Effect of water and sanitation on childhood health in a poor Peruvian peri-urban community

William Checkley, Robert H Gilman, Robert E Black, Leonardo D Epstein, Lilia Cabrera, Charles R Sterling, Lawrence H Moulton

Summary

Background Inadequate water and sanitation adversely affect the health of children in developing countries. We aimed to assess the effects of water and sanitation on childhood health in a birth cohort of Peruvian children.

Methods We followed up children once a day for diarrhoea and once a month for anthropometry, and obtained data for household water and sanitation at baseline.

Findings At 24 months of age, children with the worst conditions for water source, water storage, and sanitation were 1·0 cm (95% CI 0·1–0·8) shorter and had 54% (−1 to 240) more diarrhoeal episodes than did those with the best conditions. Children from households with small storage containers had 28% (1–63) more diarrhoeal episodes than did children from households with large containers. Lack of adequate sewage disposal explained a height deficit of 0·9 cm (0·2–1·7) at 24 months of age. Better water source alone did not accomplish full health benefits. In 24-month-old children from households with a water connection, those in households without adequate sewage disposal and with small storage containers were 1·8 cm (0·1–3·6) shorter than children in households with sewage and with large storage containers.

Interpretation Our findings show that nutritional status is a useful endpoint for water and sanitation interventions and underscores the need to improve sanitation in developing countries. Improved and more reliable water sources should discourage water storage at risk of becoming contaminated, decrease diarrhoeal incidence, and improve linear growth in children.

Lancet 2004; **363:** 112–18
See Commentary page 94

Departments of International Health (W Checkley MD, Prof R H Gilman MD, Prof R E Black MD, L D Epstein PhD, L H Moulton PhD) **and Biostatistics** (L H Moulton), **Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD, USA; Proyectos de Informática, Salud, Medicina, y Agricultura, Lima, Peru** (W Checkley, R H Gilman, L Cabrera RN)**; Universidad Catolica de Chile, Departamento de Estadística, Santiago, Chile** (L D Epstein)**; and Department of Veterinary Science, University of Arizona, Tucson, AZ, USA** (Prof C R Sterling PhD)

Correspondence to: Dr William Checkley, Johns Hopkins University, Bloomberg School of Public Health, Department of International Health, 615 North Wolfe St W5515, Baltimore, MD 21205, USA (e-mail: wcheckle@jhsph.edu)

Introduction

Improvements in water supply and sanitation have been historically documented to benefit health and improve life expectancy.[1–4] In industrialised countries, death and disease due to poor water supply and sanitation are generally restricted to occasional outbreaks affecting vulnerable subpopulations. But much less progress in water and sanitation has been attained in the developing world. Such a trend is perhaps evidenced most by the slow improvements in infrastructure achieved during the International Water and Sanitation Decade (1981–90), the coverage outcomes of which were well short of expectations, especially in sanitation.[5] Nonetheless, that period stimulated research on the benefits of water supply and sanitation on health, complemented studies that assessed the role of improved water and sanitation on childhood health, and reported reductions in death,[6–8] in diarrhoeal diseases,[8–10] and in parasitic infections.[11,12]

Nonetheless, the effects of improved water supply and sanitation on childhood growth have not been clearly established. Although most studies have documented benefits on weight gain[13] and weight-for-height,[14,15] findings have been less clear on long-term growth outcomes such as stature or height-for-age.[12,13,15–21] A better understanding of the effects of water and sanitation on linear growth is warranted, in view of current knowledge on the interaction between diarrhoea and malnutrition and their adverse effects on childhood health. Here, we assess the effects of water and sanitation on linear growth, diarrhoea, and the prevalence of parasites in a birth cohort of Peruvian children.

Materials and methods

Participants

Between April, 1995, and December, 1998, we did a field study in Pampas de San Juan, a periurban community in Lima, Peru, to assess the effects of water and sanitation on linear growth, diarrhoeal diseases, and prevalence of parasites. The study design has been described elsewhere.[22] Children were recruited at birth and followed up for 35 months. Only the first child born during the recruitment period was recruited in each household.

At recruitment we also did a survey of living conditions in the households, including water source, water storage, and sanitation. Households obtained water via a home connection, from cistern trucks operated by the public water company, from a community standpipe, or from a neighbour. A home connection was most frequently available in houses closest to paved roads. Households stored water in containers of varying sizes, from large cement cisterns to small uncovered containers.

Procedures

We classified water source, water storage, and sanitation into three categories each. The household water sources were classified as home connection, cistern truck or

	Children (n=230)
Water source	
Home connection	133 (58%)
Cistern truck or standpipe	12 (5%)
Neighbour	85 (37%)
Water storage	
Large	112 (49%)
Medium	18 (8%)
Small	100 (43%)
Sanitation facility	
Home	110 (48%)
Latrine or equivalent	77 (33%)
No facility	43 (19%)

Table 1: **Facilities in participating households 1995–98**

community standpipe, and water obtained or purchased from a neighbour. If water was stored in the household, we classified the container size as: large, medium, or small. Large containers were generally cement cisterns covered with a lid, flat platform, or large plastic bag. Small containers included pots, pans, barrels, and buckets, and were often found uncovered. Other containers were generally 50 gallon (189·5 L) drums and were classified as medium sized. Water storage quality was measured as the size of the smallest container used. Household sanitation was classified as: sewage connection, latrine or equivalent, and no facility available. We defined the best conditions for water and sanitation as having a home connection and sewage, and water storage in large containers; and, worst conditions as lack of a home connection, lack of sewage connection, and water storage in small containers.

