Investigating declining yields in a large upland spring supply with limited data

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The paper describes an assessment of a large spring-fed piped water supply scheme in Ethiopia. Constructed in the mid-1990s, the scheme has recently reported yield problems. These problems threaten the sustainability of the scheme and the success that it has achieved in supplying over 70,000 people. The assessment indicated possible reasons for this, both in terms of the natural resource and the management of the water system. The very limited data that were available with regard to the operation and functioning of the system made it difficult to draw clear conclusions and underlined the need for data collection processes to be designed into the operation and management of water supply projects.

Keywords: spring-fed water supply, rainfall data, recharge, unaccounted-for water.

THIS PAPER DISCUSSES THE DIFFICULTY of assessing the sustainability of an important water supply system given the lack of relevant data collection. The authors believe that the situation is not uncommon and that the conclusions may therefore be widely relevant.

Since 1995/96, some 75,000 people in more than 40 communities in Hitosa *wereda* in central Ethiopia have been provided with water through a spring-fed gravity water supply project that is one of the largest in the country. The entire scheme is managed by a community-based Water Administration Office (WAO). The scale and success of the Hitosa Water Supply Scheme makes it a flagship project for WaterAid, the organization that supported its development. The construction and management provide an excellent example of the combination of appropriate technology with effective, locally based operation and management. The continued success of the scheme is therefore of great significance, both to the beneficiaries and to WaterAid.

The scale and success of the Hitosa Water Supply Scheme makes it a flagship project for WaterAid

The water for the main Hitosa scheme is sourced from two springs (one much larger than the other), which are located at the head of a watercourse known as Burkitu. In 2007 an investigation was instigated as a result of concern about a reported decrease in spring flow. The combined yield had reportedly decreased from 19.4 l/s (the design

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flow) to 13.6 l/s, whereas the number of people accessing the water has increased significantly. The WAO was uncertain of the reason for the decrease in yield, but related it to climate change, together with changing patterns in vegetation and agriculture. Anecdotal evidence that other springs and seepages in the vicinity had declined or ceased (including some data collected by the local Water Office) added to concern.

The water yield had reportedly decreased from 19.4 to 13.6 l/s

The WAO reported that the main pipeline from Burkitu does not always flow full bore, as it was designed. This brings problems of air intake into the system, reduced pressure and water contamination. Furthermore, the system had been designed for a population of 71,483 – a figure that has already been exceeded by around 10%, according to WAO staff.

The objective of the investigation was to provide comments and recommendations concerning the possible causes of spring flow reduction, the future sustainability of the system and the maximum number of people that can be reliably served. As this paper shows, the objective was very difficult to achieve with the available information.

The aim was to find the causes of spring flow reduction and the future sustainability of the system

Background data

Location

The spring is located within Hitosa district, 7.5 km south-south-east of the town of Huruta, in Arsi Zone, some 164 km south-east of Addis Ababa.

A major south-west–north-east orientated scarp occurs approximately 4 km to the west of the springs. This marks the eastern edge of the Rift Valley, one of the largest physical features in Ethiopia. Ground elevations increase rapidly, from the floor of the Rift Valley at approximately 2,100 metres above sea level (m asl) to 2,300 m asl. The springs rise at around 2,400 m asl, and from there the land climbs southwards towards Mount Chilalo and the Galama Range, in excess of 4,000 m asl, some 15 km away.

The Burkitu watercourse discharges to the Keleta River, a tributary of the Awash, which drains this part of the Rift Valley (Figure 1). The Keleta River rises on the slopes of Galama. The river valley, like those of other watercourses, is deeply incised where it passes through the Rift Valley escarpment.

Geology

The site lies on the eastern edge of the Middle Ethiopian Rift (MER) system. The geology of the area comprises two distinct sub-divisions

