Determinants of compliance with drinking water standards in rural Puerto Rico between 1996 and 2000: a multilevel approach

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***Introduction*: Two hundred and thirty nine (239) drinking water systems in Puerto Rico are not connected to the Puerto Rico Aqueducts and Sewers Authority (PRASA), and are thus known as Non-PRASA drinking water systems. Population served estimates by Non-PRASA systems are in the 100,000 to 300,000 range.**

***Objectives*: To identify the determinants of compliance with drinking water standards by rural drinking water systems in Puerto Rico. To identify the best analytical methods for studying the problem of non-compliance with drinking water standards in Puerto Rico and its generalization to similar communities elsewhere.**

***Methods*: We reviewed capacity development and drinking water system evaluations performed by governmental and academic institutions between 1993 and 2004. Community and system variables were used to fit a multilevel model to predict compliance with drinking water standards. Data was obtained from the Environmental Protection Agency' Safe Drinking Water Information System and the Puerto Rico Health Department drinking water database for 231 systems, serving 90,000 persons.**

***Results*: There was an 11% increase in compliance (1996=4%; 2000=15%), a decrease of 13,634 people served by non-compliant systems (1996=86,169; 2000=72,535) and a 6% decrease in the number of non-compliant systems which had installed treatment equipment (1996=93%; 2000=87%). The prevalence of compliance among those systems that had installed treatment equipment was higher than among those systems that did not have treatment equipment, after adjusting by the time period (est. POR=2.2, 95% CI, 1.40 - 3.44).**

***Conclusions*: Our findings suggest alternative public health strategies are needed to ensure sustained safe water capacity in rural communities.**

Key words: Drinking water quality, Determinants of environmental health, Multilevel models.

Approximately 125,000 residents of Puerto Rico are at risk for acute and chronic waterborne illness due to continuous non-compliance with drinking water quality standards. Lack of compliance with drinking water standards by rural systems not connected to the government run Puerto Rico Aqueducts and Sewers Authority (Non–PRASA systems) has been recognized as a public health threat by the Department of Health in Puerto Rico (PRDOH) since the 1980's (1).

1.1. Description of Non-PRASA systems

In Puerto Rico there are 239 rural drinking water systems identified by the PRDOH as Non-PRASA aqueducts. These private drinking water systems are mostly located in rural, economically challenged areas and serve communities with low average education levels, as well as high unemployment and under-employment rates (2).

A surface water Non-PRASA system consists of a makeshift intake at a spring where a very small reservoir is made with rocks and concrete. A 2" PVC line delivers by gravity the raw water to a small distribution tank, which may or may not be properly designed and covered. Some systems have disinfection equipment installed at the distribution tank, but it may not be in use. From the distribution tank a 4" main delivers water again by gravity to each house by PVC pipes. Surface water systems usually do not filter the water and almost never monitor disinfectant residual in the distribution line (3).

Non-PRASA drinking water systems are mostly operated without adequate planning and development strategies, and often do not consider the use of treatment

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The authors have no financial interests to disclose.

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technologies. According to DOH records, approximately 30% of the systems have not installed any kind of treatment technology. Interamerican University researchers have found, while performing sanitary surveys to Non-PRASA systems, that many systems with treatment technology in place, do not use installed tablet chlorinators consistently (4). Besides being in violation of local and federal drinking water regulations, these inadequately planned and managed water systems represent a potential health risk to the communities they serve.

The multiple attempts at capacity development of Non-PRASA systems by public and private entities need to be assessed objectively, as part of a strategic planning and management approach implemented to address the chronic non-compliance of Non-PRASA systems. An eco-social framework (5) was used to develop a multilevel logistic regression model for longitudinal data, which examines the determinants of compliance by Non-PRASA systems between 1996 and 2000. The multilevel modeling strategy was utilized to predict compliance with drinking water standards by small community systems in Puerto Rico.

Materials and Methods

A review of the Non-PRASA Inventory of the DOH and of 19 unpublished Master in Environmental Health Theses from the University of Puerto Rico's Faculty of Biosocial Sciences and School of Public Health (UPR-SPH), which evaluated 45 Non-PRASA systems during the 1990's, was performed to obtain baseline characteristics of representative Non-PRASA drinking water systems. A random coefficient for longitudinal data (multilevel) model (6) was fitted to predict compliance with drinking water standards by small community systems in Puerto Rico between 1996 and 2000. Compliance was defined as a dichotomous variable measuring adherence to total coliform and turbidity standards for drinking water.