We recorded the height of each child once a month to the nearest 0·1 cm. Recumbent length was measured with a wooden platform and sliding footboard in children younger than 2 years. We measured standing height in children aged 2 years or older.

Diarrhoeal surveillance was done once a day. A diarrhoeal episode began with the first day the mother indicated that the child had diarrhoea and that the child passed three or more liquid or semiliquid stools, and ended when the child passed fewer than three liquid or semiliquid stools in each of two consecutive days. We took stool samples once a week. Field workers provided mothers regularly with 5 mL plastic cups and spoons. At the beginning of the study, field workers instructed mothers on how to fill the plastic cups with fresh stool. Stool samples were tested for *Giardia lamblia* and *Cryptosporidium parvum*. *G lamblia* was identified in fresh and concentrated fecal samples with light microscopy, and *C parvum* with a modified acid-fast Ziehl-Neelsen method.[23]

To study the effects of water and sanitation on height, we used a linear model with random effects[24] and with a continuous autoregressive error term. This model has been described in detail by us previously.[25] The dependent variable was height and predictors were age, water and sanitation, sex, breastfeeding, and maternal height. Random effects accounted for growth heterogeneity across children. The continuous autoregressive error term modelled the serial correlation among measurements within the same child (webappendix, http://image.thelancet.com/extras/03art2140webappendix.pdf).

To assess the individual effects of water source, water storage, and sanitation on height we used separate regression models. These models included interactions with age to estimate age-specific effects. With an additional regression model, we investigated the relation between height difference and sewage and storage in large-to-medium containers versus no sewage and storage in small containers in households with a home connection.

In a subsequent analysis we assessed age-specific differences in height between children with best conditions and children with the worst conditions for water and sanitation. We assessed whether diarrhoeal prevalence, maternal education, and household income per head confounded these effects. We investigated the interaction between diarrhoeal prevalence and water and sanitation in a regression model that included age-stratified indicator variables for worst conditions of water and sanitation, age-stratified cumulative diarrhoeal prevalence, and interaction terms.

We estimated the overall effect of diarrhoeal prevalence on height with a model that excluded water and sanitation but included the history of diarrhoea. For comparability with other studies, we report results on height at 24 months of age. We restricted our analysis of best versus worst conditions for water and sanitation to children aged younger than 29 months because more than half of the cohort did not have data after this age.

We used multivariate time-to-event models to study the effects of water and sanitation on diarrhoeal incidence.[22] Briefly, we fitted incidence data with the counting process model of Andersen and Gill.[26] This method extends the proportional hazards model to account for repeated events in the same child. The model accounted for seasonal effects and controlled for age, nutritional status, breastfeeding, and sex. We used bootstrapped SEs, a robust method to account for disease heterogeneity (webappendix).[27]

We regressed diarrhoeal incidence on water source, water storage, and sanitation on diarrhoeal incidence in separate models to assess their individual contributions. A second model was used to determine age-specific differences in diarrhoea between children from houses with worst conditions for water and sanitation and those from houses with the best conditions. We interpreted variables on the relative hazard scale.

We also assessed whether nutritional status, maternal education, and household income per head confounded the effects of water and sanitation on diarrhoea.

	Home connection		Cistern truck or standpipe		Water from neighbour	
	Height (cm)	n	Height (cm)	n	Height (cm)	n
Age (months)						
0 to <6	60·3 (4·8)	667	60·7 (4·8)	65	59·8 (4·7)	392
6 to <12	69·4 (3·1)	659	70·5 (3·0)	62	68·8 (3·2)	420
12 to <18	75·7 (2·9)	566	76·1 (3·0)	54	74·8 (3·2)	346
18 to <24	80·8 (2·9)	458	80·7 (2·7)	41	79·8 (3·4)	253
24 to <30	84·9 (3·0)	376	84·0 (3·0)	25	83·8 (3·2)	226
30 to <35	88·9 (3·0)	284	86·9 (2·0)	23	88·4 (3·6)	121

Data are mean height (SD) for levels of water source. n=number of anthropometric measurements in age-group.

