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Assessing water and water infrastructure quality in community-managed water supply systems in northern Pakistan

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ABSTRACT

This research assesses the quality of water and water supply infrastructure under the Water and Sanitation Extension Programme (WASEP) in Gilgit-Baltistan, Northern Pakistan. Water samples were collected from 26 randomly selected rural and urban WASEP projects and 12 control sites. Results show that 94% of rural and 83% of urban water samples from WASEP projects conformed with WHO standards for drinking water with no *Escherichia coli* colonies overall compared with 8% of rural and 0% of urban control sites. This corresponds with higher water infrastructure scores for WASEP projects based on engineering audits of water at intake, system, and network level. These findings demonstrate the importance of water infrastructure design for the delivery of clean drinking water, and the role of the WASEP model of community water management in improving the delivery of potable water.

Key words: drinking water, Gilgit-Baltistan, Pakistan, WASEP, water infrastructure, water quality

HIGHLIGHTS

- The approach was unique in solving rural water supply issues.
- Community Involvement plays a pivotal role in the success of water supply schemes.
- Upscaling of the concept rural water supply rationale to the urban setting was a major challenge.
- Water infrastructure was also assessed on a quantitative scale besides quality of water.
- Comparative assessment of two types of water supply projects provided important data.

INTRODUCTION

The provision of drinking water and sanitation facilities remains a major challenge in developing countries. An estimated two billion people around the world lack access to safely managed drinking water services (WHO 2022). Contaminated water has resulted in 1.7 billion cases of diarrhoea among children under five years old annually in developing countries, accounting for 446,000 deaths among under-fives (GBD Diarrhoeal Disease Collaborators 2018). In addition, there are three million cases of cholera and an estimated 95,000 cholera deaths (Charles *et al.* 2020) and 11 million cases of typhoid fever and an estimated 129,000 fever deaths annually (Obaro *et al.* 2017).

The availability of potable water in Gilgit-Baltistan, the mountains of northern Pakistan, has been one of the major challenges for successive governments. Gilgit-Baltistan has the largest amount of frozen water after the North and South poles but water availability is restricted in winter while water from melting glaciers in summer is affected by high turbidity in rivers (Ahmed *et al.* 2021). Access to river water is another problem given mountainous terrain and harsh weather conditions while the majority of urban centres are faced with water stress and insecurity as water from municipal sources cannot meet demand (Singh *et al.* 2020). An added challenge is the vulnerability of the entire region to natural hazards such as landslides, rock slides, avalanches, floods and earthquakes that damage water and other infrastructure leading to contamination of water and disruption of water services, with the region being vulnerable to the impacts of climate changes (Ali *et al.* 2015).

A survey by the Gilgit-Baltistan Environment Protection Agency (GB-EPA) in seven major towns in Gilgit-Baltistan revealed that 56% of water samples were contaminated with faecal material having a concentration of chloride, iron, and nitrates above WHO limits and a lack of coordination among the various state institutions dealing with water (GB-EPA 2013). Today, about 60% of the population in Gilgit-Baltistan still collects water from open irrigation channels and springs that are not protected from contamination and that sometimes involves a 3–4 km walk across mountainous terrain.

This is the wider context under which the Aga Khan Health Services (AKHS) and the Aga Khan Planning and Building Support (AKPBS), two agencies of the Aga Khan Development Network (AKDN), an NGO operating mainly in South and Central Asia, conducted a three-year study in 1993–1996 into the high incidence of waterborne diseases in Gilgit-Baltistan in northern Pakistan. The study found that waterborne diseases accounted for 50% of infant deaths in the region, with high levels of *Escherichia coli* water contamination in many areas, and only 86 out of 502 villages with water supplies with 'satisfactory' schemes. Subsequent studies also found that water quality in Gilgit-Baltistan did not meet WHO standards with only 16% of 142 water samples collected from 15 villages meeting WHO standards for drinking water, recording 48–372 *E. coli* colonies/100 ml in winter and 191–417 *E. coli* colonies/100 ml in summer compared to WHO requirements of zero *E. coli* for safe drinking water (Ahmed & Alibhai 2000).