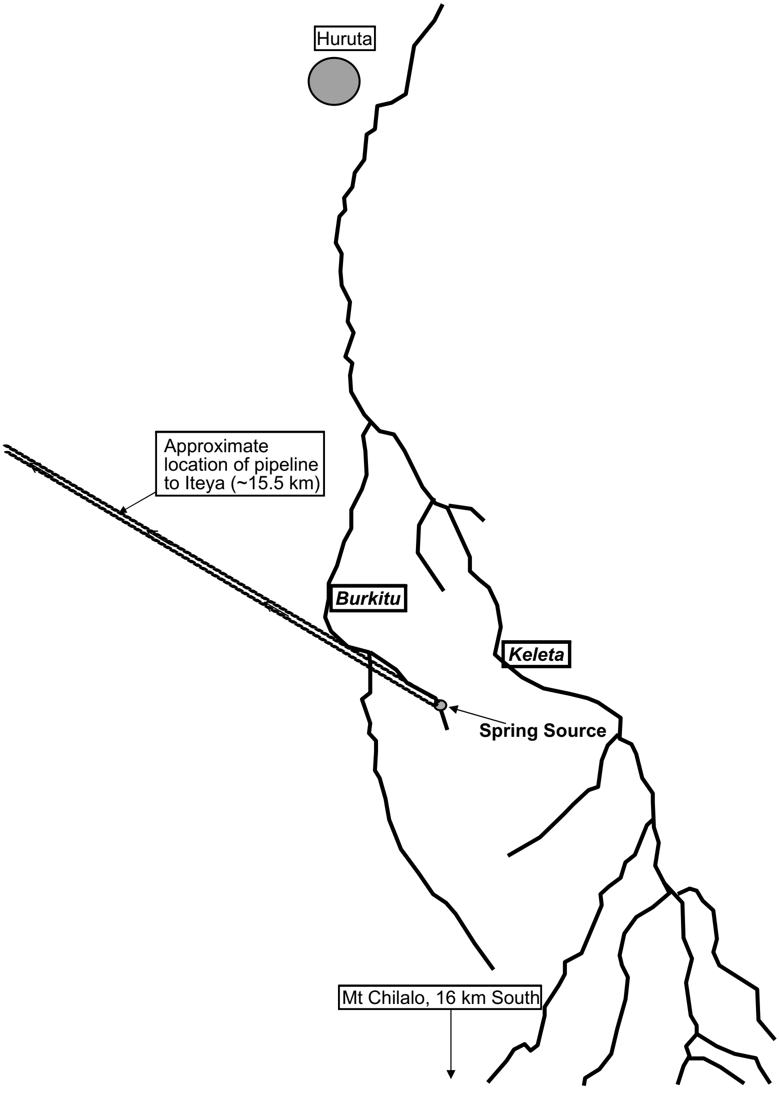

Figure 1. Location of the spring source in the Burkitu watercourse

of igneous rocks (Yemane et al., 1999). The Eastern Margin Unit (EMU, Benvenuti et al., 2002) comprises a sequence of weathered, usually coarse-grained, densely welded, varicoloured ignimbrites (mixed volcanic ash and rock fragments). The ignimbrites are interbedded with flood basalts (lava flows) and unwelded ash beds. Burkitu springs rise from this sequence, which can exceed 200 m in thickness.

The Keleta River cuts through this sequence to expose a vertical section through the EMU. The river bed runs over massive basalts. A variety of rock types was observed on the valley sides including ignimbrites and ashes.

The Arsi Shield Volcanics spread from Chilalo and Galama. They comprise a sequence of basalt lava flows and associated rocks that cover large areas spreading from the mountain peaks.

Long, SW–NE trending faults account for the straight scarps which form a distinctive feature of the landscape. The demarcation between the more recent Arsi Shield Volcanics and the EMU can be inferred by the southern termination of the fault-controlled breaks of slope, which have been overlain by the lava spreading from the peaks. The boundary between the two rock types occurs some 2 km to the south of the Burkitu springs.

Hydrogeology

Two rock characteristics are important in determining the yield of springs. The first is the ability of the rock to transmit groundwater (the transmissivity). This depends on either interconnected fractures or interconnected pores within the rock mass. The second is the ability of the rock to store water (the storage), which depends on the open space (porosity) within the rock.

A permanent, high-yield spring like Burkitu is fed by a unit with good storage, probably via fractures within the basalts

Groundwater movement and storage in the vicinity of the springs are influenced strongly by lithological variations and structural control. The lithology varies from massive and relatively unfractured ignimbrites, with very low storage and low transmissivity, to highly fractured basalts (which have low storage but high transmissivity) and relatively porous ash deposits (which provide good storage and good transmissivity). A permanent, high-yield spring like Burkitu is fed by a unit with good storage, probably via fractures within the basalts that crop out where the spring rises. When enough water is recharged to a suitable rock unit, it fills to the point at which the level reaches the ground at certain points, where it overflows as springs (see Figure 2).