Table 2: **Relation between height and household water source**

	Large containers		Medium containers		Small containers	
	Height (cm)	n	Height (cm)	n	Height (cm)	n
Age (months)						
0 to <6	60·3 (4·7)	543	60·3 (4·9)	87	59·9 (4·9)	494
6 to <12	69·4 (3·1)	564	69·1 (3·1)	87	69·1 (3·2)	490
12 to <18	75·7 (3·1)	486	75·4 (2·7)	69	75·0 (3·1)	411
18 to <24	80·8 (3·0)	392	80·1 (2·8)	65	80·0 (3·2)	294
24 to <30	84·9 (3·0)	318	84·0 (3·2)	55	84·0 (3·2)	254
30 to <35	88·8 (3·2)	240	88·1 (3·3)	38	88·6 (3·1)	150

Data are mean height (SD) for levels of water storage. n=number of anthropometric measurements in age-group.

Table 3: **Relation between height and water storage**

	Sewage connection		Latrine or equivalent		No facility	
	Height (cm)	n	Height (cm)	n	Height (cm)	n
Age (months)						
0 to <6	60·5 (4·8)	563	60·2 (4·7)	364	59·3 (4·6)	197
6 to <12	69·6 (3·1)	555	69·1 (3·3)	373	68·4 (3·0)	213
12 to <18	76·1 (2·8)	452	74·9 (3·3)	333	74·7 (2·9)	181
18 to <24	81·1 (2·8)	348	79·9 (3·3)	263	79·9 (3·1)	141
24 to <30	85·4 (2·7)	269	83·6 (3·2)	213	84·0 (3·2)	145
30 to <35	89·1 (2·7)	199	88·2 (3·3)	132	88·2 (3·8)	97

Data are mean height (SD) for levels of sanitation. n=number of anthropometric measurements in age-group.

Table 4: **Relation between height and sanitation facility**

We regressed diarrhoeal duration on water and sanitation with a mixed-effects gamma model after adjustment for age, nutritional status, breastfeeding, and sex. The gamma model we used was a generalised linear mixed model with a reciprocal link, gamma errors, and a random intercept (webappendix).[22]

We modelled the prevalence of *C parvum* and *G lamblia* with a log-linear model using a generalised linear mixed model with a log link, binomial errors, and a random intercept.[28] We used this model to investigate the effects of water and sanitation on the prevalence of parasitic infections after controlling for age, sex, breastfeeding, season, and nutritional status. Regression variables were interpreted on the rate ratio scale.

Role of the funding source
The sponsors of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results
Data for diarrhoeal surveillance, water source, water storage, and sanitation were available in 230 children. There were 159 551 child-days of diarrhoeal surveillance. To study the effects on height, we had data for 224 children, with 5038 height measurements. To study the effects on the prevalence of parasites, we had data for 226 children, with 21 294 weekly stool samples. 76% (175 of 230) of children had data for maternal education, and 94% (216) had data for household income per head.

Table 1 shows the facilities in the participating households. 25% (58 of 230) of the children lived in households with best conditions for water and sanitation (home connection and sewage, and water storage in large containers) and 23% (53) lived in households with worst conditions (lack of a home connection, lack of sewage and water storage in small containers).

Tables 2, 3, and 4 show age-stratified height averages by water source, water storage, and sanitation, respectively. Linear regression results are shown in figure 1. By the mixed-effects linear model we found that, at 24 months of age, children from households without sewage were 0·9 cm (95% CI 0·2–1·7) shorter than were children from households with a sewage connection; children from households that stored water in small containers were 0·8 cm (0·4–1·6) shorter than were children from households that stored water in medium to large containers; and children without a home connection were 0·6 cm (–0·1–1·4) shorter than were children with a home connection. In children with a home connection, those without sewage and whose family stored water in small containers were 1·8 cm (0·1–3·6) shorter at 24 months of age than those with sewage and whose family stored water in large containers.

Children from households with the worst conditions for water and sanitation grew less in height than children from households with the best conditions (figure 2). In a subsequent analysis with the linear model, children with the worst conditions at 24 months of age were 1·0 cm (0·1–1·8) shorter than those with the best conditions. Diarrhoeal prevalence, maternal education, and household income per head did not confound the effect of water and sanitation on height, and were not included in the final model. Furthermore, we did not find significant age-specific interactions between the cumulative