The AKHS-AKPBS study concluded that engineering alone would not ensure clean drinking water or reduce water-related diseases, which led directly to the introduction of a new integrated approach under the Water and Sanitation Extension Programme (WASEP) that was subsequently implemented by the Aga Khan Agency for Habitat (AKAH) (Datoo 2012). WASEP's integrated approach focuses on community participation, health and hygiene awareness, engineering solutions and water quality. Social mobilisation is central, facilitating community-based financing through connection fees that go into an operation and maintenance (O&M) fund, and a monthly tariff that pays for staff salaries. A Community Health Improvement Programme (CHIP) and School Health Improvement Programme (SHIP) provide awareness-raising sessions for women and children, and train teachers. Sound engineering and technological innovations aim to secure water storage and distribution, and to safeguard water quality through proper design, the use of durable materials, and water quality management (WQM).

WQM involves physical, chemical, and biological testing of water quality against WHO standards, and developing the capacity of technicians, engineers, and the community to monitor and maintain water quality during the implementation and post-completion stages (Datoo 2012). Periodical disinfection of intake chambers and water storage tanks is conducted during project implementation, with water tests at the tap level to record the effect of water disinfection. Continuous monitoring and microbial tests at inlet and outlet levels of storage tanks as well as at every fourth household are conducted for two years after completion of the project.

Since 1997 WASEP has delivered 395 rural projects in 271 of an estimated 750 villages and 41 (peri) urban projects in Gilgit-Baltistan, providing clean piped water to around 44,871 households. The results of WASEP's approach were first reported in 2000 where 82% of 468 water samples complied with WHO standards for safe drinking water in developing countries (0–10 colonies of *E. coli*/100 mL) (Raza & Alibhai 2000). This was subsequently confirmed in 2004 where 86% of 2,620 water samples matched WHO criteria (Abbas & Schlosser 2004).

This research updates these earlier studies and reports on the results of microbiological water quality tests undertaken during an engineering audit of 26 randomly selected rural and urban WASEP projects and 12 rural and urban control sites undertaken in 2020–2022. It is part of a larger research project funded by the British Academy's Urban Infrastructures of Well-Being that included a household survey in 50 WASEP projects and 13 control sites to determine the viability of scaling up the WASEP model to urban settings.

METHODS

The study is based on data provided by AKAH for 436 WASEP projects across the 10 districts of Gilgit-Baltistan in northern Pakistan (Figure 1). From this population (n), a random sample of 50 projects was first stratified into two groups, 25 rural and 25 urban, and then by district, with Gilgit-Baltistan's 10 districts amalgamated into six 'district groups' based on historical district areas, as well as ethnic, linguistic, religious and geographic conditions. The rural sample was divided proportionally according to the distribution of rural projects across these six district groups, and rural projects were randomly sampled in these proportions. The urban sample was stratified by district group proportionally to project distribution, with projects in urban areas only existing in Gilgit City (in Gilgit district group),

Figure 1 | Pakistan and Gilgit-Baltistan.

Aliabad (Hunza-Nagar) and Gahkuch (Ghizer). The Gilgit City sample was then stratified to include a quota of single-district-origin neighbourhoods as well as the range of community groups. From these 25 rural and 25 urban projects, a sample of 12 rural and 14 urban projects was generated for water quality tests and engineering audits based on variations of engineering features (e.g. mechanical/gravity-fed water system, pipe length, number of household connections) and then quota sampled by district group. Six rural and six urban control projects were then selected to match these engineering features in the same district groups (see Tables 3 and 4).

Water samples were collected at source, tank and household taps, where accessible. The samples were tested as per WHO standards (WHO 2022) in AKAH's laboratory in Gilgit City. Tests were conducted for microbiological (total *E. coli* colonies per 100 ml). In some remote sites with long travel times, microbial tests were not possible in the prescribed time. The results of water quality tests were classified into four categories as per WHO guidelines for drinking water (WHO 2022): A (safe: zero *E. coli*/100 ml water), B (low risk: 1–10 *E. coli* colonies/100 ml of water), C (medium risk: 11–100 *E. coli* colonies/100 ml) and D (high risk: 101–1,000 *E. coli* colonies/100 ml) (Table 1).