Spring flows are dynamic, both in the short term (between seasons) and the long term (years to decades). Flow rates respond to natural and anthropogenic influences, including climate and land use variations within the catchment. Spring flows typically show seasonal fluctuation in response to changes in temperature and rainfall. These fluctuations are generally greater where the aquifer is dominated by fissure flow and has low storage.

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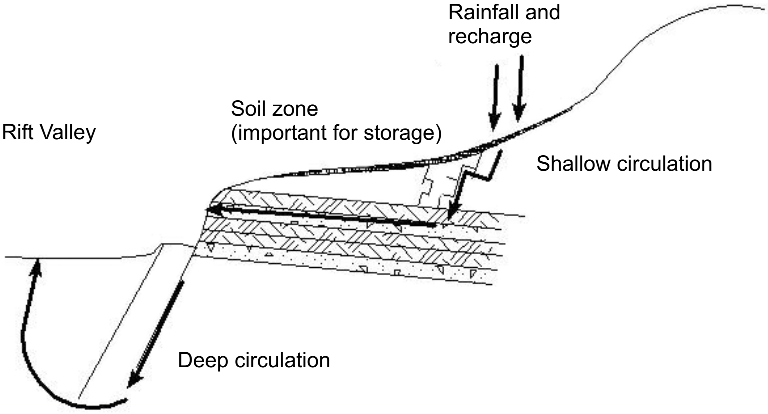

Figure 2. Groundwater movement and storage on the slopes of the Rift Valley

The resource

Rainfall

The source of the water that resurges at Burkitu is ultimately rainfall; therefore gaining a clear understanding of rainfall patterns and their variations with time is fundamental to understanding the system.

Two rainy seasons occur: Belg, from February to May and the main rains, Kiremt, from June to September. Data are not collected within the catchment, but are recorded at two nearby gauging stations. Long-term average data sourced from the National Meteorological Office are summarized in Table 1.

Huruta rainfall station is located some 7.5 km NNW of the spring at an altitude of approximately 2,000 m asl. The monthly totals were plotted together with long-term mean values (see Figure 3). The Iteya station is 18 km to the west of the spring at an altitude of some 2,200 m asl. Detailed assessment showed significant differences between the stations in the years with above-average rainfall. At Huruta the years 1992 to 1997 were particularly wet, while 2000 to 2004 was the wettest period at Iteya. The maximum monthly total at Huruta was 267 mm and at Iteya 425 mm. No clear trends in rainfall could be identified.

No clear trends in rainfall could be identified

Table 1. Monthly mean rainfall data in mm, for Huruta (top) and Iteya (bottom), 1987–2006

Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*	*Oct*	*Nov*	*Dec*	*Total*
22.8	23.8	58.8	83.7	80.8	96.8	151.9	160.4	117.7	48.1	12.0	8.9	866
23.7	27.9	66.6	88.1	85.6	97.8	201.9	201.7	151.0	49.8	11.3	6.2	1012