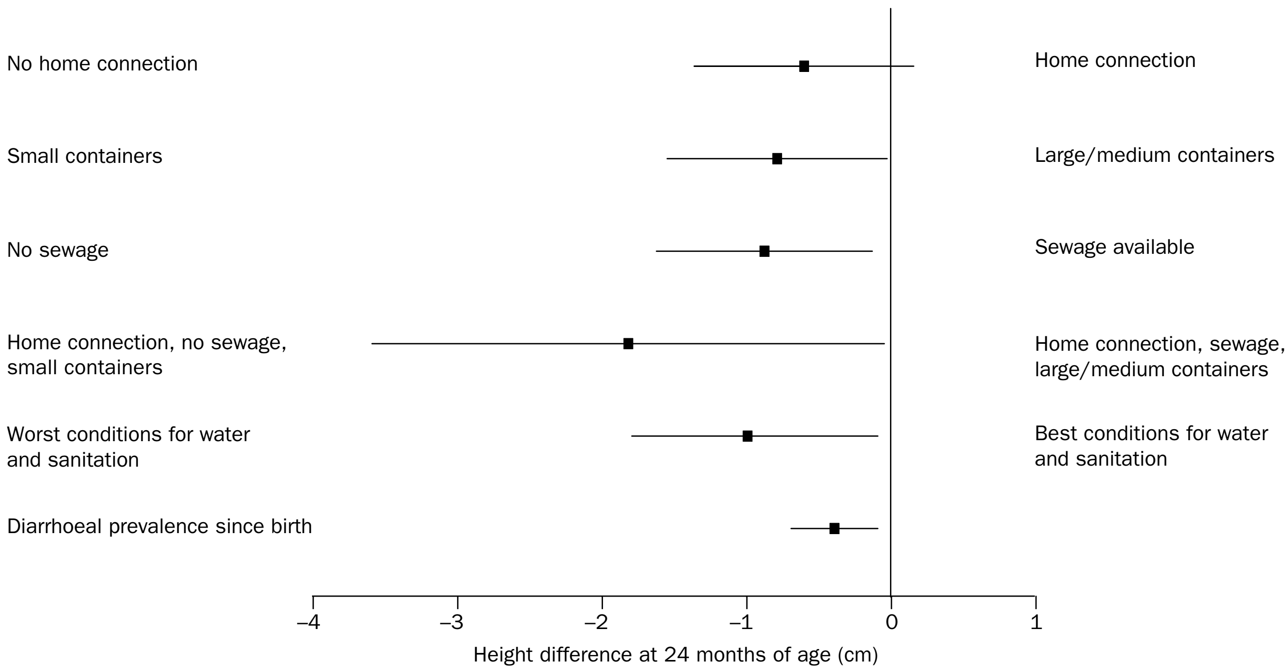

Figure 1: **Estimated height difference at 24 months of age, 1995–98**
Data are estimated height differences at 24 months of age calculated from linear model. Filled squares are mean differences in height between left and right columns. Bars are 95% CI.

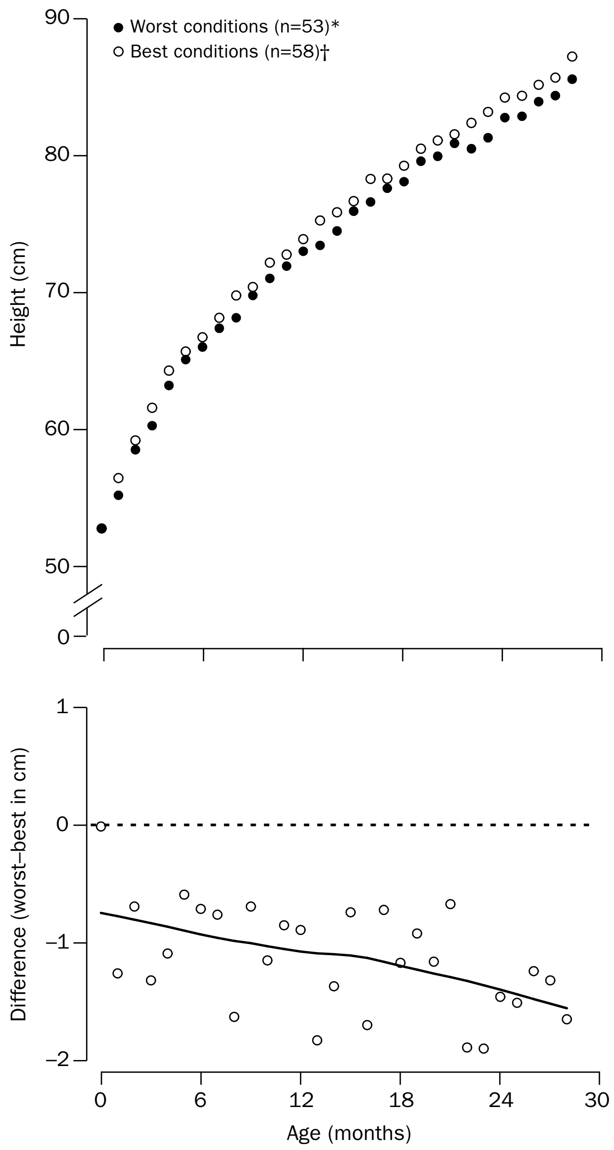

Figure 2: **Linear growth by level of water and sanitation, 1995–98**

(Upper) mean height (cm) estimates versus age (in months). (Lower) height difference between children with worst conditions and children with best conditions of water and sanitation versus age (in months). Smoothed average line highlights time trend. *No home connection, lack of sewage, and storage in small containers. †Home connection, sewage, and storage in large containers.