In addition, water quality was also tested for physiochemical properties: pH, total dissolved solids (TDS), conductivity, salinity, total hardness, and turbidity. The acceptable limits for these indicators are based mainly on WHO recommendations/guidelines for drinking water: pH (6.5–8.5), TDS (below 600 mg/l), conductivity (below 400 μS/cm), and turbidity (5 NTU or less). According to the WHO (2022) water hardness is not a health concern at levels found in drinking-water systems (soft: below 60 mg calcium carbonate per litre; moderately hard: 60–120 mg/l; hard: 120–180 mg/l, very hard: more than 180 mg/l). Similarly, the WHO guideline value for drinking water salinity is based on taste and not health considerations (250 mg/l chloride and 200 mg/l sodium) (Table 2).

Table 1 | WHO microbiological standards for drinking water

Category	Classification	Microbiological properties
A	Safe	Zero count of *E. coli* per 100ml of water
B	Low risk	1–10 *E. coli* colonies/100ml
C	Medium risk	11–100 *E. coli* colonies/100ml
D	High risk	Greater than 100 *E. coli* colonies/100ml

Source: WHO (2022).

Table 2 | WHO recommendations for physiochemical properties of drinking water

Physiochemical category	WHO recommendation/guidelines
pH	6.5–8.5
Total dissolved solids (TDS)	Below 600 mg/l
Conductivity	Below 400 µS/cm
Salinity	Below 200 mg/l sodium
Total hardness	Soft: below 60 mg calcium carbonate per litre Moderately hard: 60–120 mg/l Hard: 120–180 mg/l Very hard: more than 180 mg/l
Turbidity	5 NTU or less

Source: WHO (2022).

The engineering audit involved the physical inspection of source water intake, water supply route, and water distribution network (Figure 2). Each part of the water infrastructure network was assessed in terms of risk of contamination and damage from natural hazards/disasters and scored on a Likert scale: 1 (very poor), 2 (poor), 3 (satisfactory), 4 (good) and 5 (very good). Higher scores were awarded for water sources, water supply route and distribution networks that were well designed, secure and protected from contamination from human/livestock activity and natural hazards/disasters. Similarly, given the problem of freezing pipes in winter, water supply routes and water distribution networks were scored higher where pipes were buried 4 ft deep, below the frost line, that has the added benefit of reducing illegal water connections and the accompanying risk of contamination. Finally, the percentage of pipes with weak joints and leaks were factored into water supply route scores.

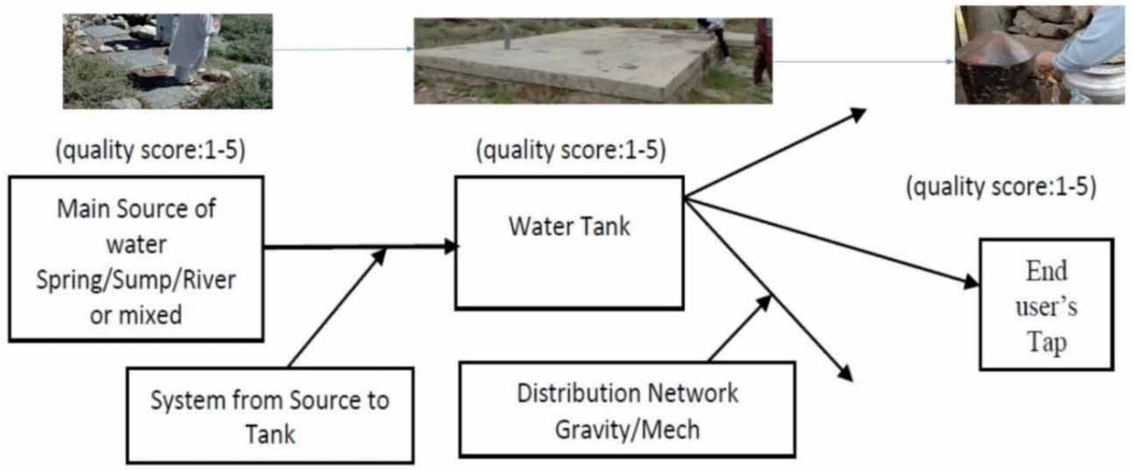

Figure 2 | System diagram of water supply system from source to tap.

