Water, sanitation, and hygiene (WASH) factors associated with growth between birth and 1 year of age in children in Soweto, South Africa: results from the Soweto Baby WASH study

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ABSTRACT

Interventions to reduce undernutrition and improve child growth have incorporated improved water, sanitation, and hygiene (WASH) as part of disease transmission prevention strategies. Knowledge gaps still exist, namely, when and which WASH factors are determinants for growth faltering, and when WASH interventions are most effective at improving growth. This study drew cross-sectional data from a longitudinal cohort study and used hierarchical regression analyses to assess associations between WASH factors: water index, sanitation, hygiene index, and growth: height-for-age (HAZ), weight-for-age (WAZ), weight-for-height (WHZ) at 1, 6, and 12 months postpartum among infants *a priori* born healthy in Soweto, Johannesburg. Household access to sanitation facilities that were not safely managed was associated with a decrease in HAZ scores at 1 month ($\beta = -2.24$) and 6 months ($\beta = -0.96$); a decrease in WAZ at 1 month ($\beta = -1.21$), 6 months ($\beta = -1.57$), and 12 months ($\beta = -1.92$); and finally, with WHZ scores at 12 months ($\beta = -1.94$). Counterintuitively, poorer scores on the hygiene index were associated with an increase at 1 month for both HAZ ($\beta = 0.53$) and WAZ ($\beta = 0.44$). Provision of safely managed sanitation at household and community levels may be required before improvements in growth-related outcomes are obtained.

Key words | children, growth, South Africa, WASH

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HIGHLIGHTS

- Provides evidence linking WASH and nutritional status in infants.
- Brings evidence regarding the associations between WASH and nutritional status in children in the South African setting.
- Highlights the importance of access to sanitation at household as well as community levels.
- Begins the process of developing indices related to WASH and nutritional status in children in the South African setting.

INTRODUCTION

Children under 2 years of age are considered as the most at-risk group for undernutrition due to their rapid growth and increased vulnerability to infectious diseases (Derso *et al.* 2017). The World Health Organization (WHO) defines three forms of undernutrition among children – namely stunting, underweight, and wasting – as being 2 standard

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deviations (SD) below the WHO age and sex-adjusted growth standard; for stunting, height-for-age (HAZ); for underweight, weight-for-age (WAZ); and for wasting, weight-for-height (WHZ) (Members of the WHO Multicentre Growth Reference Study Group 2006). *Z*-scores in this regard referring to a statistical measurement of a score's relationship to the median in a group of scores, measured in terms of a standard deviation from the median of the population.

The first thousand days (from conception to 2 years of age) is an integral phase of childhood development due to developmental plasticity and is among the most pertinent periods for interventions aimed at optimising growth and development (Victora *et al.* 2010; Adair *et al.* 2013; Prendergast *et al.* 2014; Norris *et al.* 2017). Developmental plasticity posits that environmental conditions experienced in early life, including nutrition, trigger permanent physiological adjustments that can profoundly influence human biology and long-term health outcomes (Kuzawa 2005; Hochberg *et al.* 2011; Said-Mohamed Pettifor & Norris 2018).

Inadequate nutrition and frequent illness, especially diarrhoea, are among the most commonly implicated causes of undernutrition (Humphrey *et al.* 2015; Cumming *et al.* 2019; Pickering *et al.* 2019a). Nutrition-sensitive interventions to improve undernutrition and child growth have therefore often incorporated water, sanitation, and hygiene (WASH) factors as a strategy to prevent disease transmission. However, recent results from large-scale randomised controlled trials (SHINE and WASH Benefits) have found no effect of basic WASH interventions on childhood stunting and only mixed effects on childhood diarrhoea (Cumming *et al.* 2019). Both studies concluded that more comprehensive WASH interventions may be needed to achieve a major impact on child health. Further, the authors argue that the results do not show that WASH cannot influence child linear growth, but rather that these specific interventions had no influence in settings where stunting remains an important public health challenge (Cumming *et al.* 2019).

In terms of specific WASH-related risk factors, a recent systematic review investigating WASH in sub-Saharan Africa and associations with undernutrition, and governance in children under 5 years of age, found that observational studies more often reported water as a significant risk factor while review articles tended to highlight sanitation as a significant risk factor (Momberg *et al.* 2020b). Across both observational and review studies included in the systematic review, hygiene was the least represented component (Momberg *et al.* 2020b).

The South African context is characterised by particularly high rates of stunting for a middle-income country where in 2016, the prevalence of stunting in children under 5 years of age was 27.4%, while at the same time, 5.9% of children under the age of 5 were underweight and 2.5% were wasted (Statistics South Africa 2017b; Rispel & Padarath 2018). In terms of water infrastructure in South Africa, it was reported in 2015, that 89.4% of South Africans had access to piped tap water, comprised of households having access to either piped water in their dwellings, piped water onto their property, communal and neighbours' taps, the remainder relying on water from rivers, streams, stagnant water pools, dams, wells, and springs (Statistics South Africa 2016; Parliamentary Monitoring Group 2017; Moeti & Padarath 2019). With regard to sanitation infrastructure in South Africa in 2018, 83% had access to improved sanitation facilities, with the final 17% unimproved sanitation facilities proving to be the most difficult to address (Statistics South Africa 2016; Parliamentary Monitoring Group 2017; Moeti & Padarath 2019). The Gauteng province in particular is reported to have the second-highest coverage of access to water (97.7%) and sanitation (91.8%) (Statistics South Africa 2016; Parliamentary Monitoring Group 2017; Moeti & Padarath 2019). In terms of water quality, 2019 data from Johannesburg Water indicate a total of 12 incidents of non-compliance for microbiological safety requirements (presence of *Escherichia coli*), and 10 chemical and physical incidents of non-compliance (related to turbidity). Despite these incidents of non-compliance, overall compliance targets were maintained (Johannesburg Water 2019b; Momberg *et al.* 2020a). For the City of Johannesburg, spending on water and sanitation infrastructure is decreasing, however, so too are the absolute number of people without access to basic water and sanitation services. Spending however, for repair, maintenance, and upgrading of existing infrastructure is increasing (City of Johannesburg 2019; Momberg *et al.* 2020a). Soweto is serviced by three wastewater treatment works, Goudkoppies, Bushkoppies, and Olifantsvlei wastewater treatment works, which remediate both industrial and household wastewater (Johannesburg Water 2019a). The precise configuration of sanitation provision across Soweto is quite diverse and ranges from flush toilets to pit latrines, and portable toilets that are typically arranged in latrine banks. The system of waste disposal, maintenance, and treatment associated with these facilities is decentralised to different outsourced service providers (Momberg *et al.* 2020a). Diarrhoea is still one of the leading causes of morbidity and mortality in South Africa, accounting for approximately 20% of all deaths in children under 5 years of age (Chola *et al.* 2015). Despite a number of initiatives to address the persistently high prevalence of stunting, including near-universal water and sanitation coverage in urban settings, the provision of social grants, and free primary healthcare, this prevalence rate has remained largely unchanged since 1994 (Said-Mohamed *et al.* 2015; Devereux Jonah & May 2019).

The relationship between WASH at the household level and infant growth has received little attention in the South African context, which drastically limits our capacity to disentangle which installations and/or caregiver practices expose infants to such risks (Padarath *et al.* 2016). Knowledge gaps still exist in terms of which WASH factors are risks for undernutrition, at what time during early childhood development WASH factors are implicated, and precisely when WASH interventions are most effective at improving growth.

This study therefore sought to identify specific WASH factors and subsequent associations with HAZ, WAZ, and WHZ scores in infants *a priori* born healthy in Soweto, Johannesburg. The study hypothesised that inadequate WASH is associated with a decrease in HAZ, WHZ, WAZ scores between birth and 1 year of age.