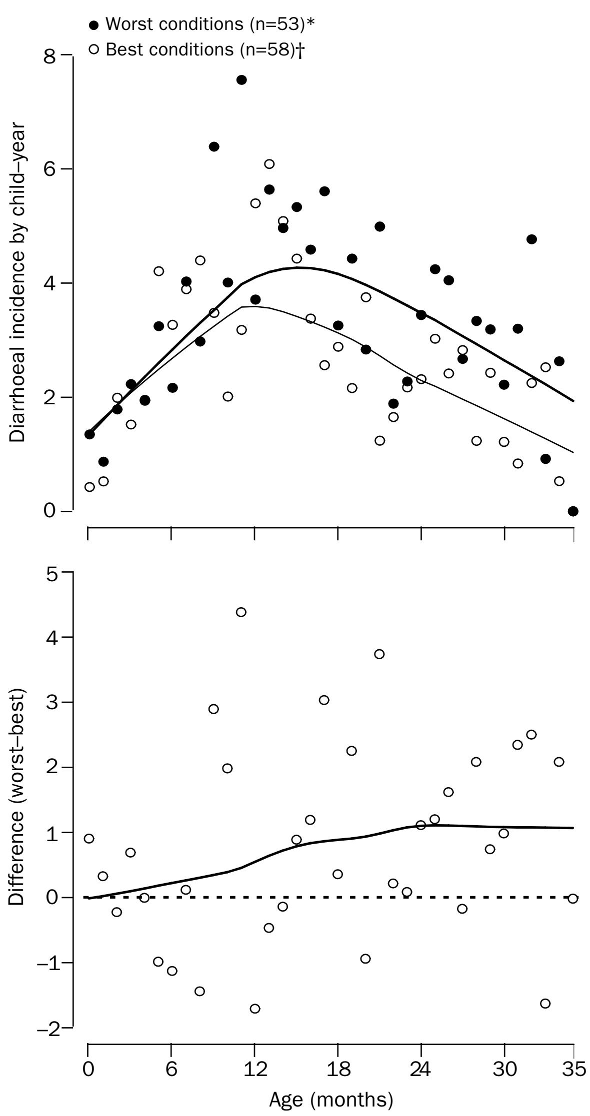

Figure 3: **Diarrhoeal incidence versus age stratified by level of water and sanitation, 1995–98**

(Upper) diarrhoeal incidence for each month of age calculated as number of episodes per 365 child-days. *No home connection, lack of sewage, and storage in small containers. †Home connection, sewage, and storage in large containers. Thick line is smoothed average of diarrhoeal incidence for worst conditions. Thin line is smoothed average of diarrhoeal incidence for best conditions. (Lower) difference in diarrhoeal incidence between children with worst conditions and those with best conditions of water and sanitation versus age (in months). Smoothed average line highlights time trend.

	Child-days	Diarrhoeal episodes	Incidence (child-years)	Relative hazard (95 % CI)	Mean diarrhoeal duration (days)
Water source					
Home connection	93 738	743	2·9	1·00	3·0
Cistern truck or standpipe	8202	75	3·3	1·09 (0·60–1·98)	3·5
Neighbour	57 611	569	3·6	1·21 (0·96–1·52)	2·8
Water storage					
Large	80 790	628	2·8	1·00	3·0
Medium	11 987	106	3·2	1·12 (0·64–1·96)	3·0
Small	66 774	653	3·6	1·28 (1·01–1·63)	2·8
Sanitation facility					
Sewage	75 324	567	2·7	1·00	3·0
Latrine or equivalent	53 125	508	3·7	1·17 (0·88–1·56)	3·1
No facility	31 102	312	3·7	1·19 (0·89–1·60)	2·9

Data are incidence rates per row. Relative hazards estimated with time-to-event regression models, and adjusted for age, nutritional status, sex, and breastfeeding practices.

Table 5: **Diarrhoeal diseases by water and sanitation**

	Child-weeks	C parvum	G lamblia
Water source			
Home connection	12399	88 (0·7%)	1711 (13·8%)
Cistern truck or standpipe	1059	5 (0·5%)	176 (14·6%)
Neighbour	7836	73 (0·9%)	940 (12·0%)
Water storage			
Large	10660	61 (0·7%)	1303 (12·9%)
Medium	1664	27 (1·1%)	242 (11·4%)
Small	8970	78 (0·9%)	1282 (14·2%)
Sanitation facility			
Sewage connection	9822	67 (0·7%)	1201 (12·2%)
Latrine or equivalent	7176	50 (0·7%)	960 (13·4%)
No facility	4296	49 (1·1%)	666 (15·5%)

Prevalence (%) was calculated as ratio of isolates to child-weeks, and presented for each row.

Table 6: **Household water source, water storage practices, sanitation facilities, and prevalence of *C parvum* and *G lamblia***

diarrhoeal prevalence and worst conditions for water and sanitation (p=0·70), as assessed by the mixed-effects linear model.

At 24 months of age, the average child from Pampas de San Juan was 2·5 cm shorter than the WHO/National Center for Health Statistics reference. Diarrhoeal prevalence since birth and throughout the first 24 months of life explained on average 0·4 cm of the height deficit (figure 1). Although the history of diarrhoeal prevalence explained 16% (0·4 cm of 2·5 cm) of the height deficit at 24 months of age, the height difference between worst and best conditions for water and sanitation explained 40% (1 cm of 2·5 cm) of this deficit.

