, indicating a less robust model finding. Lower proportions of functionality on arrival would be expected for both RR and HM programs, as they were intended to be more responsive to system breakdown. The absence of this correlation indicates they were not primarily utilized as responsive services. In practice, it proved uncommon for communities to contact mechanics for breakdowns. Pumps enrolled in these programs were instead visited on routine circuits that were much shorter than traditional CR routes. The observed trend between functionality on arrival for the HM suggests that shorter routes and more frequent servicing correlated with reduced breakdown, even while controlling for the number of days since previous maintenance visit.

3.2. Improving payment compliance

Results of Model 3 illustrate how WfG maintenance performance correlates with community valuation of services. Increasing time since the last maintenance visit correlated with decreasing odds of receiving payment (OR for 90 day change: 0.90, 95% CI: (0.87, 0.93)), visualized in Fig 3(c). This supports that increased frequency of visits could contribute to improved valuation of service, particularly when comparing over long time frames. When a pump was reported functional after maintenance services, the community is approximately 10.80 (95% CI: (7.28, 16.03)) times more likely to pay for services. The relationship between pump functionality after services and odds of payment is visualized in Fig 4[c]. In contrast, if the hand-

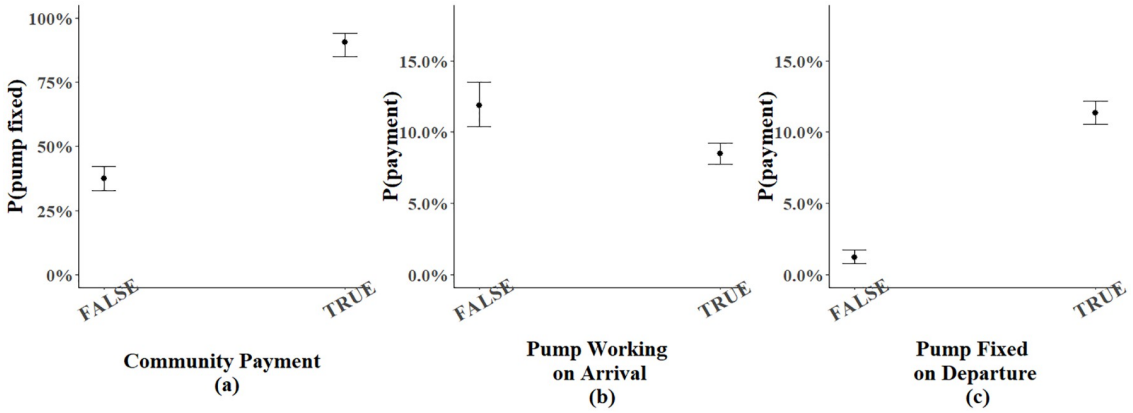

Fig 4. Marginal effects show (a) a positive correlation between presence of a community payment and probability a pump is fixed in Model 2; (b) a negative correlation between a functional pump at arrival of mechanics and the probability a community will pay for maintenance services in Model 3; (c) a positive correlation between a functional pump after maintenance services and the probability communities will pay for maintenance services in Model 3 [43].

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pump was reported as functional on arrival of technicians, maintenance teams were less likely to receive payment (OR: 0.69, 95% CI: (0.59, 0.80)), an effect shown in Fig 4(b). This suggests that communities value maintenance services when outcomes are tangible, like when a broken pump is fixed, but not necessarily for cases of preventive maintenance with no visible improvement (when a pump was functional on arrival and continued to work). A focus on messaging to communities on the value of preventive maintenance could improve payment outcomes, as this is currently uncommon. Intuitively, the correlation between pump fixed and payment validates that communities are unwilling to pay for services when their hand-pump is not fixed. The subset of maintenance visits in which a payment received has 98.8% functionality after maintenance services. Given the positive correlations between payment and pump functionality after maintenance services demonstrated by results of Models 2 and 3, investment in preventive maintenance communication could have reinforced positive influence over functionality.

3.3. The role of community—Service provider relationships

Results suggest reciprocal relationships between functionality and payment outcomes. Models 2 and 3 indicate correlations between functioning after maintenance services and payment. This suggests that high performance of mechanics contributes to improved valuation of maintenance services. As model results do not indicate causation, various underlying mechanisms could contribute to the observed trends between payment and functionality. While this correlation could signal community valuation of visible maintenance as discussed above, it also could suggest that technician performance is variable upon payment compliance. As noted in the introduction, in more recent years mechanics were given discretion to not perform maintenance services for communities that were unwilling but "perceived as able" to pay. While these visits were indicated as "monitoring" in 2020 and included as control effects in both functionality models, data is not available across the span of the study, and "mechanic discretion" remains a limitation in interpretation of results. WfG mechanics have reported that speaking with communities about payment has become a large portion of their job responsibilities, and it is feasible that payment reinforces technician motivation to repair wells. While results do not identify the driving force behind the observed relationship, it can be presumed that there is a significant dynamic between payment and mechanic performance. This

dynamic, visualized through select marginal effects from Models 2 and 3 in Fig 4, could suggest that building relationships of trust between mechanics and communities promotes service valuation and contributes to payment compliance.