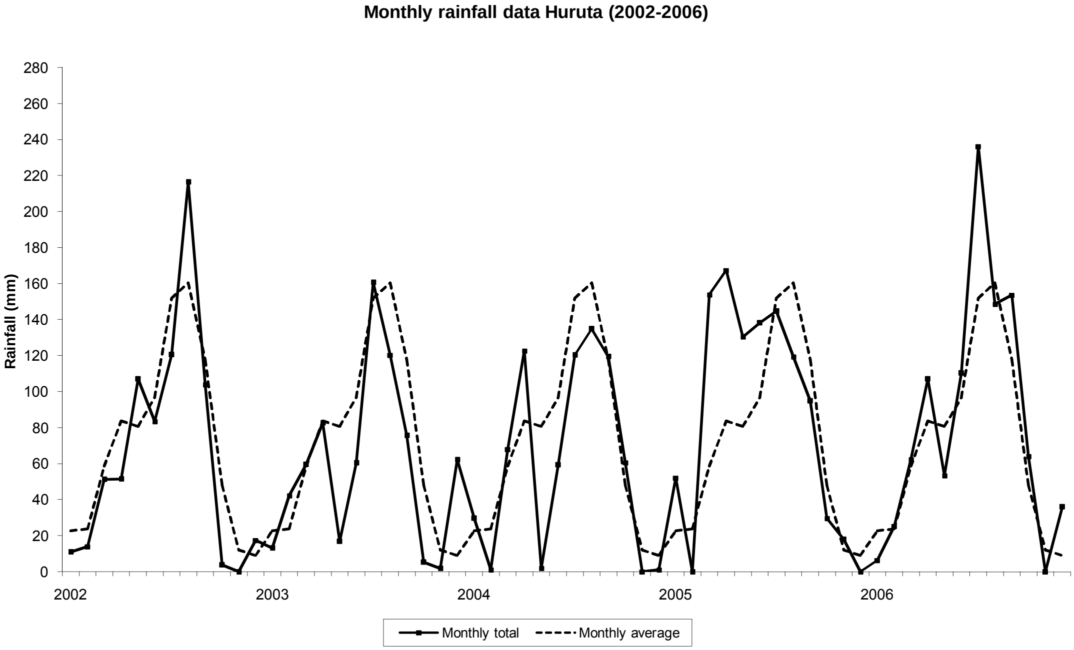

Figure 3. Huruta monthly rainfall data 1997 to 2006

Land use

Arsi is an important food-producing region in Ethiopia, and the Hitosa *Wereda* is generally very fertile and extensively farmed for wheat, barley and oilseeds. Rearing of goats, sheep and cattle is also widespread.

The most productive land is found between 2,200 and 2,500 m asl, and 70% of the population supplied by the scheme inhabits these elevations, where almost all flat areas and even some steep slopes are utilized for agriculture. Pockets of land are irrigated, where suitable springs exist; in the remainder, crops rely on rainwater. Within this area sporadic stands of planted eucalyptus occur, but natural vegetation including a few remaining forest trees is restricted to the most inaccessible parts of the ravines and steep slopes bordering rivers and gullies. Above Burkitu, however, most of the land is still farmed as far as the edge of the rocky outcrops close to the mountain summits at around 3,350 m asl. On the uppermost slopes of the mountains, where it is too cold to grow crops, some degraded remnants of the original forest cover remain.

Baseline data on land use were not collected at the start of the project, so it is not possible to say with certainty how it has changed in the interim. Local people say that several decades ago much of the area was still forested. The *wereda* Natural Resources Office reported that in 1990 there was still some natural forest left on the higher slopes, with *aster* scrub on the highlands beyond the tree line. Villagers have continued to cut this wood for fuel and construction, and even today they use the remaining scrub high on the mountain to supplement the newly planted eucalyptus. However, discussion with local farmers and comparison of historic aerial photographs with more recent satellite images indicate strongly that there have not been marked changes in land use since 1973.

There have not been marked changes in land use since 1973

The soil in the catchment is a deep, black, loam soil typical of volcanic regions. It has the ability to absorb large volumes of water and allows it to recharge slowly to groundwater. Soil loss might therefore be an important factor in decreasing recharge. Site visits and aerial photos suggest that soil erosion is a limited problem. In some places gullies have opened up and soil has been lost along shallow dry valley features that take storm runoff.

Soil loss might be an important factor in decreasing recharge

Recharge

Recharge is rainfall-derived water that percolates into underground strata. In this region of Ethiopia, this water is believed to be discharged at springs such as Burkitu, to perennial rivers such as the Keleta, and to springs and lakes in the Rift Valley floor.

Kebede (1987) estimated the likely volume of recharge entering the aquifer at 6% of incident rainfall, using baseflow analysis of the River Keleta. (Baseflow analysis calculates the proportion of flow in a river that can be shown to be dependent on groundwater, rather than runoff.) From the rainfall data for Huruta and Iteya, this equates to between 52 mm and 60.5 mm per annum. A study in the drier Eritrean highlands (Solomon, 2003) gave a recharge estimate of 8% of rainfall in basalt terrain. An estimate of 50 mm per annum for Burkitu therefore appears a conservative value (i.e. the actual recharge is likely to be higher than this value).

Catchment area of the springs

An estimate of the catchment area of the Burkitu sources can be made based upon a measured spring flow rate and the assumed value of recharge defined above.

Flow rate = 20 l/second = 1,728 m^3/d = 630,720 m^3 per annum

Assuming recharge of 50 mm per annum, a total catchment area of 1,261 hectares would be required to supply the springs with the observed water volumes. This is necessarily a gross approximation, as the spring flow changes with time (the average flow may be more or less than the measured flow at any time) and the recharge value is not precise. However, it provides an indication of the likely recharge area, which equates to some 3.5 km x 3.5 km. The indicated area also informs the search area for the assessment of changes in land use. Even if the true catchment were double this size it remains a small proportion of the Keleta River basin.