Inadequate water and sanitation increased risk of diarrhoea. Children with the worst conditions for water and sanitation had more diarrhoea than did those with best conditions (figure 3). The multivariate time-to-event model showed that children from households with small water containers had a 28% greater frequency of diarrhoea than did children with large water containers (table 5). The risk of diarrhoea did not change significantly with less adequate levels of water source and sanitation.

A second analysis with the multivariate time-to-event model showed that the risk of diarrhoea per month of age in children with worst conditions was 2% greater (relative hazard, exp(0·018)=1·02; 95% CI 1·00–1·04, p=0·057) than in children with best conditions. At age 24 months, children with worst conditions for water and sanitation had a 54% greater frequency (exp(0·018×24)=1·54; −1 to 240) of diarrhoea than did children with best conditions. Nutritional status confounded the effect of water and sanitation on diarrhoeal incidence and was thus included in the model, but household income per head or maternal education did not.

Water and sanitation were not associated with diarrhoeal duration (table 5). The largest difference seen in diarrhoeal duration was between children in households with a latrine or equivalent and those with no facility available. However, this difference was not significant (difference 0·7 days, p=0·48). Children with the worst conditions for water and sanitation did not have longer disease episodes than children with best conditions (p=0·81), as assessed by the mixed-effects gamma regression model.

The prevalence of *C parvum* and *G lamblia* was greater in children who did not have adequate sanitation than in those with adequate sanitation (table 6). Children without sewage had a 62% greater prevalence of *C parvum* (relative risk 1·62, 95% CI 1·03–2·56) than those with sewage, as assessed by the log linear model. The log linear model also showed that inadequate sanitation did not significantly increase the prevalence of *G lamblia* (p=0·17).

Discussion

Inadequate water and sanitation were associated with poorer childhood health. Children with worst conditions for water source, water storage and sanitation were 1·0 cm shorter in stature and had 54% more diarrhoeal episodes than did those with the best conditions.

Our findings show that nutritional status is a useful measure for water and sanitation interventions. In field trials, morbidity, and in particular diarrhoea, is more commonly used as an indicator of childhood health than is nutritional status. Nutritional status, as measured by child anthropometry, however, is one of the most important long-term childhood health indicators second to mortality. Our results support nutritional status as a primary endpoint in water and sanitation interventions.

Second, we found that better water source does not accomplish full health benefits if it is not accompanied by improved sanitation and better practices of water storage. This is best illustrated by our finding that among children with a home connection, those from households without sewage that stored water in small containers were significantly shorter than children from households with sewage that stored water in large containers. Our results are consistent with those of a large cross-sectional multicountry study[29] that showed increases in height for children aged younger than 3 years ranging from 0·8 cm to 1·9 cm with better sanitation.

Third, the effect of water and sanitation on height was independent of the effect of diarrhoeal prevalence. One interpretation of these data is that some of the effect of water and sanitation might have been confounded by socioeconomics. In our analysis, however, neither household income per head nor maternal education confounded the effects of water and sanitation on height. An alternative interpretation is that inadequate water and sanitation is a source of asymptomatic gastrointestinal infections, which are known to affect adversely nutrient absorption and linear growth.[30–32]

Fourth, inadequate water and sanitation were associated with an increased diarrhoeal incidence but were not associated with diarrhoeal duration. Better water and sanitation probably reduces exposure to fecal contamination but might have no effect on host response once diarrhoea has occurred. Thus, water and sanitation interventions are not likely to affect the severity of diarrhoea and it underscores the need for multiple interventions to reduce mortality and severe morbidity from diarrhoea.

Fifth, inadequate water and sanitation services were associated with an increased diarrhoeal frequency and reflects the importance of water storage practices on childhood health. All households in our study stored water, even those with a water connection. Although several studies discuss the role of water source on diarrhoeal risk,[10,13,21] in our study the greatest risk reductions were associated with better storage practices as measured by container size. Small containers recycle their water more frequently than large containers, however, small containers are generally kept inside the household uncovered and open to fecal contamination. By contrast, most households keep large containers outside and covered. These findings would be further strengthened by a measurement of water quality, which we did not do in this study. In a separate field trial, 70 drinking water samples were obtained from households in Pampas de San Juan. Culture on MacConkey agar revealed that 53% of the samples contained potentially pathogenic coliform bacteria (Gilman RH, personal communication). Our data are consistent with studies done in various settings,[33,34] including an earlier study in a Peruvian pueblo joven, which found an association between uncovered water storage and a greater diarrhoeal incidence.[35] We cannot exclude the possibility, however, that container size reflects socioeconomic status. Although the relative effects of water and sanitation on diarrhoea were independent of socioeconomic status (ie, household income and maternal education), unmeasured differences in access and period of time living in Pampas might explain in part household water-storage practices. Other factors that contribute to the practice of water storage, even among households with a water connection, include low water pressure, frequent water rationing, and inadequate if any indoor plumbing. Hence, although in our study population the proportion of households with a private water connection has increased from less than 1% in 1980 to more than 50% in 1995, unreliable water supply and high cost of water[36,37] has forced most households in pueblo jovenes to continue to store water for long periods of time.