The idea of trust as a motivator behind payment is supported by observed correlations in Model 3 for both Time Since Last Visit and Distance to Nearest WfG Office, as pumps in close proximity to offices have higher odds of payment (OR for 20 km change: 0.95, 95% CI: (0.95, 0.99)) and tend to be visited more frequently. The fact that WfG collected its highest total revenue in 2020 suggests that the program's extended presence in communities has established levels of trust contributing to payment compliance. WfG experienced a larger average payment per community and the highest number of communities with a payment, growing from 533 communities in 2019 to 733 in 2020.

3.4. Insecurity

Maintaining functional water services is especially a challenge in conflict affected areas. Between 2012 and 2020, the civil war and ongoing insecurity in the CAR has caused variability in the number of hand-pumps serviced and has limited the geographic scope of WfG's maintenance program. For example, in December 2020, WfG suspended all maintenance service across the country in response to political unrest surrounding the CAR's general election. More often, insecurity has impacted the program by restricting regions of travel, with areas that are most insecure having fewer hand-pumps installed and serviced. In Model 1 this impact is observed through the correlation between increased distance to an urban center and decreased odds of pump functionality, as insecurity in remote regions compounds upon accessibility issues, such as challenges accessing resources, which further contribute to dysfunctionality. Excessively long gaps in service delivery resulting from insecurity also correlate with decreased odds of functionality, as indicated by model results. The influence of insecurity on WfG maintenance operations can be seen in Fig 5, which plots annual number of maintenance

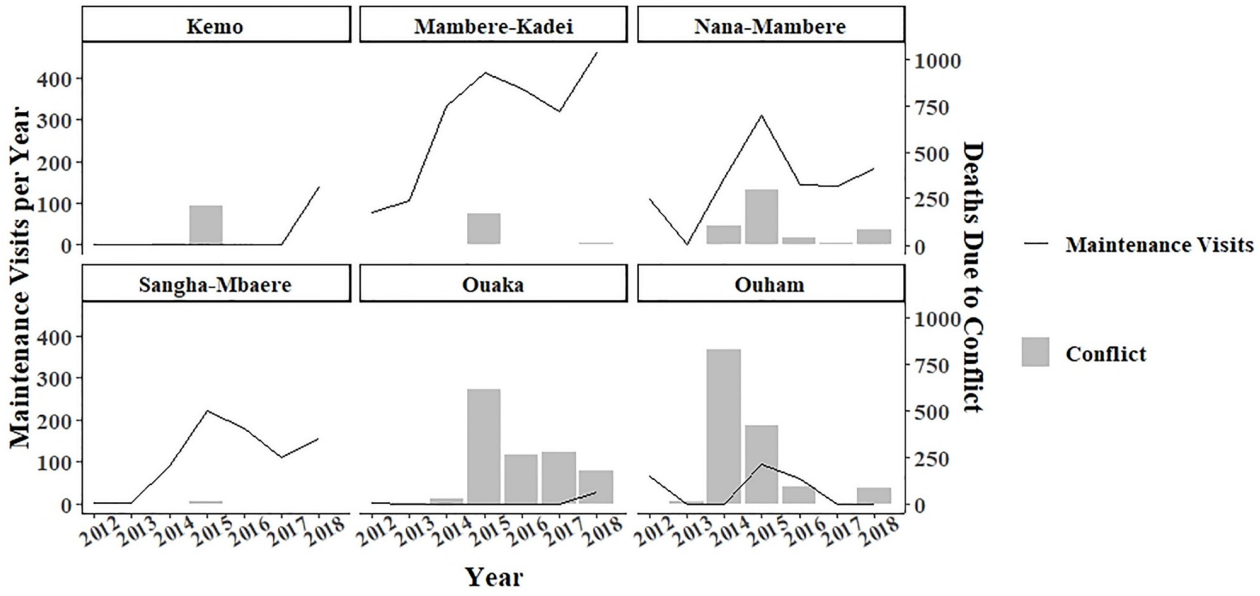

Fig 5. The frequency of WfG maintenance visits compared to reported deaths due to conflict in six prefectures in the CAR demonstrates how insecurity restrains service delivery.

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visits against events of organized violence across six select CAR prefectures. Data for conflict is from the Uppsala Conflict Data Program which catalogs events of lethal violence in geo-coded data [44, 45].