RESULTS AND DISCUSSION

Water quality

A total of 56 water samples were collected from 18 rural sites – 39 samples from 12 WASEP projects and 17 samples from six control sites (Table 3). All rural sites were gravity-based, relying on spring or stream (*nallah*) water. All WASEP water sources were from springs while only one control site relied solely on a spring water source. Both WASEP and control sites were on average around the same age (14.1 years WASEP, 12.2 years control). However, once we remove the outlier Damas (36 years) from control sites, the average age of control sites is around half the age of WASEP at 7.4 years.

Table 3 | Sample overview, rural WASEP and control

Site (rural)	District	District group	Source	Water system (G/M)	Water samples (no.)	Project completion (year)	Project age (years)
WASEP:							
Broshal	Nagar	Hunza-Nagar	Spring	G	3	1998	24
Chandupa	Shigar	Baltistan	Spring	G	N/A	2000	22
Daeen Chota	Ghizer	Ghizer	Spring	G	4	2006	16
Duskhore	Shigar	Baltistan	Spring	G	3	2008	14
Dushkin	Astore	Astore	Spring	G	3	2006	16
Hatoon Paeen	Ghizer	Ghizer	Spring	G	3	2011	11
Kirmin	Hunza	Hunza-Nagar	Spring	G	5	2018	4
Nazir Abad	Ghizer	Ghizer	Spring	G	4	2011	11
Rahimabad	Gilgit	Gilgit	Spring	G	4	2012	10
Shamaran	Ghizer	Ghizer	Spring	G	3	2008	14
Shilati	Diamer	Diamer	Spring	G	3	2013	9
Singul	Ghizer	Ghizer	Spring	G	4	2004	18
Control:							
Doyan	Astore	Astore	Spring	G	4	2014	8
Thorgu Paeen	Skardu	Baltistan	Stream	G	0	2017	5
Samigal	Darel	Diamer	Stream	G	4	2014	8
Damas	Punial	Ghizer	Spring/ stream	G	3	1986	36
Jutal	Gilgit	Gilgit	Stream	G	3	2014	8
Hussainabad	Hunza	Hunza-Nagar	Stream	G	3	2014	8

A total of 58 water samples were collected from 20 urban sites – 42 from 12 WASEP projects and 16 from six control sites (Table 4). In contrast to rural projects, 64% of urban WASEP projects were mechanical systems, relying on rivers. Urban WASEP projects are also significantly younger compared to rural WASEP and urban control projects, having only been recently introduced and with an average age of 6.9 years compared to 35.5 years for control sites.

Despite rural WASEP projects being older, the overall water quality based on *E. coli* colonies, was in the range of safe and low risk, with 100% WASEP water samples at the source and 92% at system and tap coming under category A (safe drinking water). In comparison, no water samples from control sites came under category A, with 100% of collected water samples at source, 80% at system and 40% at tap falling under category B (low risk) and the rest in category C (medium risk) (Table 5). Water samples could not be collected from Chandupa as the project was not functional (discussed below).

As with the rural sample, microbial water quality was significantly better in urban WASEP projects with 86% (at source), 75% (system) and 86% (tap) of water samples falling under category A. This compares with no water samples testing in category A for control sites and 33% (source), 0% (system) and 17% tap falling under category B, with the remainder in category C (Table 6).