METHODS

Study design and setting

The study is based on cross-sectional data from 4 timepoints (delivery, 1, 6, and 12 months postpartum) drawn from a larger longitudinal prospective cohort study, entitled 'Interaction between nutrition, infection, household environment and care practices and their impact on growth and development in infants between birth and one year of age.' Colloquially referred to as Soweto Baby WASH study, the aim was to document household environment, maternal and infant morbidity and illness, and infant feeding and care practices, and assess the association between these factors and infant growth and development in the first-year postpartum. The Soweto Baby WASH study had 37 timepoints over the course of 12 months, with weekly follow-up home visits from birth to 6 months, and fortnightly from 6 to 12 months postpartum. Visits at 6 and 12 months were conducted at the Developmental Pathways for Health Research Unit facilities at Chris Hani Baragwanath Academic Hospital. Data collected included maternal and infant anthropometric and body composition measurements; household WASH; maternal and infant morbidity, illness, and healthcare access; infant feeding practices; household socio-economic status and demographics; maternal social support, stress, and depression; quality of care in the home; infant temperament; and infant development.

Recruitment commenced in January 2018 and data collection ended when the last recruited infant turned 1 year of age in March 2019. All the participants were screened and recruited at the maternity services at Chris Hani Baragwanath Academic Hospital in Soweto, Johannesburg.

Soweto is the largest township in South Africa with an estimated population of 1.3 million residents and is situated in the City of Johannesburg in the Gauteng Province (Harrison & Harrison 2014; Government of the Republic of South Africa 2020). In 2018, it was reported that Gauteng had near-universal water and sanitation coverage with 97.7% of the population having access to piped tap water in their dwellings, and 91.8% having access to improved sanitation (Moeti & Padarath 2019; Government of the Republic of South Africa 2020). Despite the economic and infrastructure advantages of the province, in 2016, Gauteng reported the highest prevalence of stunting in the country at 34.2% (Rispel & Padarath 2018).

Ethical considerations

The study received clearance from the University of the Witwatersrand's Human Research Ethics Committee (Medical) (Certificates: M170753, M170872, and M170955). Written informed consent was obtained from all participants.

Participants

In order to identify which determinants affect growth at what time, infants who *a priori* had a better start at birth in terms of physical growth and health were recruited. Women who were 1–3 days postpartum were screened for eligibility. Mother–infant pairs eligible for inclusion were: ≥18 years of age at time of screening; singleton pregnancy; birthweight between ≥2,500 and <4,000 g, and term pregnancy between ≥38 and <42 weeks gestational age. Mother–infant pairs were not eligible for inclusion if infants were diagnosed with physical, mental, or congenital disorders at birth or if a mother was living with HIV.

Outcome variables

Infant growth

Anthropometric measurements were performed by trained research assistants using standardised techniques (Members of the WHO Multicentre Growth Reference Study Group 2006, 2007). Infant weight was measured to the nearest 0.01 kg using an infant scale (seca 367) and recumbent length to the nearest 0.01 cm using an infantometer (seca 416). Anthropometric related data (sex, age, length, weight) were analysed using the WHO Anthro Survey Analyser software to generate HAZ, WAZ, and WHZ scores (World Health Organization 2020).

Exposure variables

Table 1 summarises the variables and survey questions drawn from the Soweto Baby WASH study, as well as the coding of composite variables created for use in the analyses that follow.

Water, sanitation, and hygiene

Household WASH was assessed using a questionnaire adapted from the WHO/UNICEF Core Questions on Drinking-Water and Sanitation for Household Surveys (WHO/UNICEF 2006), the WHO/UNICEF Joint Monitoring Programme (United Nations Joint Monitoring Programme (JMP) 2015; WHO/UNICEF Joint Monitoring Programme (JMP) 2015), and the Global Analysis and Assessment of Sanitation and Drinking Water (World Health Organization 2019).

Variables pertaining to water source were aggregated into two categories, safely managed and not safely managed. Safely managed water sources were defined as: a basic drinking water source located on the premises (piped into the home/property), available when needed and free of faecal and chemical contamination (WHO/UNICEF Joint Monitoring Programme (JMP) 2015). Not safely managed water sources comprised all other installations. Variables including access to water source (coded 1 if the water source was on the property, and 0 if not), water treatment, and interruptions to water supply were also collected (Table 1). A water index (scored 0–4, with 0 representing the lowest level of water infrastructure and behaviours, and 4 the highest); was constructed as a sum of the items pertaining to water source, access, treatment, and supply (Manzoni *et al.* 2019).

Data on the type of sanitation infrastructure (Table 1) were aggregated into two categories, safely managed and not safely managed. Safely managed sanitation facilities were defined as a basic sanitation facility (flush/pour to piped sewer system) where excreta are safely disposed *in situ* or treated off-site (WHO/UNICEF Joint Monitoring Programme (JMP) 2015). Not safely managed sanitation facilities incorporated all other infrastructure installations.

In order to create a composite hygiene index (scored 0–5: with 0 representing the lowest level of hygiene behaviours and infrastructure, and 5 the highest), three indices to assess hygiene behaviours and circumstances were created (Webb *et al.* 2006). Firstly, a Household Hygiene Index – scored 0–2, (Table 1) included type of house, and presence of animals on the property (coded 0 if there were animals on the property, and 1 if not). Secondly, a Personal Hygiene Index – scored 0–2 (Table 1), included handwashing, and handwashing detergent. And thirdly, a Food Hygiene Index – scored 0–1 (Table 1), cleaning of the breast and cleaning of utensils prior to feeding. The Household Hygiene Index, Personal Hygiene Index, and Food Hygiene Index were calculated as the sum of the individual items and the overall hygiene index as the sum of the Household Hygiene Index, Personal Hygiene Index, and Food Hygiene Index (Webb *et al.* 2006; Manzoni *et al.* 2019).

Table 1 | Composite variables for water index, sanitation, and hygiene index

Descriptor	Description	Aggregated variable	Coding	Survey question
Type of water source	Piped into dwelling	Safely managed	1	What are the most common (within past 2 weeks) sources of water you have access to?
	Piped into yard/plot			
	Bottled water	Not safely managed	0	
	Public tap			
	Borehole			
	Protected dug well			
	Protected spring			
	Rainwater			
	Tanker/Cart with small tank			
	Unprotected dug well			
	Unprotected spring			
	Surface water			
Interruptions to water supply	Daily	> Once a month	0	How often do you have interruptions to your water supply?
	Once a week			
	Once a month			
	Rarely/Never	Rarely	1	
	Don't know			
Water treatment	Bleach/Chlorine	Treatment	1	What methods do you use to treat your water?
	Boiling			
	Strain it through a cloth			
	Use a water filter			
	Solar disinfection			
	Let it stand/settle			
	Other			
	None	No treatment	0	
Type of sanitation	Flush/Pour to piped sewer system	Safely managed	1	What type of toilet facilities are available?
	Flush/Pour to septic tank	Not safely managed	0	
	Flush/Pour to pit latrine			
	Flush/Pour to elsewhere			
	Ventilated Improved pit latrine			
	Pit latrine with slab			
	Composting toilet			
	Portable toilet			
	Bucket			
	Pit latrine without slab			
	No facilities (bush or field)			
Type of house	Shack/Zozo	Informal	0	How would you describe the home you are living in?
	Hostel			
	Flat/Cottage	Formal	1	
	House			
	Room/Garage			
	Residence (attached to education or employment)			
	Government housing			
	Other			
Handwashing	Before and after eating	Before/After handling food	1	When do you wash your hands?
	Before preparing food			
	Before and after feeding			
	After using toilet	Before/After using sanitation	1	
	After changing diaper			
	When hands are dirty	Other	0	
	Never/Rarely			
	Other			

(*continued*)

Table 1 | continued

Descriptor	Description	Aggregated variable	Coding	Survey question
Handwashing detergent	Soap and water Water and ash	Water and soap/ash	1	What do you wash your hands with?
	Only water		0	
Cleaning of breast/nipple	Yes, Always Yes, Sometimes	Food hygiene practices (Recommended)	1	Do you clean your breast or nipples before feeding? How do you usually clean the utensils used for feeding?
Cleaning of utensils	Cold water and soap Boiled water Boiled water and soap Sterilisation solution			
Cleaning of breast/nipple	No Don't know	Food hygiene practices (Not Recommended)	0	
Cleaning of utensils	Cold water Other			

For both the water and hygiene indices, each of the items was scored as either 0 or 1, with 1 representing a positive behaviour or circumstance. Positive behaviour or circumstance was defined as an activity or condition that is protective towards or acts as a barrier to the transmission of pathogens (Webb *et al.* 2006; United Nations Joint Monitoring Programme (JMP) 2015; WHO/UNICEF Joint Monitoring Programme (JMP) 2015; Cumming & Cairncross 2016).