It should be noted that groundwater flow within complex aquifers such as the local volcanic sequence is highly unlikely to be uniform. Fissures and fractures have the potential to transmit groundwater over long distances, so that the actual spring catchment area may extend for several kilometres in specific directions.

Water quality

A single water quality test was carried out at the time of the system design. The results show that the water is poorly mineralized, and dominated by calcium and bicarbonate. Because groundwater dissolves minerals from the host rocks slowly, the low mineralization indicates that it is relatively recently recharged and has not spent long underground.

Conceptual hydrogeology

Recharge of the groundwater is relatively local

The evidence suggests that the springs are fed by the relatively shallow groundwater system of the Rift Valley margins, and this is likely given the position of the spring well above the valley floor. Recharge is therefore relatively local. The calculation above suggests an area of perhaps 3.5 km by 3.5 km. Infiltration into the soil is believed to be high. Recharge to the underlying rocks then depends on the degree of fracturing, but wherever a zone of fracturing is found, shallow flow within the soil or water flowing in streams and rivers will provide significant recharge.

The springs are probably supported by storage in the more porous ash beds and less well cemented ignimbrites, recharged through fissures in the interleaved basalts and cemented ignimbrites.

Holistic view of the catchment

Because of the fractured nature of the rocks that feed Burkitu, it is difficult to determine precisely where the recharge originates. This in turn makes it hard to identify activities that may have a direct bearing on the amount and quality of that recharge and therefore of the flow from the spring. Taking a wider view, however, there are many springs that rise within similar terrain in Arsi Zone, on the eastern flank of the Rift Valley. Several of these, in similar fashion to Burkitu, have been used to support large gravity-fed water supply systems. Other such systems include those that serve Dodota, Huruta, Ticho, Tereta, Gonde-Iteya and Robe-Maliyu (the last four being systems that were supported by WaterAid). Between them these systems serve an estimated half a million people.

The catchment for this group of springs is likely to be common: the highlands and slopes of the Chilalo and Galama mountains. Therefore a larger-scale assessment would be of potential benefit to all of these water supply systems.

Flow rates of Burkitu springs

Data relating to spring flow is extremely sparse. The only known measurements are summarized in Table 2.

The source was investigated in detail during site visits made on 5 and 6 December 2007. The water level in the outlet chamber was 4 cm above the top of the outlet pipe and below the overflow level. There was therefore no overflow of water and local inhabitants reported that the chamber had not overflowed for a 'considerable' time.

A flow measurement was made by closing the gate valve on the outlet pipe and diverting all the flow to discharge via the overflow. A stopwatch was used to measure the time taken to fill half an oil drum. The exercise was repeated three times and consistent values of 20 l/s were recorded.

Possible causes of spring flow reduction

The scarcity of spring flow data is such that it is not possible to state categorically whether flow has reduced over time. However, this is suggested by anecdotal evidence, including the observations of no recent overflow and that other springs and seepages formerly existed in the vicinity of Burkitu. Note that it has not been possible to substantiate these observations because of the lack of consistent spring flow measurement.

Plotting of spring flow against time generates a hydrograph, which is of great use in determining the long-term sustainable yield of a spring. It also serves to allow the identification of flow trends and hence provide an early warning if there are long-term declines in flow rates.

Table 2. Flow rates of Burkitu spring

Date	*Flow rate (l/s)*	*Flow rate (m3/d)*	*Comments*
1996	35	3,024	Pre-project, dry season spring flow rate
May 2007	13.6	1,175	Reported by Hitosa WAO to WaterAid, dry season
6 December 2007	20	1,728	Measured during site visit

Measuring the flow rate of Burkitu spring

Changes in relative intensity of rainfall might cause changes to the balance between runoff and infiltration

There is no evidence of any new abstraction of groundwater (no boreholes exist in the area) or changes to the groundwater flow pattern. If spring flows are reducing, the most likely cause is therefore a change in recharge, which might be induced by alterations in rainfall or other climatic variables, land use and soil erosion. As noted above, there is no strong evidence for changes in these variables. However, any changes in these variables could be subtle and several influences may act in unison, thereby amplifying their individual effects. Changes in relative intensity of rainfall, for example, could not be discerned from the rainfall data available, but this might cause changes to the balance between runoff and infiltration. Significant changes to the property of the rocks are unlikely, either by alteration of the rock material through weathering or by changes to faults and fractures caused by earth movements. Geo-Engineering Service (2003) discounted the possibility of earth movements in the area when assessing the nearby Gonde-Iteya system.