Data was obtained from the Environmental Protection Agency' Safe Drinking Water Information System and the Puerto Rico Health Department drinking water database. The study population was the 231 community systems included in the Non-PRASA Strategy in 1996 serving approximately 90,000 people. The statistical analysis consisted of two parts: First, the description of the systems and the population served until 2004; Second, the quantification of the association between compliance and the following variables: population served, watershed, treatment, year, treatment modality, neighborhood index and capacity development. The prevalence odds ratio (POR) was used to estimate this quantification with 95% confidence intervals by using a logistic regression model. The parameter estimation of this model was performed with the following methods: 1) Assuming independent observations, the parameters were considered fixed and were estimated with a Generalized Linear Model (GLM) using maximum likelihood method (7); 2) Assuming correlated observations, the parameters were estimated using Generalized Estimating Equations (GEE) with population averaged approach (8); 3) Assuming correlated observations, considering the within variability (for each aqueduct) and the between variability (between aqueducts), the parameters were estimated with a Generalized Linear and Latent Mixed model using adaptive quadrature approach (GLLAMM) (9). All the statistical analysis was performed using STATA 8.0, (Stata Corporation, Texas, 2003).

Results

PRASA updated the Non-PRASA Inventory of the DOH in 2004. The main results are summarized in Table 1. The large majority of the systems do not comply with minimum health requirements (87%). The majority of systems do not want to connect to PRASA´s distribution network (61%). More than half of the systems are within two miles (3,600 meters) of PRASA´s distribution network (56%). The total estimated capacity of the systems is almost 11 million gallons per day (MGD). Per capita water consumption was 93.4 gallons per day. The mean annual budget of the systems was $8,867, with a lowest budget of $100 and a highest budget of $80,000. The total population served was 114,640 people. The mean population served by Non-PRASA systems was 507 people (10).

The review of UPR Master Theses showed that the mean monthly income was $678, with a maximum of $1,038, a minimum of $200 and a standard deviation of $248. The population served mean was 280, with a maximum of 1,131, a minimum of 31 and a standard deviation of 267 people. Half of the 44 systems analyzed by the Master students had a ground water source, 50% disinfected the water, 50% cleaned the tank regularly, 67% used chlorine tablets dispensers for disinfection and only one system had any type of filtration equipment installed. Yet, 60% tested positive for contamination with fecal coliforms and 50% exceed the turbidity standard.

An 11% increase in compliance was observed by the drinking water systems during the study period (1996=4%; 2000=15%). During this same time period the number of people served by non-compliant systems decreased by 13,634 (1996=86,169; 2000=72,535) and the number of non-compliant systems which had installed treatment equipment also decreased (1996=93%; 2000=87%).

Table 1. Summary findings of 2004 update to Non-PRASA Inventory.

	Number	Percentage	Comments
Total number of systems contacted	239	100%	All the Systems in Non-PRASA Inventory
Total number of systems evaluated	227	95%	
Superficial sourcewater	101	45%	
Groundwater sourcewater	132	58%	
System provides disinfection	159	70%	Percentage of systems visited
System does not provide treatment	67	30%	High health risk
Superficial systems w/o disinfection	54	24%	Highest health risk
Superficial systems w/o filtration	98	43%	Do not comply with EPA treatment rule
System close to PRASA network	128	56%	Two miles (3,600 meters) or less
PRASA & Non/PRASA connections	59	26%	Potential contamination risk to PRASA network
Superficial systems w/o disinfection close to PRASA network	51	23%	PRASA is a real compliance alternative
Superficial systems w/o filtration close to PRASA network	32	14%	Highest connection priority
System willing to connect to PRASA	85	39%	
System willing to connect to PRASA	133	61%	Main reason is lack of trust in PRASA's dependability
Good operation and maintenance	11	5%	
Operation needs improvement	17	8%	
Deficient operation	93	87%	Do not comply with minimum health requirements
Provided budgetary information	182		
Mean annual budget		$8,867	
Lowest annual budget		$100	
Highest annual budget		$80,000	
Total population served		114,640	
Mean population served		$507	
Total number of houses served		25,266	
Mean number of houses served		$112	
Mean number of people per housing unit		4,53	
Total estimated capacity (gpd)		10,689,110	
Mean estimated capacity (gpd)		47,296	
Daily water use per household (gpd)		423	
Daily water use per capita (gpd)		93.4	

Source PRASA, 2004

Most of the Non-PRASA systems (96%) serve less than 100 persons. Of those systems that serve between 100 and 500 people, most (93%) do not comply with drinking water regulations. The results of the bivariable analyses shown in Table 2, show that a higher probability of compliance was associated with the use of treatment technology (est. POR=7.02, 95% CI: 2.23-22.1), the use of a well as a drinking water source (est. POR=9.83, 95% CI: 4.92-19.62), and a higher number of population served (est. POR=4.33,1.65-11.35).