Table 4 | Sample overview, urban WASEP and control

Site (urban)	Union	District group	Source	Water system (G/M)	Water samples (no.)	Project completion (year)	Project age (years)
WASEP:							
Aliabad Centre	Hunza	Hunza-Nagar	Spring	G	3	2014	8
Aminabad	Jutial	Gilgit	Sump	M	3	2013	9
Astore Colony	Jutial	Gilgit	Sump	M	3	2018	4
Chokoporo	Municipal area	Ghizer	Spring	G	3	2015	7
Diamer Colony	Jutial	Gilgit	Sump	M	3	2018	4
Domial	Municipal area	Ghizer	Spring	G	3	2015	7
Khanabad	Municipal area	Ghizer	Spring	G	3	2015	7
Noor Colony	Gilgit	Gilgit	Sump	M	3	2014	8
Noorabad Ext.	Jutial	Gilgit	Sump	M	3	2014	8
Rahimabad Ali Abad	Aliabad	Hunza-Nagar	Stream	G	3	2012	10
Soni_Kot	Gilgit	Gilgit	Sump	M	3	2011	11
Wahdat Colony	Jutial	Gilgit	Sump	M	3	2018	4
Yasin Colony	Jutial	Gilgit	Sump	M	3	2018	4
Zulfiqarabad	Jutial	Gilgit	Sump	M	3	2016	6
Control:							
Gakuch Khari	Ghakuch	Ghizer	Sump	M	2	1987	35
Jutial Kot Mohalla	Gilgit	Gilgit	Stream	G	3	1984	38
Jagir Baseen	Gilgit	Gilgit	Stream	G	3	1988	34
Konodas	Gilgit	Gilgit	River	G	2	1984	38
Sikandarabad	Nagar	Hunza-Nagar	Stream	G	3	1992	30
Sakwar	Gilgit	Gilgit	Stream	G	3	1984	38

Notes: Water system covers G (gravity) and M (mechanical). Project age is taken at 2022. Water samples could not be collected from Chandupa as the project was not functional.

T-tests to confirm these findings could only be run for rural (system) and urban (source, tap) because of zero variance for rural (source, tap) and urban (system). The difference between *E. coli* water quality scores in rural WASEP and control sites were statistically significant based on T-tests for rural (system) and urban (source, tap) (Table 7).

The physiochemical water scores for rural WASEP projects were on average higher than control sites, aside from turbidity: pH (7.5 WASEP, 7.3 control), TDS (165 WASEP, 119 control), conductivity (343 WASEP, 249 control), salinity (155 WASEP, 120 control), total hardness (136 WASEP, 123 control), turbidity (0.7 WASEP, 1.9 control) (Table 8). These average scores were within WHO recommendations (Table 2) although three WASEP projects (Dushkin, Kirmin, Rahimabad) and one control site (Jutal) exceeded WHO guidelines for conductivity, three WASEP projects (Daeen Chota, Dushkin, Kirmin) and two control sites (Jutal, Hussainabad) had very hard water, and one control site (Hussainabad) greatly exceeded turbidity limits (Table 8). These higher values are normally attributable to seasonal fluctuations when high temperatures in summer create floods leading to erosions of riverbanks and subsequent high TDS, turbidity and conductivity. Bacteria and physiochemical contaminations in drinking water also depends on season, as these tend to be higher in summer and reduces gradually in autumn (GB-EPA 2019).

Physiochemical properties were more mixed for urban WASEP and control projects, with higher average scores for WASEP for pH (7.8 vs 7.6 for control) and conductivity (324 vs 275), and lower scores for WASEP for total hardness (119 vs 139) and turbidity (2.9 vs 3.9). These average scores were within WHO recommendations but as with several rural projects, 39% of individual WASEP projects (Noor Colony, Noorabad Extension, Soni Kot, Wahdat Colony, Zulfiqarabad) and 17% of control sites (Sikandarabad) exceeded WHO guidelines for conductivity, and 8% of WASEP (Zulfiqarabad) and 17% of control sites (Gakuch Khari) recorded

Table 5 | Water quality (microbiological), rural WASEP and control

Site (rural)	Microbial: source	Microbial: system	Microbial: tap
WASEP:			
Broshal	A	B	C
Chandupa	N/A*	N/A*	N/A*
Daeen Chota	A	A	A
Duskhore	A	A	A
Dushkin	A	A	A
Hatoon Paeen	A	A	A
Kirmin	A	A	A
Nazir Abad	A	A	A
Rahimabad	A	A	A
Shamaran	A	A	A
Shilati	A	A	A
Singul	A	A	A
Control:			
Doyan	B	C	C
Thorgu Paeen	N/A**	N/A**	N/A**
Samigal	B	B	B
Damas	B	B	B
Jutal	B	B	C
Hussainabad	B	B	C

Notes: N/A* (Water samples could not be collected from Chandupa as the project was not functional); N/A** (site too far to transport water sample to the lab in time).