Covariates

Maternal anthropometry

Maternal height, to the nearest 0.1 cm, was measured using a wall-mounted stadiometer (Holtain), and weight, to the nearest 0.1 kg using a digital scale (seca 877), was measured by trained research assistants using standardised techniques, from which maternal Body Mass Index (BMI) was calculated as (kg/m^2) (de Onis *et al.* 2014).

Morbidity and illness

Maternal and infant, morbidity, illness, and healthcare access were assessed using interviewer-administered surveys, validated in the study setting, and confirmed against clinic records (Said-Mohamed *et al.* 2019). Incidence of diarrhoea was recorded by 7-day recall from birth to 6 months, and 14 day recall from 6 months to 1 year of age.

Infant feeding practices

Infant feeding practices were assessed using a locally adapted version of the WHO/UNICEF Infant and Young Child Feeding Questionnaire (World Health Organization 2008, 2010; Nieuwoudt Manderson & Norris 2018). Prevalence of exclusive breastfeeding (EBF) from birth to 6 months was determined using the WHO definition which allows the infant to receive breastmilk (either expressed or from a wet nurse), oral rehydration solution, drops, syrups (vitamins, minerals, medicines), but nothing else (World Health Organization 2008, 2010).

Household socio-economic status and demographics

The household socio-economic status questionnaire was developed based on the National Income Dynamics Study (University of Cape Town 2016), and the Living Conditions Survey (Statistics South Africa 2017a). Data pertaining to household crowding, maternal employment, and education were collected. A Household Wealth Index was calculated using latent household variables: household assets (bicycle, motorcycle, motor vehicle, fridge, microwave, washing machine, landline telephone, camera, cellphone, television, DVD-player, paid television subscription, computer/laptop, internet access), housing characteristics (home ownership, land ownership, and main type of energy) (Rutstein & Johnson 2004; Vyas & Kumaranayake 2006). The Household Wealth Index was built using principal component analysis

(Vyas & Kumaranayake 2006). Based on the Household Wealth Index, the sample was divided in half into two categories (the richest and the poorest)

Sample size

A total of 1,289 mothers were screened post-delivery at the maternity wards at Chris Hani Baragwanath Academic Hospital. Of those screened, 243 were eligible. Because 87 did not consent, 156 mother–infant pairs were enrolled in the study (Figure 1).

Statistical analyses

The statistical software used for analysis was Stata version 13.1 (StataCorp 2013). Descriptive statistics, including frequencies, proportions, means, and standard deviation, or median and range were used to summarise the variables. The Shapiro–Wilk test for normality, and tests of homogeneity of variance were performed to identify the type of distribution for continuous variables. Differences by sex were assessed using a Pearson's chi-squared test, or an independent Student's t-test.

Using the social-ecological model (Neal & Neal 2013) informed by the UNICEF Conceptual Framework (The United Nations Children's Fund 1990), three hierarchical models were hypothesised in order to assess the associations between WASH components and HAZ, WAZ, and WHZ, while controlling for individual infant and maternal factors, as well as household characteristics at 1, 6, and 12 months postpartum (Victora et al. 1997). Model 1 (M1) investigated the unadjusted and independent association between WASH factors and growth outcomes. Model 2 (M2) examined the effect after controlling M1 for individual infant factors (birthweight, gestational age). Model 3 (M3) explored the effect after controlling M2 for maternal factors (age, height, BMI, employment, education). Finally, Model 4 (M4) investigated the effect after controlling M3 for household factors (crowding, wealth index). Collinearity between variables was tested by assessing the variable inflation factor and covariance correlation matrices. Significance levels were set at $p \leq 0.05$ with 95% Confidence Intervals.

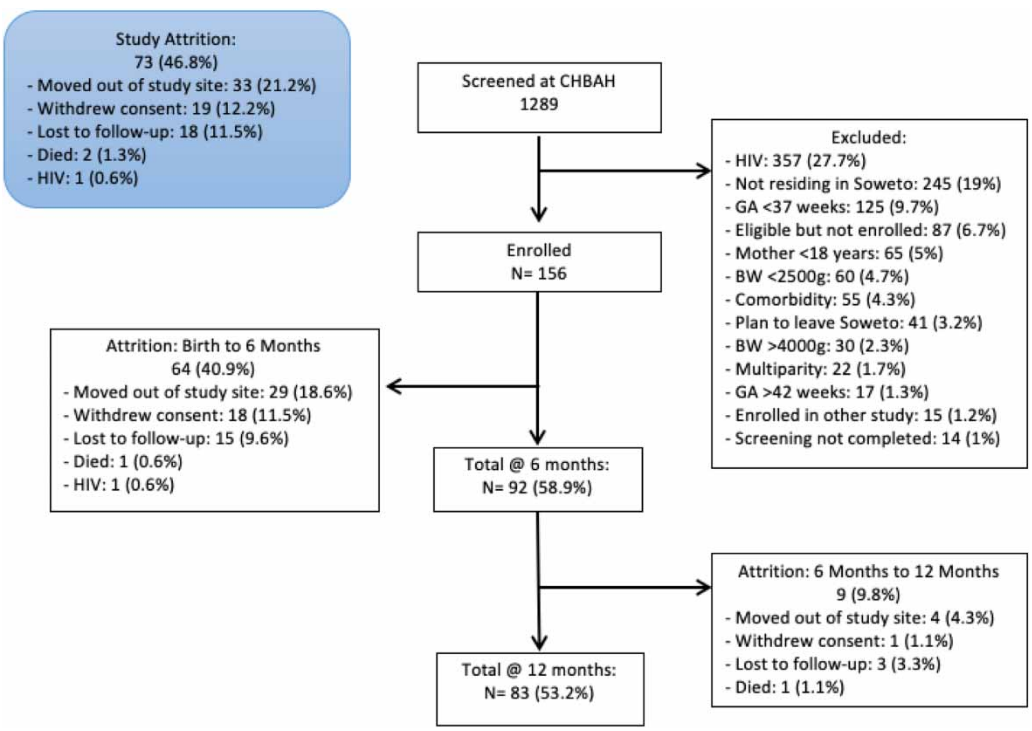

Figure 1 | Screening, follow-up and attrition flow diagram of the Soweto Baby WASH study.

RESULTS

Over the duration of the study, 73 (46.8%) participants were lost to follow-up. A total of 83 mother–infant pairs exited the study after 12 months of follow-up, comprising the final sample (Figure 1).

At birth (Table 2), despite having been born within normal ranges for birthweight (mean = 3.055 g, SD = 0.35) and gestational age (mean = 38.9 weeks, SD = 1.2), the prevalence of stunting was 9.7%, underweight 0.7%, and wasting 2%. Stunted largely persisted being at a higher prevalence than other forms of undernutrition as the study progressed with 10.2% of participants being stunted at 1 month, 10.1% at 6 months, and 11% at 12 months (Table 3). Mean maternal BMI values were as follows, 27.5 (SD = 5.9) at 1 month, 29.9 (SD = 6.1) at 6 months, and 29.9 (SD = 6.6) at 12 months (Table 3). At 1 month postpartum, more than two-thirds of mothers were employed, while conversely at 12 months postpartum, approximately two-thirds (65.3%) were unemployed.