The multivariable model that was chosen with a Stepwise selection approach for multiple logistic regression modeling, included as predictors: treatment technology; drinking water source; and population served. The difference between the Deviance (517) and Degrees of Freedom (1084) was significant (p<.001), a sign of under-dispersion, was proof that the model is inadequate for this data.

The prevalence of compliance estimated with GLM (prev.=0.080) and GEE (prev.=0.081) was four times higher than the estimate obtained with multilevel modeling using a Generalized Linear Mixed Model (GLLAMM) (prev.=0.02). A high intra-class (intra-aqueduct) correlation (ρ=0.59) was observed under the fixed effects model. The intra-class correlation decreased to 0.43 when the random intercept model was fitted, adjusting for source water and population served. The prevalence of compliance among those systems that had installed treatment equipment was higher than among those systems that did not have any treatment equipment installed, after adjusting for time period (est. POR=2.2, 95%CI, 1.40 - 3.44).

The prevalence of compliance modeled with posterior Bayes estimates for all Non-PRASA systems using a Random Intercept Crude Model is shown in Figure 1a. Some clustering is observed at different values of compliance prevalence. There are close to 10% of the systems with a compliance prevalence range that fluctuates between 0.2 and 0.8. The rest have almost no probability of compliance. The prevalence of compliance obtained with

Table 2. Predictors of compliance with drinking water regulations.

		Odds Ratio*	95% Confidence Interval		p**
Population served	<100	1.00			
	100-499	1.89	0.83	4.29	0.123
	500-999	3.76	1.56	9.02	0.001
	≥ 1000	4.33	1.65	11.35	0.001
Watershed	Surface	1.00			
	Ground Water	9.23	4.92	19.62	<0.001
Treatment	No	1.00			
	Yes	4.91	2.55	9.43	<0.001
Year	1996	1.00			
	1997	2.16	0.94	4.93	0.067
	1998	2.69	1.20	6.02	0.012
	1999	1.69	0.71	3.99	0.229
	2000	3.14	1.41	6.99	0.003
Treatment modality	No Treatment	1.00			
	Filter and Disinfection	7.02	2.23	2.21	<0.001
Neighborhood index	Low	1.00			
	Average	0.67	0.34	1.32	0.24
	High	1.61	0.31	1.21	0.15
Capacity development	2.17	1.00			
	2.22	0.32	0.14	0.71	0.003
	2.42	0.54	0.27	1.07	0.073
	2.77	0.69	0.36	1.31	0.251
	3.02	0.86	0.46	1.58	0.620

*Crude Odds Ratio **Chi-square χ^2

posterior Bayes estimates for all Non-PRASA systems using a Random Intercept Model adjusted for population served and source water is shown in Figure 1b. The results indicate that approximately 20% of the systems show high variability in the rates of compliance, although overall predicted compliance is low for all the systems.

The marginal probability of compliance (population-based average) for all Non-PRASA systems using a Random Intercept Model, adjusted for population served and source water, is shown in Figure 2a. This model describes an accepted fact in drinking water compliance: groundwater systems have higher probability of compliance than surface water systems. Nonetheless, this multilevel model shows that in some instances, ground water systems have an equal or lower probability of compliance than surface water systems.

The marginal probability of compliance (population-based average) for all Non-PRASA systems using a Random Intercept Model, adjusted for population served and source water, is compared with the conditional probability of compliance in Figure 2b. This contrast shows that the conditional probability model can provide insight into the variability of compliance between each individual system, which cannot be ascertained from the population average estimates.