Table 6 | Water quality (microbiological), urban WASEP and control

Site (urban)	Microbial: source	Microbial: system	Microbial: tap
WASEP:			
Aliabad Centre	B	B	B
Aminabad	A	A	A
Astore Colony	A	N/A*	A
Chokoporo	A	A	A
Diamer Colony	A	A	A
Domial Buridur	A	A	A
Khanabad	A	A	A
Noor Colony	A	N/A*	A
Noorabad Extension	A	N/A*	A
Rahimabad Ali Abad	B	B	B
Soni_Kot	A	N/A*	A
Wahdat Colony	A	N/A*	A
Yasin Colony	A	A	A
Zulfiqarabad	A	N/A*	A
Control:			
Gakuch Khari	B	N/A**	B
Jutial Kot	B	C	C
Jagir Baseen	C	C	C
Konodas	C	N/A*	C
Sikandarabad	C	C	C
Sakwar	C	C	C

Notes: N/A* (not applicable as water is supplied to consumers directly from sump through pumps and no water tank is required); N/A** (water is supplied from a shallow well through pumps with no water tank).

Table 7 | Water quality (microbiological), T-test results, selected WASEP and control

Water source	T-value	df	*P*-value	95% confidence interval	Mean
Rural system	−5.0484	5.7259	0.002677	−1.6529578 −0.5652241	2.909091 (WASEP) 1.8 (control)
Urban source	−6.5657	7.2192	0.0002752	−2.0692446 −0.9783745	2.857143 (WASEP) 1.333333 (control)
Urban tap	−8.7651	8.5861	0.00001438	−2.129994 −1.250958	2.857143 (WASEP) 1.166667 (control)

Table 8 | Water quality (physiochemical), rural WASEP and control

Site (rural)	pH	Total dissolved solids	Conductivity	Salinity	Total hardness	Turbidity
WASEP:						
Broshal	7.6	130	268	200	65	0
Chandupa	N/A	N/A	N/A	N/A	N/A	N/A
Daeen Chota	7.8	173	360	200	210	0
Duskhore	7.2	82	172	100	75	0
Dushkin	7.8	280	578*	300	225	0
Hatoon Paeen	7.6	111	233	100	90	2.3
Kirmin	7.6	512	1,042*	200	450	3.26
Nazir Abad	7.4	47	99	50	60	0
Rahimabad	7.2	311	667*	300*	65	0
Shamaran	7.6	59	126	100	60	1.5
Shilati	7.4	61	129	100	60	0
Singul	7.6	46	99	50	60	0.26
Control:						
Doyan	6.8	42	91	0	60	0
Thorgu Paeen						
Samigal	6.8	68	142	100	60	0
Damas	7.6	89	187	100	75	0
Jutal	7.8	233	481*	200	210	0
Hussainabad	7.4	165	342	200	210	9.65*

Notes: *Exceeds WHO recommendations for drinking water. Water samples could not be collected from Chandupa as the project was not functional.

very hard water. High turbidity was also recorded at 14% of WASEP projects (15 Aliabad Centre, 15 Rahimabad Ali Abad) and 33% of control sites (10 Sikandarabad, 8.4 Sakwar) compared to WHO recommendations of 5 NTU or less (Table 9).

Water infrastructure

The higher (microbial) water quality scores in rural WASEP projects are reflected in similarly higher infrastructure scores based on an engineering audit of water infrastructure at source intake (average 4.3 out of 5), route (4.2), and distribution network (4.0). In comparison the average scores for rural control sites were 2.7 (source intake), 3.3 (route), and 1.3 (distribution network) (Table 10). The differences in average infrastructure scores were even higher for (newer) urban WASEP projects: source intake (WASEP 4.7, control 2), route (WASEP 5, control 3.2), and distribution network (WASEP 5, control 1) (Table 11).