Table 2 | Maternal and infant characteristics at birth in the Soweto Baby WASH study

		Delivery	
		Total	
		n	Mean, SD, or percentages
Infant characteristics			
Sex	Male	76	50.3%
	Female	75	49.7%
Age (mean, SD)	Months	154	0.039 (0.029)
Gestational age (mean, SD)	Weeks	151	38.9 (1.2)
Weight (mean, SD)	kg	151	3.055 (0.35)
Length (mean, SD)	cm	151	48.3 (1.7)
Stunted	Yes	14	9.3%
	No	136	90.7%
Underweight	Yes	1	0.7%
	No	149	99.3%
Wasted	Yes	3	2%
	No	144	98%
Maternal characteristics			
Age (mean, SD)	Years	153	27.7 (6.1)
Height (mean, SD)	cm	77	157.8 (6.9)

Additional participant characteristics are presented in Supplementary Material, Table 1.

The water index did not vary much over the course of the study with the sample mean remaining around 3.11 over a maximum score of 4 across all 3 timepoints (Table 3). With regards to sanitation, more than 90% of participants had access to a safely managed sanitation facility. The hygiene index did also not vary much over the course of the study with sample means remaining around 3.35 (SD = 0.87) at 1 month, 3.38 (SD = 0.89) at 6 months, and 3.14 (SD = 0.97) at 12 months.

Tables 4–6 show the results for the hierarchical regression analyses on HAZ, WAZ, and WHZ at 1, 6, and 12 months postpartum, respectively. All significant associations for the fully adjusted M4 models are diagrammatically displayed in Figure 2.

Using a safely managed sanitation facility was associated with an increase in HAZ scores by 2.24 (M4, $p = 0.03$), at 1 month, but this effect size decreased to 0.98 ($p = 0.04$), at 6 months postpartum and no association was detected at 12 months (Table 4). An improvement by 1 unit in the hygiene index was associated with a decrease of 0.53 in HAZ scores (M4, $p = 0.04$) at 1 month postpartum but no associations were detected at 6 or 12 months. No associations between the water index and HAZ scores were detected at any of the timepoints. At 1 month, 6 months, and 12 months, WASH factors (M1) explained 2, 10, and 6% of the variance in HAZ, respectively, while infant, maternal, and household characteristics (M4) at the same time points, explained, 56, 29, and 28% of HAZ variance, respectively.

With regard to WAZ (Table 5), a 1-unit improvement in the hygiene index was associated with a decrease in WAZ by 0.44 (M4, $p = 0.001$) at 1 month, while no associations were detected at either 6 or 12 months postpartum. Use of a safely managed sanitation facility was associated with an increase in WAZ by 1.21 (M4, $p = 0.01$) at 1 month, 1.57 (M4, $p = 0.01$) at 6 months, and 1.92 (M4, $p = 0.01$) at 12 months. No associations between the water index and WAZ scores were detected at either 1, 6, or 12 months in the fully adjusted models (M4). At 1 month, 6 months, and 12 months, WASH factors (M1) explained 1, 6, and 19% of the variance in WAZ scores, respectively, while infant, maternal, and household characteristics (M4) at the same

Table 3 | Maternal and infant characteristics at 1, 6, and 12 months postpartum in the Soweto Baby WASH study

		1 month postpartum		6 months postpartum		12 months postpartum	
		Total		Total		Total	
		n		n		n	
Infant characteristics							
Sex	Male	76	50.3%	42	52.5%	42	57.5%
	Female	75	49.7%	38	47.5%	31	42.5%
Age (mean, SD)	Months	59	0.961 (0.098)	79	5.752 (0.506)	73	11.931 (0.654)
Weight (mean, SD)	kg	59	4.088 (0.56)	79	7.498 (1.002)	73	9.250 (1.164)
Length (mean, SD)	cm	59	52.5 (1.9)	79	64.7 (2.4)	73	73.4 (2.1)
Stunted	Yes	6	10.2%	8	10.1%	8	11%
	No	53	89.8%	71	89.9%	65	89%
Underweight	Yes	2	3.4%	2	2.5%	2	2.7%
	No	57	96.6%	77	97.5%	71	97.3%
Wasted	Yes	2	3.4%	2	2.5%	2	2.7%
	No	57	96.6%	77	97.5%	71	97.3%
Exclusive breastfeeding	Yes	3	5.2%	0	–	–	–
	No	55	94.8%	78	100%	–	–
Maternal characteristics							
Age (mean, SD)	Years	57	27.5 (5.9)	74	27.9 (5.9)	70	28.7 (6.4)
Weight (mean, SD)	kg	57	71.2 (13.4)	74	74.3 (16.4)	70	73.9 (17.7)
BMI (mean, SD)		45	27.5 (4.9)	74	29.9 (6.1)	66	29.9 (6.6)
Education	No formal education, primary, and secondary	68	71.6%	61	77.2%	59	80.2%
	Tertiary	27	28,4%	18	22.8%%	14	19.8%
Employment	Yes	54	66.7%	55	70.5%	25	34.7%
	No	27	33.3%	23	29.5%	47	65.3%
Household characteristics							
Crowding (mean, SD)		97	4.4 (2.6)	79	5.9 (2.9)	73	5.8 (2.7)
Wealth Index	Poorest	42	47.7%	37	50.7%	35	50.7%
	Richest	46	52.3%	36	49.3%	34	49.3%
WASH characteristics							
Water source	Safely managed	69	74.2%	62	77.5%	51	69.9%
	Not safely managed	24	25.8%	18	22.5%	22	30.1%
Water source on premises	Yes	77	82.8%	62	77.5%	57	78.1%
	No	16	17.2%	18	22.5%	16	21.9%

(*continued*)

Table 3 | continued

		1 month postpartum		6 months postpartum		12 months postpartum	
		Total		Total		Total	
		n		n		n	
Water treatment	Treatment	18	19.4%	15	18.7%	11	15.1%
	No treatment	75	80.6%	65	81.3%	62	84.9%
Interruptions to supply	Rarely	70	75.3%	60	75%	57	78.1%
	> Once a month	23	24.7%	20	25%	16	21.9%%
Water storage	Bucket	20	90.9%	25	96.2%	19	95%
	Other (pot, bottle, tub, water can)	2	9.1%	1	3.8%	1	5%
Water Index	(mean, SD)	93	3.13 (0.91)	80	3.11 (0.84)	73	3.11 (0.68)
Type of sanitation	Safely managed	87	93.5%	77	96.3%	71	97.3%
	Not safely managed	6	6.5%%	3	3.7%	2	2.7%
Household hygiene characteristics							
Type of house	Formal	78	82.1%	63	80.7%	59	80.8%
	Informal	17	17.9%%	15	19.3%	3	19.2%
Type of flooring	Improved	–	–	75	96.2%	65	89%
	Unimproved	–	–	3	3.8%	8	11%
Animals on property	No	69	74.2%	59	73.4%	56	76.7%
	Yes	24	25.8%	21	26.3%	17	23.3%
Waste storage	Outside house/off property	87	94.6%	72	90%	66	90.4%
	Inside house	5	5,4%	8	10%	7	9.6%
Frequency of household cleaning	Everyday	88	94.6%	76	95%	66	90.4%
	<7 times a week	5	5.4%	4	5%	7	9.6%
Personal hygiene characteristics							
Hand washing	Before/after handling food	29	31.2%	32	40	41	56.2%
	Before/after using sanitation	48	51.6%%	38	47.5	26	35.6%
	Other (when hands dirty, rarely, after touching money, after cleaning)	16	17.2%%	10	12.5%	6	8.2%
Hand washing detergent	Water & soap/ash	66	71.7%	60	76.9%	52	72.2%
	Only water	26	28.3%	18	23.1%	20	27.8%
Food hygiene characteristics							
Food hygiene practices	Recommended behaviour[a]	46	86.8%	54	68.4%	33	44.6%
	Not recommended behaviour	7	13.2%	25	31.6%	41	55.4%
Main type of water used[b]	Tap water boiled	25	100%	36	100%	33	100%
Hygiene index	(mean, SD)	46	3.35 (0.87)	65	3.38 (0.89)	65	3.14 (0.97)

(*continued*)

Table 3 | continued

		1 month postpartum		6 months postpartum		12 months postpartum	
		Total		Total		Total	
		n		*n*		*n*	
Morbidity and illness							
Diarrhoea	Yes	1	1.8%	6	8.3%	9	12.3%
	No	55	98.2%	66	91.7%	64	87.7%

[a]This variable was constructed by combining two variables pertaining to the cleaning of the breast and cleaning of utensils prior to feeding. Recommended behaviour was defined as an activity that is protective towards, or acts as a barrier to, the transmission of pathogens.