Discussion

Bringing safe water to rural isolated populations is one of the pending tasks of modernization, given that in 2007 there are still 1 billion persons worldwide who lack access to safe drinking water, many of whom live in rural, geographically isolated communities (11). The results reported in this study underline some of the major themes

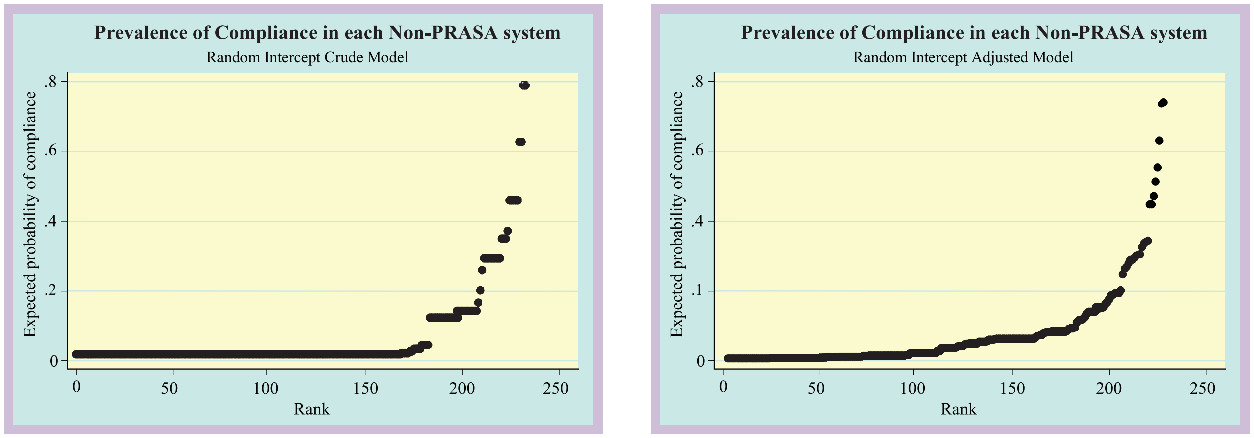

Figure 1. a) Expected probability of compliance by each Non-PRASA drinking water system (prevalence of compliance) estimated with a crude random intercept model. b) Expected probability of compliance by each Non-PRASA drinking water system (prevalence of compliance) estimated with random intercept adjusted model.

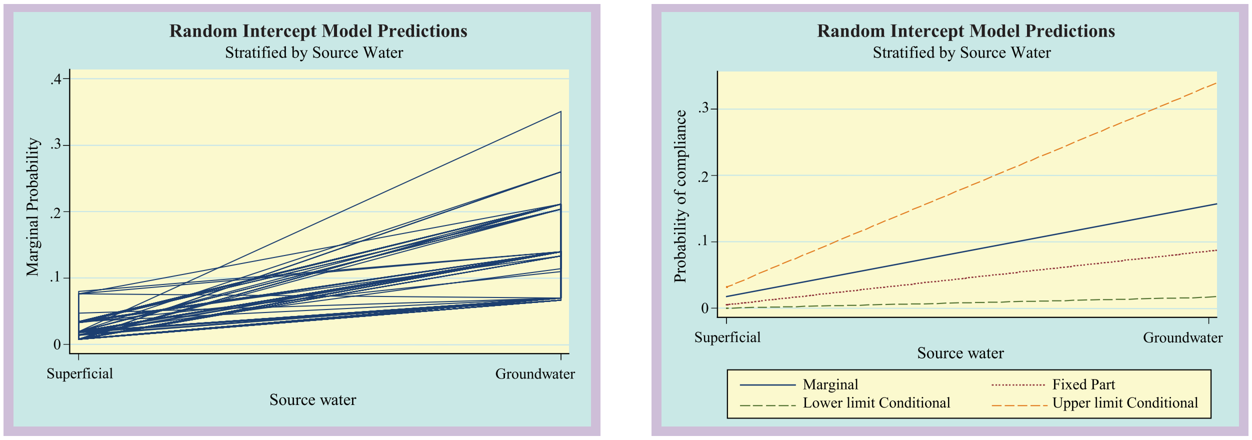

Figure 2. a) Marginal probability of compliance by drinking water systems estimated with a random intercept model stratified by source water. b) Marginal and conditional probability of compliance by drinking water systems estimated with a random intercept model stratified by source water systems estimated with a random intercept model. The upper and lower limit boundaries of the conditional probability indicate a higher level of variability in the predictions of compliance for ground water systems.

that have characterized the implementation of capacity development programs in rural Non-PRASA systems since 1992: Chronic non-compliance with drinking water standards; lack of financial resources to upgrade Non-PRASA systems' infrastructure; some systems do not treat the water at all; a lack of novel alternatives to deal with the problem; and no information available relating violations of drinking water standards by Non-PRASA systems to adverse health outcomes in the communities they serve.