Design and management of the water supply system

Overview

The Hitosa project taps protected springs to serve an extensive piped system that conveys water over a large area to the west. Movement of the water is achieved entirely by gravity flow. It includes two separate systems, with the characteristics shown in Table 3.

The first system is relatively small and was built to serve the town of Boru Jawe. The second system serves all of the remaining communities and is the subject of this paper.

The source works

The water for the Hitosa scheme is sourced from two protected springs. A retaining wall and collection chamber impound water from the main spring, prevent contamination and convey water into the reticulation system. The second spring, which is much smaller, is impounded in a similar fashion and piped to the same chamber.

The reticulation system (pipes and reservoirs)

The main pipeline is 8′ (203 mm) diameter ductile iron and 6′ (152 mm) galvanized iron. Other sections are in PVC in diameters from 3′ to 6′ (76–152 mm). The branch lines from the reservoirs are in MDPE with diameters from 25 mm to 63 mm. There is one break pressure tank between the source and the escarpment to the lowlands. Flow controls are not installed on the reservoir inlets, ensuring a steady but never high pressure in the system and avoiding considerable maintenance. This has allowed regular overflow from the reservoirs (at least at certain times). Detailed design drawings were prepared, but there are no as-built drawings and subsequent additions to the system have not been surveyed.

Extensions and private connections

The Water Administration Office (WAO) is naturally concerned with the sustainability of the system – including the financial aspect. Following concerns over revenue from water sales, the WAO encouraged additional water usage and revised its tariffs, including promoting additional connections, so that income can be sure to cover operation

Table 3. Design characteristics

No of people served 1994–2007	*43,000 (initially) to >75,000 (estimated in 2007)*
Spring capping	4 (2 at Burkita and 2 at Boru Jawe)
River and stream crossings	19
Main pipeline	33 km
Distribution pipelines	109 km
Reservoir capacity	(1 x 100 m^3 + 1 x 50 m^3 + 17 x 25 m^3) = 575 m^3
Design flow (main system)	19.6 litres per second
Design life	15 years (ending around 2010)

and maintenance costs. Information from the WAO indicated that the system hydraulics had not always been properly considered when new extensions and connections were implemented.

Figure 4 shows that sales of water have risen from around 100,000 m^3/yr in the first years of full operation to around 300,000 m^3/yr in 2007 (WAO figures). The increase has been particularly rapid during the last three years. The graph also shows that, despite the extension of the system to new villages, consumption of water at public tapstands has remained relatively constant since 1998/9, at around 125,000 m^3/yr. The recent consumption increase is due entirely to a rapid rise in private water consumption. The number of private connections has also increased correspondingly, as shown in Table 4.

The recent consumption increase is due entirely to a rapid rise in private water consumption