[b]All respondents reported using boiled tap water. There were no observations of the other categories (mineral water boiled, tap water not boiled, mineral water not boiled).

time points explained, 90, 34, and 26% of the variation in WAZ, respectively.

Finally, in terms of WHZ (Table 6), use of a safely managed sanitation facility was associated with an increase in WHZ, at 12 months, by 1.94 (M4, $p = 0.02$) while no associations were detected at 1 or 6 months. No associations with WHZ were detected for either the hygiene or water indices at any of the timepoints. At 1 month, 6 months, and 12 months, WASH factors (M1) explained 2, 4, and 18% of the variance in WHZ respectively, while infant, maternal, and household characteristics (M4) at the same time points explained 55, 18, and 24% of the variation in WHZ, respectively.

DISCUSSION

This study aimed to identify specific postnatal environmental factors related to WASH, and subsequent associations with HAZ, WAZ, and WHZ scores in infants born healthy in Soweto, Johannesburg. This study identified statistically significant associations with each of the specific WASH components and growth outcomes, dependent on infant age. In summary, household access to sanitation facilities that were not safely managed was associated with a decrease in HAZ scores at 1 and 6 months (but not at 12 months) with WAZ at all timepoints; and finally, with WHZ scores at 12 months (but not at 1 or 6 months). The hygiene index was negatively associated with HAZ and WAZ scores at 1 month, but not at 6 or 12 months, or with WHZ scores at any of the timepoints. The evidence therefore suggests that the greatest impact relating to water is likely to affect WAZ around 12 months while the greatest impact of hygiene is around 1 month postpartum and is likely to affect HAZ and WAZ. Access to safely managed sanitation facilities is critical throughout the first year and impacts HAZ, WAZ, and WHZ.

Improvements in water, as it relates to WASH, are expected to have positive effects on diarrhoea which has been implicated as a major cause of undernutrition (Nabwera *et al.* 2017). However, interventions delivered in the WASH Benefits trials, in Bangladesh and Kenya, and the SHINE trials in Zimbabwe found no effect of basic water interventions on linear growth, or on childhood

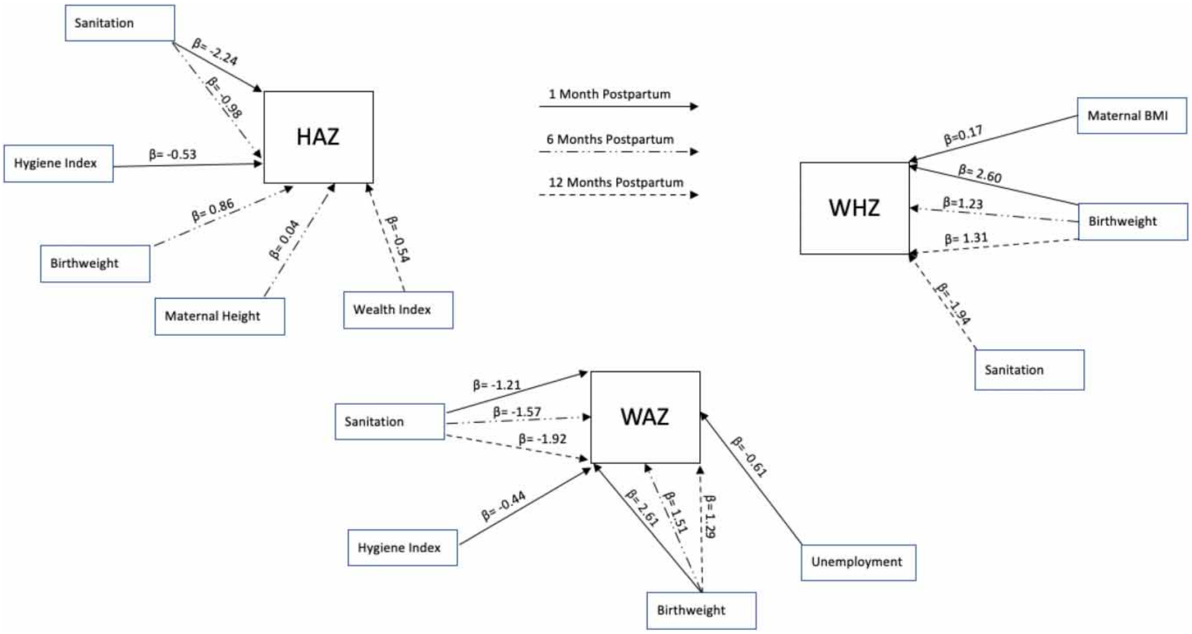

Figure 2 | Significant associations between HAZ, WAZ, WHZ, and WASH components, infant, maternal, and household factors in model 4.

diarrhoea (Null *et al.* 2018; Cumming *et al.* 2019; Pickering *et al.* 2019b). We found that in the current South African context, there was no association between water conditions and growth outcomes in the various models. Noteworthy, however, is the negative association between the water index and WAZ at 12 months after adjusting for infant characteristics at birth, but not after adjusting for maternal or household characteristics, which may mean that the effect might be relative to nutritional status at birth.

This finding was also consistent with a recent study in South Africa (Eastern Cape) which found that an increase in the prevalence of use of an improved water source was associated with an increase in systemic inflammation among children under 5 years of age (Voth-Gaeddert *et al.* 2019). Therefore, in the South African context, factors such as informal pipe connections, water quality, water removal devices, and household water storage practices may be associated with water source quality and to a certain extent affect infant growth.

In addition, early introduction of formula feeding and complimentary foods, as is seen in our study population through the extremely low rates of EBF may also result in infants being exposed to pathogens, resulting in impaired intestinal function, or environmental enteric dysfunction (EED) (Keusch *et al.* 2013; Mbuya & Humphrey 2016). EED is thought to explain a significant portion of unresolved and unexplained undernutrition in the developing world, through nutrient malabsorption and systemic inflammatory responses (Mbuya & Humphrey 2016). In Zimbabwe for instance, it was found that non-EBF may lead to faeco-oral transmission of bacteria among infants living in conditions of poor sanitation and hygiene; and that frequent exposure to potentially pathogenic organisms likely drives enteric inflammation (Prendergast *et al.* 2014).

In this study, we showed that household access to sanitation facilities that were not safely managed was associated with a decrease in HAZ, WAZ, and WHZ. Similar associations between sanitation and undernutrition have been seen in a number of African settings. In Ethiopia, for instance, unavailability of a latrine was associated with significant higher odds of stunting in children between 6 and 24 months (Derso *et al.* 2017) and poor household sanitary facilities were associated with undernutrition between 6 and 12 months (Medhin *et al.* 2010) and in Zimbabwe, poor sanitation was associated with stunting and chronic inflammation between birth and 24 months (Prendergast *et al.* 2014).