The update of the Non-PRASA inventory in 2004 revealed that most of the systems fail to provide safe water after 12 years of receiving capacity development interventions, working with community leaders to provide technical, managerial and administrative educational sessions as recommended by United States Environmental Protection Agency' Capacity Development Program (CDP). The CDP was designed to develop the technical, financial and managerial capacity of existing drinking water systems, as well as requiring it of new systems in the US (12). There are no clear answers as to why the capacity development efforts in Non-PRASA communities have not produced the desired results after 12 years of sustained implementation, but a better grasp on this issue will benefit similar interventions, in similar communities world-wide.

Shanaghan and Bielanski (13) define the three basic dimensions of capacity development. *Technical capacity* is the physical and operational ability of water systems to meet Safe Drinking Water Act (SDWA) requirements. The three key elements of technical capacity are source water adequacy, infrastructure adequacy, and technical knowledge and implementation. *Managerial capacity* relates to a system's institutional and administrative capabilities. It is the ability of a water system to conduct its affairs in a manner enabling the system to achieve and maintain SDWA compliance. The key elements of managerial capacity are ownership, accountability, staffing and organization, and effective external linkages. *Financial capacity* refers to the water system's ability to acquire and manage sufficient financial resources to allow the system to achieve and maintain compliance with SDWA requirements. The three key elements of financial capacity are revenue sufficiency, creditworthiness, and fiscal management and controls. The considerable overlap between all three dimensions is best considered in the context of strategic planning and management. Perhaps it is the lack of financial capacity of some Non-PRASA systems that limits the effectiveness of capacity development efforts.

Our revision of governmental and academic assessments of Non-PRASA systems revealed that many of them could be classified as Environmental Justice communities. Environmental Justice (EJ) communities are defined as those where the residents (1) are a minority and/or low income group, (2) are excluded from the environmental policy setting and/or decision-making process, (3) are subject to a disproportionate impact from one or more environmental hazards, and (4) experience a disparate implementation of environmental regulations, requirements, practices and activities in their communities (14). EJ is concerned with the environmental protection of impoverished minority communities. Most EJ efforts have focused on industrial pollution sites. Drinking water suppliers have not been usually concerned with EJ issues. The United States Environmental Protection Agency (EPA), which sets the drinking water standards in the United States and Puerto Rico, first addressed EJ concerns in regulating drinking water only recently, while developing its proposed rule for radon (15). Framing the issue of unsafe drinking water in rural communities as an EJ justice issue may provide a better understanding of all the dynamic factors that determine the availability of safe drinking water in impoverished rural communities. An objective predictive model that incorporates community and drinking water system variables may be a useful tool to design, implement, and evaluate safe drinking water capacity development interventions, geared to reduce the health risks associated with unsafe drinking water.

Risk models have been proposed for drinking-water-borne risks (16). Multilevel modeling has previously been used to evaluate drinking water compliance (17). The insights gained with the analytic approach used in this research project cannot be obtained with the univariable, bivariable and multivariable analyses that are used in drinking water research and public policy setting. For example, the analytic strategy used in this paper can identify rural ground water systems that should be targeted for special educational and capacity development interventions, because of their lower probability of compliance when compared to other ground water systems and to surface water systems.

The intra-class correlation in this model represents the correlation between two compliance measurements taken at each aqueduct, which was also randomly selected. This correlation is attributable to variables and characteristics of the drinking water systems which are not measured, but have an effect on the compliance probability. The difference between both intra-class correlation measures is due to factors associated to the source water and the population served, which impinge on the correlation among the repeated measures, independently of the characteristics of the aqueducts themselves. It is important to highlight that the variance at the aqueducts level (second level) is not directly observed when comparing the means across the aqueducts level, because there is an additional variance, which corresponds to the variance at the repeated measures level (first level), which has a binomial distribution.