In summary, diarrhoea and stunting are important health concerns in children from Peruvian pueblos jovenes. Malnutrition, even when moderate, can affect cognitive ability[38–41] and might lead to decreased work and social mobility later in adulthood. In our study, better water and sanitation were associated with an improved rate of linear growth and a decreased risk of diarrhoea.

Provision of water and sanitation to disadvantaged sectors might be one of the most reliable policies to achieve poverty reduction in developing countries. Such an approach requires multinational agencies and governments to make water and sanitation infrastructure one of their highest priorities.

Contributors
W Checkley conceived the idea of the study, was responsible for statistical analysis and writing of the report, and assisted in data collection. R Gilman was responsible for study design and data collection. He coordinated with field-team members, and participated in writing of the report. R Black participated in writing and editing of the report. L Epstein assisted in developing the analytical framework for the height-growth data and contributed with major editorial comments. L Cabrera was the field-team coordinator. C Sterling participated in the field study. L Moulton assisted in developing the analytical framework for the diarrhoeal incidence data and contributed important editorial comments.

Conflict of interest statement
None declared.

Acknowledgments
This study was supported by a National Research Service Award of the National Institutes of Child Health and Development (F31-HD08488) awarded to W Checkley, an ICTDR grant of the National Institutes of Allergy and Infectious Diseases awarded to The Johns Hopkins School of Public Health (U01-A135894), and by the charitable RG-ER fund, concerned with childhood health in developing countries. We thank M D Chestnut for her substantive contributions to this manuscript, and J B Phu and D Sara for their technical assistance.

References

1 van Poppel, van der Heijden C. The effects of water supply on infant and childhood mortality: a review of historical evidence. *Health Transit Rev* 1997; **7:** 113–48.
2 Preston SH, van der Walle E. Urban French mortality in the nineteenth century. *Popul Stud (Camb)* 1978; **32:** 275–97.
3 Huttly SR. The impact of inadequate sanitary conditions on health in developing countries. *World Health Stat Q* 1990; **43:** 118–26.
4 Esrey SA, Habicht JP. Epidemiologic evidence for health benefits from improved water and sanitation in developing countries. *Epidemiol Rev* 1986; **8:** 117–28.
5 WHO. The international drinking water supply and sanitation decade: end of decade review (WHO/CWS/92·12). Geneva: World Health Organization,1992.
6 Rahman M, Rahaman MM, Wojtyniak B, Aziz KM. Impact of environmental sanitation and crowding on infant mortality in rural Bangladesh. *Lancet* 1985; **2:** 28–31.
7 Victora CG, Smith PG, Vaughan JP, et al. Water supply, sanitation, and housing in relation to the risk of infant mortality from diarrhoea. *Int J Epidemiol* 1988; **17:** 651–54.
8 Esrey SA, Feachem RG, Hughes JM. Interventions for the control of diarrhoeal diseases among young children: improving water supplies and excreta disposal facilities. *Bull World Health Organ* 1985; **63:** 757–72.
9 Huttly SR, Morris SS, Pisani V. Prevention of diarrhoea in young children in developing countries. *Bull World Health Organ* 1997; **75:** 163–74.
10 Aziz KM, Hoque BA, Hasan KZ, et al. Reduction in diarrhoeal diseases in children in rural Bangladesh by environmental and behavioural modifications. *Trans R Soc Trop Med Hyg* 1990; **84:** 433–38.
11 Esrey SA, Potash JB, Roberts L, Shi. C. Effects of improved water supply and sanitation on ascariasis, diarrhoea, dracunculiasis, hookworm infection, schistosomiasis, and trachoma. *Bull World Health Organ* 1991; **69:** 609–21.
12 Huttly SA, Blum D, Kirkwood BR, et al. The Imo State (Nigeria) Drinking Water Supply and Sanitation Project, 2. Impact on dracunculiasis, diarrhoea and nutritional status. *Trans R Soc Trop Med Hyg* 1990; **84:** 316–21.
13 Esrey SA, Habicht JP, Latham MC, Sisler DG, Casella G. Drinking water source, diarrheal morbidity, and child growth in villages with both traditional and improved water supplies in Rural Lesotho, southern Africa. *Am J Public Health* 1988; **78:** 1451–55.
14 Herbert JF. Water quality and wasting in South India. *Trop Geogr Med* 1984; **36:** 375–81.
15 Tomkins AM, Drasar BS, Bradley AK, Williamson WA. Water supply and nutritional status in rural northern Nigeria. *Trans R Soc Trop Med* 1978; **72:** 239–43.
16 Christiansen N, Mora JO, Herrera G. Family social characteristics related to physical growth of young children. *Br J Prev Soc Med* 1975; **29:** 121–30.
17 Henry FJ. Environmental sanitation infection and nutritional status of infants in rural St. Lucia, West Indies. *Trans R Soc Trop Med Hyg* 1981; **75:** 507–13.
18 Herbert JR. Effects of water quality and quantity on nutritional status: findings from a South Indian community. *Bull World Health Organ* 1985; **63:** 143–55.
19 Hasan KZ, Briend A, Aziz KM, Hoque BA, Patwary MY, Huttly SR. Lack of impact of a water supply and sanitation intervention on the nutritional status of children in rural Bangladesh. *Eur J Clin Nutr* 1989; **43:** 837–43.
20 Lindskog U, Bjorksten B, Gebre-Medhin M. Child health and household water supply: a longitudinal study of growth and its environmental determinants in rural Malawi. *Hum Nutr Clin Nutr* 1987; **41:** 409–23.
21 Pickering H. Social and environmental factors associated with diarrhoea and growth in young children: child health in urban Africa. *Soc Sci Med* 1985; **21:** 667–69.
22 Checkley W, Gilman RH, Black RE, et al. Effects of nutritional status on diarrhea in Peruvian children. *J Pediatr* 2002; **140:** 210–18.
23 Arrowood MJ. Diagnosis. In: Fayer R, ed. Cryptosporidium and cryptosporidiosis. Boca Raton, CRC Press, 1997: 43–64.
24 Laird NM, Ware JD. Random-effects models for longitudinal data. *Biometrics* 1982; **38:** 963–74.
25 Checkley W, Epstein DL, Gilman RH, Cabrera L, Black RE. Effects of acute diarrhea on linear growth in Peruvian children. *Am J Epidemiol* 2003; **157:** 166–75.
26 Andersen PK, Gill RD. Cox's regression model for counting processes: a large sample approach. *Ann Stat* 1982; **10:** 1100–20.
27 Moulton LH, Dibley MJ. Multivariate time-to-event models for studies of recurrent childhood diseases. *Int J Epidemiol* 1997; **26:** 1334–39.
28 Littell RC, Milliken GA, Stroup WW, Wolfinger RD, eds. SAS System for Mixed Models. SAS Institute Inc, Cary, 1996.
29 Esrey SA. Water, waste, and well-being: a multicountry study. *Am J Epidemiol* 1996; **143:** 608–23.
30 Checkley W, Epstein LD, Gilman RH, et al. Asymptomatic and symptomatic cryptosporidiosis: their acute effect on weight gain. *Am J Epidemiol* 1997; **145:** 156–63.
31 Lunn PG, Northrop-Clewes CA, Downes RM. Intestinal permeability, mucosal injury, and growth faltering in Gambian infants. *Lancet* 1991; **338:** 907–10.