DISCUSSION

The poor and variable water quality and infrastructure scores in control sites are in part a reflection of the fragmented delivery of water services by the Water and Sanitation Authority (WASA) of the Government of the

Table 9 | Water quality (physiochemical), urban WASEP and control

Site (urban)	pH	Total dissolved solids	Conductivity	Salinity	Total hardness	Turbidity
WASEP:						
Aliabad Centre	7.8	144	299	0.1	165	15*
Aminabad	7.6	97	203	0.1	125	5
Astore Colony	7.8	164	340	0.2	105	0
Chokoporo	7.8	40	86	0	45	0
Diamer Colony	7.8	164	340	0.2	105	0
Domial	7.8	40	86	0	45	0
Khanabad	7.8	40	86	0	45	0
Noor Colony	7.6	268	553*	0.3	150	0
Noorabad Extension	7.6	233	482*	0.2	120	0
Rahimabad Ali Abad	7.8	144	299	0.1	165	15*
Soni_Kot	7.6	201	416*	0.2	125	5
Wahdat Colony	8.2	238	491*	0.2	175	0
Yasin Colony	7.8	164	340	0.2	105	0
Zulfiqarabad	7.6	251	518*	0.2	190	0
Control:						
Gakuch Khari	7.6	166	344	0.2	330	5
Jutial Kot	7.5	84	176	0.1	60	0
Jagir Baseen	7.5	41	88	0	40	0
Konodas	7.6	275	567*	0.3	180	0
Sikandarabad	7.6	153	318	0.1	150	10*
Sakwar	7.5	75	157	0.1	75	8.4*

Notes: *Exceeds WHO recommendations for drinking water.

Table 10 | Water infrastructure scores, rural WASEP and control sites

Site (rural)	Infrastructure score: source intake	Infrastructure score: route	Infrastructure score: distribution network
WASEP:			
Broshal	3	4	4
Chandupa	3	2	3
Daeen Chota	4	4	4
Duskhore	5	5	5
Dushkin	5	5	4
Hatoon Paeen	4	4	4
Kirmin	3	1	4
Nazir Abad	5	5	5
Rahimabad	5	5	2
Shamaran	4	5	4
Shilati	5	5	5
Singul	5	5	4
Control:			
Doyan	2	3	1
Thorgu Paeen	2	4	1
Samigal	3	3	1
Damas	4	3	1
Jutal	2	3	2
Hussainabad	3	4	2

Table 11 | Water infrastructure scores, urban WASEP and control

Site (urban)	Infrastructure score: source intake	Infrastructure score: route	Infrastructure score: distribution network
WASEP:			
Aliabad Centre	2	5	5
Aminabad	5	5	5
Astore Colony	5	5	5
Chokoporo Gahkuch Bala	5	5	4
Diamer Colony	5	5	5
Domial Buridur Gahkuch Bala	5	5	4
Khanabad Gahkuch Bala	5	5	4
Noor Colony	5	5	5
Noorabad Extension	5	5	5
Rahimabad Ali Abad	2	5	5
Soni_Kot	5	5	5
Wahdat Colony	5	5	5
Yasin Colony	5	5	5
Zulfiqarabad	5	5	5
Control:			
Gakuch Khari bazaar area	N/A*	N/A*	N/A*
Jutial Kot Mohalla	1	3	1
Jagir Baseen	4	3	1
Konodas	3	3	0
Sikandarabad	0	3	1
Sakwar	1	4	1

Notes: N/A* (no water infrastructure).

Gilgit-Baltistan (GoGB) and communities dependant on piecemeal funding from local government departments and NGOs. This is in contrast to high standards of engineering design and WQM for WASEP projects. The overall results indicate that WASEP projects have (significantly) higher water quality (microbial) and infrastructure scores compared to control sites in both rural and urban projects. This was despite the differences in age of WASEP and control projects in rural and urban sites, with rural WASEP projects being older than rural control sites, and urban WASEP projects significantly younger (seven years) than urban control sites (36 years). This indicates that aside from operations and maintenance, engineering design and WQM play an important part in ensuring the safety water sources and distribution networks.