The prevalence of compliance by Non-PRASA systems in this study was calculated utilizing different estimation methods. The reason for the large differences in the estimated prevalence when utilizing GLM, GEE and GLLAMM can be attributed to the high correlation between compliance measures in each system (>.4). The differences in the estimated prevalence of compliance is attributed to the fact that GLLAMM takes into account the correlation between repeated measures and models the variability across two or more levels. GLM assumes independent observations and does not model different levels. GEE takes into consideration the correlation in the data and creates a population based average, but it treats the different levels' variance as a nuisance (18).

The change in POR estimated with different models: Fixed parameters (est. POR=2.23; p-value=0.03), Random Intercept (est. POR=7.51; p-value=0.03) and Random Coefficient (est. POR=4.51, p-value=0.178) suggests the importance of multilevel modeling for public policy development and implementation. Depending on the scientific question an analytic method that provides population averages might be better than a method that can discern individual system-specific characteristics.

This study relies quite significantly on unpublished data from different governmental sources, as well as Master Theses from the Environmental Health Sciences Department of UPR-SPH. It is inevitable that the different methodological frameworks and scope used in these documents lead to discrepancies in fundamental characteristics such as population served by Non-PRASA drinking water systems. Estimates of population served range from approximately 100,000 to 300,000 people served, but there is not yet a consensus on an approximate figure. The methodology and scope of the 2004 PRASA survey resulted in an arithmetic mean of 507 people served by Non–PRASA system, while the population served arithmetic mean obtained in the review of UPR Master Theses was 280 people served. The larger scope of the 2004 PRASA survey lends more weight to their results.

The reliance on unpublished data also limits the accessibility of said documents to other scientists. Obtaining access to these documents, while challenging at times, was an important part of this study. The documents can be requested from the governmental agencies that produced them. Most of them are on file at the Caribbean Division of the Environmental Health Protection Agency, since they were prepared to comply with SDWA requirements or with the goals and objectives of the Non-PRASA Strategy. The Master Theses from UPR-SPH can be located at the Conrado F. Asenjo Health Sciences Library, located in UPR's Medical Sciences Campus.

System-specific determinants of compliance obtained in this project, such as source water and population served may be utilized to develop evidenced based interventions in Non-PRASA communities. These results underline the need to use alternative strategies in public policy implementation to ensure that rural drinking water systems in Puerto Rico have safe drinking water. Furthermore, this article provides a framework of interpretation and analysis which can be adopted by public health agencies to evaluate the effectiveness of their regulatory compliance efforts.

Resumen

La mayoría de los sistemas de agua potable en Puerto Rico no están conectados a la red de la Autoridad de Acueductos y Alcantarillados (AAA), razón por la cual se identifican como sistemas No-AAA. Los estimados de la población servida por los sistemas No-AAA varían entre 100,000 y 300,000 personas. El objetivo de este estudio fue identificar los determinantes de cumplimiento con los estándares de agua potable en los sistemas rurales de Puerto Rico. Además, se identificaron métodos analíticos para estudiar los determinantes de cumplimiento con los estándares de agua potable en los sistemas rurales de Puerto Rico y su generalización a otros sistemas. Para lograr los objetivos, revisamos las evaluaciones de desarrollo de capacidad y de evaluación de sistemas que instituciones académicas gubernamentales le hicieron a los sistemas No-AAA entre 1993 y 2004. Ajustamos un modelo de niveles múltiples para predecir el cumplimiento de los sistemas No-AAA con los estándares de agua potable utilizando variables de sistema y variables de la comunidad. Los datos utilizados para este estudio fueron obtenidos del Sistema de Información de Agua Potable de la Agencia Federal de Protección Ambiental (US EPS, por sus siglas en inglés) y de la base de datos del Departamento de Salud de Puerto Rico. Se encontró un aumento en el cumplimiento (1996=4%; 2000=15%), una reducción en la población servida por los sistemas que no estaban en cumplimiento (1996=86,169; 2000=72,535) y una reducción de un 6% en el numero de sistemas que no estaban en cumplimiento que habían instalado equipo de tratamiento (1996=93%; 2000=87%). El análisis jerárquico reveló que el cumplimiento de los sistemas que tenían equipo de tratamiento instalado era dos veces mayor (POR 2.19, 95% CI, 1.40, 3.44) que el cumplimiento de los sistemas que no tenían equipo de tratamiento instalado (p<.001). Los resultados de la investigación se pueden utilizar para racionalizar la inversión de recursos fiscales y humanos en el desarrollo de la capacidad de los sistemas No-AAA existentes.

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