A peculiarity in this respect is the fact that the infants are not, at this early stage, using sanitation facilities, which

Table 4 | Hierarchical regression analyses of WASH components on HAZ at 1, 6, and 12 months postpartum, the Soweto Baby WASH study

		HAZ											
		1 month postpartum				**6 months postpartum**				**12 months postpartum**			
		M1 $n = 45$	**M2** $n = 44$	**M3** $n = 31$	**M4** $n = 30$	**M1** $n = 65$	**M2** $n = 64$	**M3** $n = 60$	**M4** $n = 59$	**M1** $n = 65$	**M2** $n = 64$	**M3** $n = 57$	**M4** $n = 56$
Model 1: WASH characteristics													
Water Index		−0.10 (−0.44–0.24)	−0.02 (−0.31–0.27)	0.20 (−0.21–0.61)	0.20 (−0.27–0.66)	−0.20 (−0.46–0.05)	−0.17 (−0.41–0.08)	−0.16 (−0.41–0.08)	−0.12 (−0.37–0.13)	−0.20 (−0.52–0.12)	−0.25 (−0.56–0.06)	−0.24 (−0.57–0.09)	−0.21 (−0.53–0.12)
Sanitation	Safely managed	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	Not safely managed	−0.14 (−1.19–0.90)	−0.45 (−1.36–0.46)	−2.22* (−3.98– − 0.47)	−2.24* (−4.28– − 0.20)	−0.88 (−1.90–0.14)	−1.02* (−1.99– − 0.05)	−0.96* (−1.92– − 0.01)	−0.98* (−1.93– − 0.03)	−0.93 (−2.15–0.28)	−0.95 (−2.12–0.22)	−0.64 (−1.91–0.63)	−1.03 (−2.29–0.24)
Hygiene Index		−0.13 (−0.51–0.24)	−0.22 (−0.54–0.10)	−0.52* (−0.96– − 0.08)	−0.53* (−1.02– − 0.03)	−0.18 (−0.43–0.06)	−0.17 (−0.40–0.06)	−0.20 (−0.43–0.03)	−0.12 (−0.36–0.13)	0.00 (−0.22–0.23)	0.05 (−0.16–0.26)	0.11 (−0.12–0.35)	0.12 (−0.11–0.35)
R^2		0.02	–	–	–	0.10	–	–	–	0.06	–	–	–
F		0.83	–	–	–	0.08	–	–	–	0.28	–	–	–
Model 2: Addition of infant characteristics													
Birthweight		–	1.47** (0.65–2.29)	1.09* (0.05–2.13)	1.09 (−0.13–2.30)	–	0.83** (0.24–1.42)	0.81** (0.21–1.42)	0.86** (0.25–1.47)	–	0.73* (0.09–1.37)	0.65 (−0.06–1.36)	0.62 (−0.07–1.30)
Gestational age		–	0.09 (−0.12–0.30)	0.05 (−0.22–0.32)	0.04 (−0.31–0.39)	–	−0.04 (−0.22–0.14)	−0.03 (−0.22–0.16)	0.03 (−0.17–0.23)	–	0.02 (−0.16–0.19)	0.03 (−0.18–0.23)	0.00 (−0.19–0.20)
R^2		–	0.34	–	–	–	0.22	–	–	–	0.16	–	–
ΔR^2		–	0.32**	–	–	–	0.11*	–	–	–	0.10*	–	–
F		–	0.005**	–	–	–	0.01**	–	–	–	0.07	–	–
Model 3: Addition maternal characteristics													
Age		–	–	0.07 (−0.01–0.15)	0.08 (−0.04–0.19)	–	–	0.01 (−0.03–0.04)	0.01 (−0.03–0.05)	–	–	−0.03 (−0.07–0.01)	−0.03 (−0.07–0.01)
Height		–	–	0.01 (−0.05–0.08)	0.01 (−0.06–0.09)	–	–	0.04* (0.01–0.07)	0.04* (0.01–0.07)	–	–	0.03 (−0.00–0.07)	0.02 (−0.01–0.06)
BMI		–	–	−0.10* (−0.19– − 0.01)	−0.10 (−0.22–0.01)	–	–	0.01 (−0.02–0.05)	0.02 (−0.02–0.06)	–	–	0.01 (−0.02–0.05)	0.00 (−0.03–0.04)
Education	No formal education, primary & secondary	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	Tertiary	–	–	−0.17 (−0.94–0.59)	−0.17 (−1.02–0.68)	–	–	−0.14 (−0.63–0.35)	−0.03 (−0.53–0.47)	–	–	0.06 (−0.51–0.64)	0.04 (−0.52–0.60)
Employment	Yes	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	No	–	–	−0.35 (−1.16–0.45)	−0.36 (−1.27–0.55)	–	–	0.24 (−0.23–0.71)	0.38 (−0.12–0.89)	–	–	−0.12 (−0.60–0.36)	−0.05 (−0.53–0.44)
R^2		–	–	0.58	–	–	–	0.36	–	–	–	0.25	–
ΔR^2		–	–	0.23	–	–	–	0.14	–	–	–	0.09	–
F		–	–	0.03*	–	–	–	0.009**	–	–	–	0.17	–

(*continued*)

Table 4 | continued

		HAZ											
		1 month postpartum				6 months postpartum				12 months postpartum			
		M1 $n = 45$	**M2** $n = 44$	**M3** $n = 31$	**M4** $n = 30$	**M1** $n = 65$	**M2** $n = 64$	**M3** $n = 60$	**M4** $n = 59$	**M1** $n = 65$	**M2** $n = 64$	**M3** $n = 57$	**M4** $n = 56$
Model 4: Addition of household characteristics													
Family size		–	–	–	0.00 (−0.13–0.14)	–	–	–	−0.02 (−0.09–0.05)	–	–	–	0.00 (−0.08–0.08)
Wealth Index	Poorest	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	Richest	–	–	–	0.03 (−0.83–0.88)	–	–	–	−0.31 (−0.79–0.18)	–	–	–	−0.54* (−1.00– −0.07)
R^2		–	–	–	0.58	–	–	–	0.39	–	–	–	0.34
ΔR^2		–	–	–	0.00	–	–	–	0.03	–	–	–	0.09
F		–	–	–	0.11	–	–	–	0.01**	–	–	–	0.07

may allude to the importance of sanitation and hygiene at household as well as community levels, transmitted through the mother or caregiver. Results from a study conducted in an urban setting in Maputo, Mozambique, reported associations with risk factors for faecal contamination of water, soil, and surfaces in households sharing poor-quality sanitation, and described a setting impacted by pervasive domestic faecal contamination, including from human sources, that was largely disconnected from the observed variation in socio-economic and sanitary conditions (Holcomb *et al.* 2020).

It is noticeable that the effect size of sanitation decreased for HAZ between 1 month up until 12 months while the opposite effect was seen for WAZ and WHZ where the effect of sanitation increased from 1 month up to 12 months, with the greatest the effect size seen in WHZ.

This may be indicative of WASH factors, such as sanitation, having a greater impact on weight, rather than height, during this initial period of early childhood growth, with height generally being a marker of chronic undernutrition persisting over a number of years. This is consistent with literature that suggests that adiposity is more sensitive to fluctuations driven by external environmental factors, including food security, and recurrent infections, and therefore more likely to affect children over the course of months rather than years (Victora *et al.* 2010; Richard *et al.* 2013, 2014; Osgood-Zimmerman *et al.* 2018). As such, the extent of WASH factors on height may only become evident later on during childhood. In turn, WASH interventions targeted on linear growth, with limited effects on the burden of diarrhoea, may reduce the likelihood of catch-up growth in the first 2 years (Richard *et al.* 2013, 2014). This is seen in the contribution of WASH factors to the variation in *z*-scores being minimal for all indices at 1 month, increasing somewhat to around 6–10% for HAZ between 6 and 12 months; however, significant increases in explanatory contribution up to about 20% are seen when it comes to WHZ and WAZ at 12 months.