Regions such as Ouham and Ouaka prefectures that experienced higher rates of violence continued to have low numbers of maintenance visits, whereas regions such as the Mambéré-Kadéï and Sangha-Mbaéré that experienced low levels of violence had more maintenance visits. Maintenance visits in the Kémo prefecture were very low until 2017, and although data for conflict is unavailable in 2019 and 2020, maintenance visits in the region continued to grow throughout these years as security in the prefecture improved. The CR approach is adaptable to regional changes in security and allows service provision to be continued uninterrupted in some regions while others are inaccessible. However, instability and violence are a severe limiting factor in sustaining water service provision within this maintenance model. Increased research and attention to WASH in fragile contexts is critical as humanitarian need are on the rise with conflicts becoming more frequent, affecting more people and lasting longer [19].

3.5. Limitations

The regression models presented in this report are exploratory and do not provide evidence of causation. Additionally, variables included in models are not exhaustive of factors that could influence water system functionality and payment compliance. Notably, the payment model lacks relevant demographic or cultural information, such as community income levels, which represent social determinants of payment compliance, and functionality models lack data on infrastructure age and hydrological information, such as water table depth. Studies indicate a strong relationship between infrastructure age and functionality [5, 6, 10, 46]. While borehole deterioration is inevitable over time, CR, HM, and RR programs highlighted in this study provide only hand-pump maintenance services and do not include borehole rehabilitation. Infrastructure age is unknown for a majority or water points in this study, preventing this important determinant from being accounted for. Additionally, data limitations constrain this study from considering more nuanced metrics for water service delivery, such as duration of system downtime or indicators of water quality, that could provide a more holistic portrait of sustainability beyond binary functionality [47]. Errors in model results additionally could have incurred from errors in data entry at maintenance visits. Data availability is a challenge in fragile contexts, resulting in water systems in the CAR being under reported and under researched. Despite data limitations, analysis of the existing data can still provide valuable insight and draw attention to the unique issues of service delivery in the most challenging contexts.

4. Conclusion

This paper explored nine years of data from the NGO Water for Good's circuit rider hand-pump maintenance program in the Central African Republic. Using mixed effect logistic regression models, this study identified determinants of water point functionality and payment compliance within the maintenance program. Results of the regression models suggest that improved response time, proximity to urban centers, and proximity to other WfG hand-pumps correlate with improved water point functionality. Proximity to maintenance program headquarters, hand-pump functionality, and frequency of maintenance visits emerged as significant determinants of payment compliance. Increased community awareness and socialization activities around the value of preventive maintenance for CR programs and on reporting system breakdowns for responsive HM and RR programs are recommended for improving WfG service delivery.

This analysis presents a case study of the utility of partnering with implementing organizations and long term data sets to improve understanding of sustainable WASH service delivery. Partnering with implementation organizations can help elicit unique insights from monitoring data by applying a more rigorous statistical lens than might otherwise occur. Improved digital monitoring technologies, such as the mobile data platform utilized by WfG mechanics, have potential to support improved data quality in data scarce regions like the CAR to further support WASH research and asset management. Longitudinal data analysis could potentially be applied to help build sector knowledge about various water system maintenance models and further optimize water service provision.

While functionality outcomes in this maintenance program were promising, conflict and general insecurity remain a barrier to sustaining service delivery even within the CR model. The CAR government capacity for supporting and regulating the water sector is limited and the WfG maintenance program is highly subsidized by external donors. Low levels of payment compliance and cost recovery indicate that external support is currently essential to maintain these programs within the context. Although the high functionality rates of hand-pumps observed within WfG's service program underscores the effectiveness of professionalized preventive maintenance through the CR model in fragile contexts, the challenge of implementing fully professionalized maintenance services and sustainable systematic improvements to reliable service delivery is contingent upon a stable and enabling context.

Supporting information

S1 Text. Model covariate summary, details, and calculations.
(DOCX)

S2 Text. Conceptual diagrams for relationships among variables.
(DOCX)

S3 Text. Full model and sensitivity analysis results.
(DOCX)

S4 Text. Inclusivity in global research questionnaire.
(DOCX)

S1 Data. Operational data used in modeling.
(CSV)

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Author Contributions

Conceptualization: Eliza Lynn Fink, Pranav Chintalapati, Adrienne Lane.

Data curation: Eliza Lynn Fink, Andrew Wester.

Formal analysis: Eliza Lynn Fink.

Funding acquisition: Amy Javernick-Will, Karl Linden.

Investigation: Eliza Lynn Fink, Pranav Chintalapati, Adrienne Lane.

Methodology: Eliza Lynn Fink.

Project administration: Amy Javernick-Will, Karl Linden.

Supervision: Pranav Chintalapati, Karl Linden.

Visualization: Eliza Lynn Fink.

Writing – original draft: Eliza Lynn Fink.

Writing – review & editing: Pranav Chintalapati, Adrienne Lane, Andrew Wester, Amy Javernick-Will, Karl Linden.

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