Lower water quality in urban control sites for example were due to water being sourced from a shallow well near a river (Gakuch Khari) or taken directly from a river without treatment (Konodass). In several cases, population growth and increased water demand led to residents mixing water from open irrigation channels with existing sump water, which contaminated the water supply. These channels were not properly protected against wastewater and other contaminants, and in some cases, were used for drinking water of animals. Low infrastructure scores for control sites can be illustrated by water pipes laid on the surface of the ground where these are susceptible to damage from freezing weather, natural hazards, and illegal connections, all of which introduce contamination to the water supply through leaks (Figure 3).

Lower individual urban WASEP project scores for water quality (Aliabad) were due to damage to water infrastructure from natural hazards (glacial movement). The WASEP project in Chandupa was non-functional due to flood damage and the subsequent theft of pipes and other parts. Lower water quality (microbial) scores in Broshal (B system and C tap) were related to a lower infrastructure score at source (3 out of 5) because of age-related wear and tear (the project is 24 years old), leaks, and subsidence at the water source. Poor water quality was exacerbated by the mixing of stream water with the spring source to meet the demands of a growing population.

Figure 3 | Water infrastructure at selected WASEP and control sites. (a) Water source chamber (left) and water tank control valve box (right) at Singul (rural WASEP). Photos by Manzoor Ali. (b) Water tank in Konodas (urban control, left) and Dushkin (rural WASEP, right). Photos by Manzoor Ali. (c) Water source (left) and distribution network (centre) at Konodas (urban control), and distribution network at Doyan (rural control, right). Photos by Manzoor Ali.

CONCLUSION AND RECOMMENDATIONS

The availability of clean drinking water has always been a challenge in Gilgit-Baltistan and has worsened with the impact of climate change, which has increased water-borne disease due to unpredictable floods (WWF 2010). The current research follows up on earlier studies of water quality (Raza & Alibhai 2000; Abbas & Schlosser 2004; Parpia 2016) and confirms the viability of the WASEP model in delivering clean drinking water in Gilgit-Baltistan in contrast to the poor quality of water and water infrastructure at control sites.

This illustrates the challenges of governance, source protection, quality assurance and equitable distribution in developing countries with both rural and urban control sites exhibiting higher levels of *E. coli* at source, distribution and household levels, that was compounded by the mixing of open channel water with spring water to meet the growing water needs of an increasing population. This was related to poor engineering design as reflected in lower infrastructure scores, with water sources not properly protected and the system pipes connecting the source inlet and tank exposed and leaking at many sites. The distribution system was badly designed and there was a general complaint of inequitable water distribution. Water governance is one of the major challenges in these areas, with no organised community involvement observed.

Appropriate engineering design, effective water testing and treatments play an important role in the provision of clean drinking water (Findikakis *et al.* 2020). The WASEP model illustrates how water contamination has been reduced through better engineering design, quality, and testing, along with the active involvement of communities in monitoring and maintaining water systems (Abbas & Schlosser 2004). Effective water quality management has delivered safe drinking water as per WHO guidelines. Engineering design has been a major difference between WASEP and control sites by securing and protecting water sources and pipes in distribution networks that is necessary to safeguard water quality (Raza & Alibai 2000).

Higher water quality in rural WASEP projects is related to the careful selection of water sources from springs, which are tested and properly protected. Where this is not possible in urban centres, riverbed filtration systems have delivered category A water quality for all nine mechanical urban projects (Tables 4 and 6). The water system route from source to water tank is buried 3–4 ft deep (depending on elevation and the frost line) to prevent freezing and damage from natural hazards. As a result, water quality at household taps falls under category A for 86% of urban WASEP projects (Table 6).

The problems identified for both control and WASEP projects relate to ageing water infrastructure, increasing demand from growing populations, and damage from natural hazards that negatively impact water infrastructure and water quality. The lifecycle of rural WASEP water infrastructure is 15 years which means that five (42%) rural WASEP projects have already exceeded their natural lifespan, with another two projects (17%) almost at the end of their lifecycle at 14 years (Table 3). A key challenge and recommendation here are for the rehabilitation and expansion of water systems as they approach the end of their lifecycle.

DATA AVAILABILITY STATEMENT

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

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