Negative associations for the hygiene index for HAZ and WAZ were detected at 1 month postpartum, contrary to the initial hypothesis, that an increase in the hygiene index would yield positive associations with the nutritional status outcomes. Given the significance of sanitation, during a period when infants are not themselves using sanitation facilities, a point of reflection that emerges is again whether

Table 5 | Hierarchical regression analyses of WASH components on WAZ at 1, 6, and 12 months postpartum, the Soweto Baby WASH study

		WAZ											
		1 month postpartum				6 months postpartum				12 months postpartum			
		M1 $n = 45$	M2 $n = 44$	M3 $n = 31$	M4 $n = 30$	M1 $n = 65$	M2 $n = 64$	M3 $n = 60$	M4 $n = 59$	M1 $n = 65$	M2 $n = 64$	M3 $n = 57$	M4 $n = 56$
Model 1: WASH characteristics													
Water index		−0.05 (−0.36–0.25)	0.02 (−0.15–0.20)	0.17 (−0.03–0.38)	0.17 (−0.04–0.37)	−0.10 (−0.42–0.23)	−0.03 (−0.32–0.27)	0.01 (−0.31–0.33)	0.07 (−0.25–0.39)	−0.36 (−0.73–0.01)	−0.41* (−0.74–−0.07)	−0.33 (−0.69–0.03)	−0.35 (−0.73–0.03)
Sanitation	Safely managed	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	Not safely managed	0.17 (−0.78–1.11)	−0.35 (−0.91–0.20)	−1.32** (−2.19–−0.44)	−1.21* (−2.12–−0.30)	−1.28 (−2.57–0.00)	−1.50* (−2.69–−0.31)	−1.51* (−2.75–−0.26)	−1.57* (−2.78–−0.36)	−2.21** (−3.63–−0.79)	−2.12** (−3.39–−0.84)	−1.84* (−3.24–−0.45)	−1.92* (−3.39–−0.46)
Hygiene Index		−0.06 (−0.40–0.28)	−0.21* (−0.40–−0.01)	−0.39** (−0.61–−0.17)	−0.44** (−0.66–−0.22)	−0.04 (−0.34–0.26)	−0.03 (−0.31–0.25)	−0.06 (−0.36–0.25)	0.04 (−0.28–0.35)	−0.07 (−0.33–0.19)	0.01 (−0.22–0.25)	0.03 (−0.23–0.29)	0.00 (−0.26–0.27)
R^2		0.01	–	–	–	0.06	–	–	–	0.19	–	–	–
F		0.92	–	–	–	0.26	–	–	–	0.005**	–	–	–
Model 2: Addition of infant characteristics													
Birthweight		–	2.18** (1.68–2.68)	2.52** (2.00–3.04)	2.61** (2.06–3.15)	–	1.35** (0.63–2.07)	1.52** (0.73–2.31)	1.51** (0.72–2.29)	–	1.41** (0.71–2.11)	1.30** (0.52–2.09)	1.29** (0.50–2.09)
Gestational age		–	0.01 (−0.12–0.13)	−0.01 (−0.14–0.13)	−0.05 (−0.21–0.11)	–	−0.06 (−0.28–0.16)	−0.10 (−0.34–0.14)	−0.07 (−0.33–0.19)	–	−0.11 (−0.30–0.08)	−0.12 (−0.35–0.10)	−0.14 (−0.37–0.09)
R^2		–	0.71	–	–	–	0.25	–	–	–	0.37	–	–
ΔR^2		–	0.70**	–	–	–	0.19**	–	–	–	0.18**	–	–
F		–	0.000**	–	–	–	0.004**	–	–	–	0.000**	–	–
Model 3: Addition Maternal Characteristics													
Age		–	–	0.02 (−0.02–0.06)	0.02 (−0.03–0.07)	–	–	0.00 (−0.05–0.05)	0.01 (−0.04–0.05)	–	–	0.00 (−0.04–0.05)	0.00 (−0.05–0.05)
Height		–	–	0.03 (−0.01–0.06)	0.02 (−0.01–0.06)	–	–	0.02 (−0.02–0.06)	0.02 (−0.02–0.06)	–	–	0.03 (−0.01–0.07)	0.03 (−0.02–0.07)
BMI		–	–	0.03 (−0.02–0.07)	0.02 (−0.03–0.08)	–	–	0.02 (−0.03–0.07)	0.03 (−0.02–0.07)	–	–	0.00 (−0.04–0.04)	0.00 (−0.04–0.04)
Education	No formal education, primary & secondary	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	tertiary	–	–	0.37 (−0.02–0.75)	0.36 (−0.02–0.74)	–	–	−0.06 (−0.70–0.58)	0.07 (−0.56–0.71)	–	–	0.17 (−0.46–0.80)	0.15 (−0.50–0.80)
Employment	Yes	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	No	–	–	−0.53* (−0.93–−0.13)	−0.61** (−1.02–−0.21)	–	–	0.17 (−0.45–0.78)	0.39 (−0.25–1.03)	–	–	−0.27 (−0.80–0.25)	−0.30 (−0.87–0.26)
R^2		–	–	0.89	–	–	–	0.33	–	–	–	0.42	–
ΔR^2		–	–	0.18	–	–	–	0.08	–	–	–	0.05	–
F		–	–	0.000**	–	–	–	0.02*	–	–	–	0.002**	–

(*continued*)

Table 5 | continued

	WAZ											
	1 month postpartum				6 months postpartum				12 months postpartum			
	M1 $n = 45$	M2 $n = 44$	M3 $n = 31$	M4 $n = 30$	M1 $n = 65$	M2 $n = 64$	M3 $n = 60$	M4 $n = 59$	M1 $n = 65$	M2 $n = 64$	M3 $n = 57$	M4 $n = 56$
Model 4: Addition of household characteristics												
Family size	–	–	–	−0.01 (−0.07–0.05)	–	–	–	−0.09 (−0.18–0.00)	–	–	–	0.06 (−0.04–0.15)
Wealth Index Poorest	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
Richest	–	–	–	0.36 (−0.03–0.74)	–	–	–	−0.57 (−0.99–0.24)	–	–	–	−0.12 (−0.65–0.42)
R^2	–	–	–	0.91	–	–	–	0.40	–	–	–	0.45
ΔR^2	–	–	–	0.02	–	–	–	0.07	–	–	–	0.03
F	–	–	–	0.000**	–	–	–	0.01**	–	–	–	0.005**

95% Confidence Interval in parentheses. Significance levels: $*p \leq 0.05$ and $**p \leq 0.01$.

undernutrition is driven through maternal and caregiver practices and health, with maternal and caregiver health being driven through WASH.

This study has a number of strengths. Firstly, using data-driven processes, this study produced water and hygiene indices which are the first step in exploring various methodologies for creating WASH indicators that relate to child growth in the South African setting. This contributes to broader issues surrounding the fact that current indices have not been sufficient to detect associations with growth (Null *et al.* 2018; Cumming *et al.* 2019; Pickering *et al.* 2019b).

Secondly, this study, as far as the authors can tell, is the first, in the South African setting, specifically aimed at providing detailed information about WASH exposures, and precisely when in early childhood they affect growth. Limited data exist looking specifically at the effect of timing in the role that WASH plays in determining nutritional status in the African context (Momberg *et al.* 2020b). Furthermore, only a handful of studies in this context have considered the link between WASH factors and nutritional status during early childhood (Momberg *et al.* 2020b). As such, this study begins to build the body of evidence in the South African setting and allows for the translation of existing evidence relating to WASH and nutritional status into the sub-Saharan context, particularly in South Africa (Momberg *et al.* 2020a, 2020b).

This study, like all studies investigating complex interactions, has a number of limitations. Despite attempting to validate respondents' answers with multiple questions, social desirability bias, whereby the participant is inclined to deny undesirable traits, may influence some of the variables that pertain to behavioural characteristics, including the hygiene index.