32 Steiner TS, Lima AA, Nataro JP, Guerrant RL. Enteroaggregative *Escherichia coli* produce intestinal inflammation and growth impairment and cause interleukin-8 release from intestinal epithelial cells. *J Infect Dis* 1998; **177:** 88–96.
33 Mintz ED, Rei FM, Tauxe RV. Safe water treatment and storage in the home: a practical new strategy to prevent water borne disease. *JAMA* 1996; **273:** 948–53.
34 Jonnalagadda PR, Bhat RV. Parasitic contamination of stored water used from drinking/cooking in Hyderbarad. *Southeast Asian J Trop Med Public Health* 1995; **26:** 789–94.
35 Yeager BA, Lanata CF, Lazo F, Verastegui H, Black RE. Transmission factors and socioeconomic status as determinants of diarrhoeal incidence in Lima, Peru. *J Diarrhoeal Dis Res* 1991; **9:** 186–93.
36 Gilman RH, Marquis S, Ventura G, Campos M, Spira W, Diaz F. Water cost and availability: key determinants of family hygiene in a Peruvian shantytown. *Am J Public Health* 1993; **83:** 1554–58.
37 Andrianzen BT, Graham GG. The high cost of being poor: water. *Arch Environ Health* 1974; **28:** 312–15.
38 Berkman DS, Lescano AG, Gilman RH, Lopez SL, Black MM. Effects of stunting, diarrhoeal disease, and parasitic infection during infancy on cognition in late childhood: a follow-up study. *Lancet* 2002; **359:** 564–71.
39 Guerrant DI, Moore SR, Lima AA, Patrick PD, Schorling JB, Guerrant RL. Association of early childhood diarrhea and cryptosporidiosis with impaired physical fitness and cognitive function four–seven years later in a poor urban community in northeast Brazil. *Am J Trop Med Hyg* 1999; **61:** 707–13.
40 Niehaus MD, Moore SR, Patrick PD, et al. Early childhood diarrhea is associated with diminished cognitive function 4 to 7 years later in children in a northeast Brazilian shantytown. *Am J Trop Med Hyg* 2002; **66:** 590–93.
41 Guerrant RL, Kosek M, Lima AA, Lorntz B, Guyatt HL. Updating the DALYs for diarrhoeal disease. *Trends Parasitol* 2002; **18:** 191–93.