During the course of the study, unanticipated cultural dynamics were discovered, in terms of in- and out-migration of the child, where the child moved relatively frequently between caregivers and extended family in the urban Soweto setting and rural context (Ginsburg *et al.* 2009; Said-Mohamed *et al.* 2015; Hall *et al.* 2018). As a result, it was not always the mother responding to the various surveys but sometimes another caregiver, usually another family member, which is likely indicative of mothers seeking social and possibly economic support, in terms of childcare (Ginsburg *et al.* 2009; Said-Mohamed *et al.* 2015; Hall *et al.* 2018). This is consistent with our finding that maternal unemployment was associated with a decrease in WAZ at 1 month. Furthermore, infants were

Table 6 | Hierarchical regression analyses of WASH components on WHZ at 1, 6, and 12 months postpartum, the Soweto Baby WASH study

		WHZ											
		1 month postpartum				**6 months postpartum**				**12 months postpartum**			
		M1 $n = 45$	**M2** $n = 44$	**M3** $n = 31$	**M4** $n = 30$	**M1** $n = 65$	**M2** $n = 64$	**M3** $n = 60$	**M4** $n = 59$	**M1** $n = 65$	**M2** $n = 64$	**M3** $n = 57$	**M4** $n = 56$
Model 1: WASH characteristics													
Water Index		0.06 (−0.33–0.45)	0.07 (−0.30–0.44)	0.02 (−0.48–0.52)	0.01 (−0.54–0.56)	0.04 (−0.32–0.40)	0.10 (−0.26–0.45)	0.15 (−0.25–0.55)	0.19 (−0.22–0.59)	0.35 (−0.75–0.06)	0.38 (−0.76–0.01)	0.29 (−0.70–0.11)	− 0.33 (−0.76–0.09)
Sanitation	Safely managed	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	Not safely managed	0.45 (−0.74–1.64)	0.05 (−1.10–1.21)	0.79 (−1.34–2.92)	0.93 (−1.49–3.35)	0.90 (−2.35–0.54)	1.06 (−2.48–0.35)	1.12 (−2.66–0.43)	1.18 (−2.71–0.35)	2.38** (−3.94– − 0.83)	2.25** (−3.72– − 0.79)	2.08* (−3.65– − 0.50)	− 1.94* (−3.59– − 0.30)
Hygiene Index		0.09 (−0.34–0.52)	0.01 (−0.42–0.40)	0.11 (−0.42–0.64)	0.05 (−0.54–0.64)	0.11 (−0.23–0.45)	0.11 (−0.23–0.44)	0.10 (−0.28–0.47)	0.15 (−0.24–0.55)	0.08 (−0.36–0.20)	0.01 (−0.28–0.26)	0.02 (−0.31–0.27)	− 0.06 (−0.36–0.24)
R^2		0.02	–	–	–	0.04	–	–	–	0.18	–	–	–
F		0.87	–	–	–	0.48	–	–	–	0.008**	–	–	–
Model 2: addition of infant characteristics													
Birthweight		–	1.41** (0.37–2.45)	2.46** (1.20–3.73)	2.60** (1.16–4.05)	–	1.05* (0.19–1.91)	1.29* (0.31–2.26)	1.23* (0.24–2.21)	–	1.32** (0.52–2.13)	1.30** (0.42–2.19)	1.31** (0.42–2.20)
Gestational age		–	0.12 (−0.39–0.15)	0.11 (−0.44–0.22)	0.16 (−0.57–0.26)	–	0.05 (−0.31–0.21)	0.10 (−0.41–0.20)	0.11 (−0.44–0.22)	–	0.16 (−0.38–0.06)	− 0.18 (−0.43–0.08)	0.18 (−0.44–0.08)
R^2		–	0.18	–	–	–	0.13	–	–	–	0.31	–	–
ΔR^2		–	0.16*	–	–	–	0.09	–	–	–	0.13**	–	–
F		–	0.17	–	–	–	0.14	–	–	–	0.0005**	–	–
Model 3: addition maternal characteristics													
Age		–	–	0.06 (−0.16–0.04)	0.07 (−0.20–0.07)	–	–	0.00 (−0.06–0.06)	0.00 (−0.06–0.06)	–	–	0.02 (−0.03–0.07)	0.02 (−0.03–0.07)
Height		–	–	0.03 (−0.05–0.11)	0.02 (−0.07–0.12)	–	–	0.01 (−0.06–0.04)	0.01 (−0.06–0.04)	–	–	0.02 (−0.03–0.07)	0.02 (−0.03–0.07)
BMI		–	–	0.17** (0.06–0.28)	0.17* (0.03–0.31)	–	–	0.02 (−0.04–0.08)	0.02 (−0.04–0.08)	–	–	− 0.00 (−0.05–0.04)	0.00 (−0.05–0.04)
Education	No formal education, primary & secondary	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	Tertiary	–	–	0.82 (−0.12–1.75)	0.81 (−0.19–1.82)	–	–	0.04 (−0.75–0.83)	0.13 (−0.68–0.93)	–	–	0.20 (−0.51–0.91)	0.19 (−0.53–0.92)
Employment	Yes	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	No	–	–	0.32 (−1.30–0.66)	0.42 (−1.50–0.66)		–	0.02 (−0.74–0.78)	0.19 (−0.62–1.00)	–	–	− 0.26 (−0.86–0.33)	0.35 (−0.98–0.28)
R^2		–	–	0.57	–	–	–	0.18	–	–	–	0.38	–
ΔR^2		–	–	0.39*	–	–	–	0.05	–	–	–	0.07	–
F		–	–	0.03*	–	–	–	0.41	–	–	–	0.007**	–

(*continued*)

Table 6 | continued

WHZ		1 month postpartum				6 months postpartum				12 months postpartum			
		M1 $n = 45$	M2 $n = 44$	M3 $n = 31$	M4 $n = 30$	M1 $n = 65$	M2 $n = 64$	M3 $n = 60$	M4 $n = 59$	M1 $n = 65$	M2 $n = 64$	M3 $n = 57$	M4 $n = 56$
Model 4: addition of household characteristics													
Family Size		–	–	–	0.02 (−0.18–0.14)	–	–	–	0.10 (−0.21–0.02)	–	–	–	0.07 (−0.03–0.18)
Wealth Index	Poorest	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref	Ref
	Richest	–	–	–	0.44 (−0.58–1.46)	–	–	–	0.24 (−1.02–0.53)	–	–	–	0.18 (−0.42–0.78)
R^2		–	–	–	0.57	–	–	–	0.22	–	–	–	0.42
ΔR^2		–	–	–	0.00	–	–	–	0.04	–	–	–	0.04
F		–	–	–	0.12	–	–	–	0.41	–	–	–	0.01*

95% Confidence Interval in parentheses.
Significance levels: $*p \leq 0.05$ and $**p \leq 0.01$.

likely exposed to a number of different care practices and infrastructure installations during the first year. WASH interventions in this setting would therefore benefit from including considerations surrounding social support while reinforcing best WASH practices at the individual, household, and community levels.

Due to the relatively small sample size, not all of the variables that the authors would have hoped to include in the indices and covariates were possible due to the low number of observations for variables, such as water storage, EBF, and incidence of diarrhoea. Notwithstanding the small sample size, the fact that associations were detected allows the authors to postulate that these associations would be potentiated given a larger sample. Despite sample sizes being limited in-lieu of collecting more routine and detailed data, home visits allowed the study team to limit biases in participant answers by probing and having first-hand experience of the household.

In light of the evidence raised in this study, interventions focussed on sanitation during the first 1,000 days are likely to be most effective in improving infant length (and thus reducing stunting) between birth and 6 months, weight (and thus reducing wasting) around 12 months, and overall underweight between birth and one year postpartum. Given that these infants were *a priori* born healthy, yet started short, might allude to the need for WASH interventions to begin earlier than previously anticipated, perhaps as early as pre-conception, targeting women, as well as the household and surrounding community (Bhutta *et al.* 2008, 2013). These findings are particularly relevant for policy makers in so far as the importance of service provision of safely managed sanitation facilities is concerned; thus suggesting that radical changes and improvements to both household and community level sanitation may be required before meaningful impacts on targets related to undernutrition are achieved. In addition, within the South African setting, it is critical that these interventions are accompanied by universal promotion of EBF, and additional provision of social support to the most vulnerable.

CONCLUSION

The evidence suggests that the biggest impact relating to water is likely to affect WAZ around 12 months while the greatest impact of hygiene is around 1 month postpartum and is likely to affect HAZ and WAZ. Access to safely managed sanitation facilities is critical throughout the first year and impacts HAZ, WAZ, and WHZ. Interventions intending to address issues surrounding WASH in early childhood and nutritional status would therefore benefit from taking this timing into account and recognising specific timepoints in early childhood, and associated WASH factors for intervention. WASH is an important factor influencing infant growth, and improvements to both household and community level sanitation may be required in order to achieve targets in terms of minimising undernutrition.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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