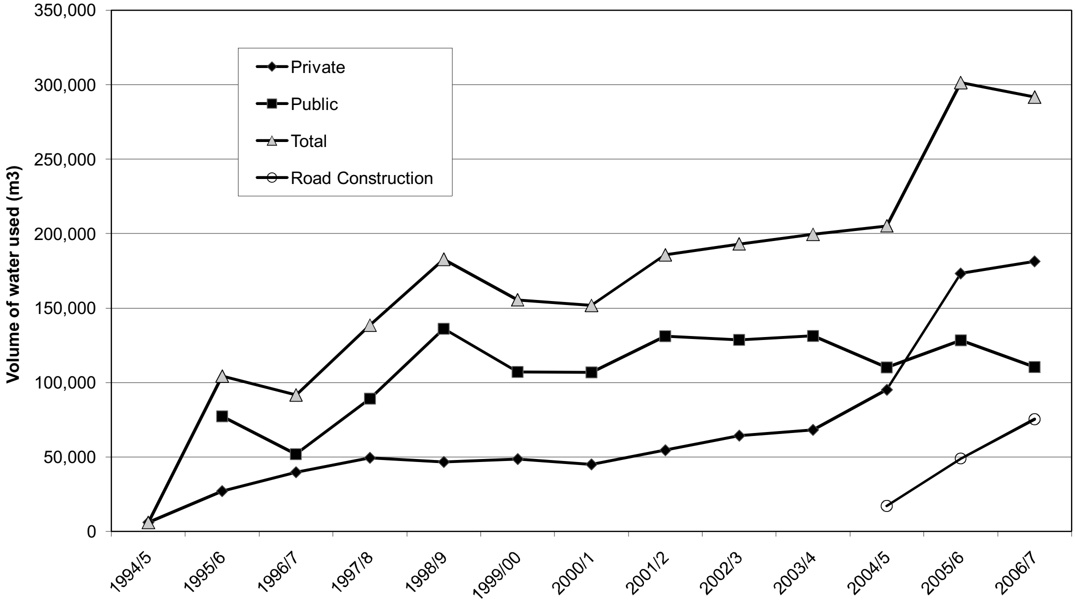

Figure 4. Consumption of water at Hitosa, 1994-2007

Table 4. Consumption (sales) at connections

Year	*Public tapstands*	*Institutional connections*	*Private connections*
1995/96	122	ND	ND
2004/05	138	93	965
2005/06	140	96	1302
2006/07	145	96	1671

A further important detail is that the scheme has one very large private consumer – the project that has been rebuilding the Nazret-Assela road. It received a connection from the Hitosa scheme in December 2004 and in 2006/07 used 75,000 m^3 of water. This single connection therefore accounts for a large proportion of the increase in private water usage.

Problems with pressure

In some locations public tapstands do not receive sufficient water

Generally the system performs well, and most consumers are reportedly happy with the service. However, there are some problem locations where public tapstands do not receive sufficient water, indicating that the system is not always functioning as intended.

Ladawi, west of the town of Iteya, is an example. This location is at the end of a branch line that passes through the town and design water pressure at the tapstand is low. The tapstand reportedly functioned well for several years, but in the dry season of 2005 it failed each day by mid-morning, as pressure in the system dropped. Since November 2007 the tapstand has been completely dry. It appears that, for this location, stress on the system has reduced available water pressure too much and it has ceased to function.

A second problem site was at Sero Badosa. Several tapstands in this area (all on the same branch line) reportedly dry up regularly. The WAO explained that this was due to the creation of airlocks higher up the system, which are formed when a break-pressure tank sometimes runs dry. The technician then has to come out and remove air from the system so that these tapstands have water.

Discussion

Balance of supply and demand

The estimate for total population served has been based upon an estimated population growth rate and the number of private connections. That this approximation may be inaccurate makes it difficult to forecast future demand. However, sales figures are available.

Water losses from overflows and leakages may be very significant

Figure 4 indicates that the total volume of water sold in 2006/7 is around 300,000 m^3. Comparing this figure with the design capacity (19.6 l/s, or 618,000 m^3) suggests that there should still be a significant surplus of water available. However, there are two further factors that have to be considered: one of these is the variability in the flow from the source (discussed above) and the other is water lost from the system. Water losses (often described as UFW, or unaccounted-for water) may be very significant and are expected to have two major components: overflows and leakage.

Because of the way the system is designed, overflows occur whenever reservoir tanks and break-pressure tanks are full. The system design anticipates that storage reservoirs will gradually empty during the day (when usage is greater than inflow) and refill during the night (when inflow is greater than usage). These overflows have never been monitored. Assuming the design inflow from the spring and a period of 12 hours during the night without significant water use, reservoirs should overflow for approximately 4 hours each night. This amounts to a loss of more than 100,000 m^3/yr.

It is very difficult to estimate leakage from pipes in the absence of any flow data from the system, but it is likely that undetected leaks will increase as the pipe components age. If we assume an increase in leakage losses of 2% per year from installation, by 2006/7 the leakage would have amounted to more than 75,000 m^3/yr.

If we then factor in a reduction in water availability from the spring (based on the single dry season measurement available from 2004), we can construct a graph that shows the possible availability of water and the water use (consumption + losses). This is shown in Figure 5.

The lowest line in the figure shows the monitored consumption figures from the WAO. The middle line shows the total estimated water usage, including recorded consumption and estimated water losses. The heavy line indicates how the spring flow might vary through the year. If the availability of water indicated by the heavy line ever dips below the line showing total water usage, demand exceeds supply and problems will follow. Although the graph is illustrative, it suggests that the Hitosa water supply system may be in a marginal position and that it may be unable to supply all of the demand, at least at certain times of the year.

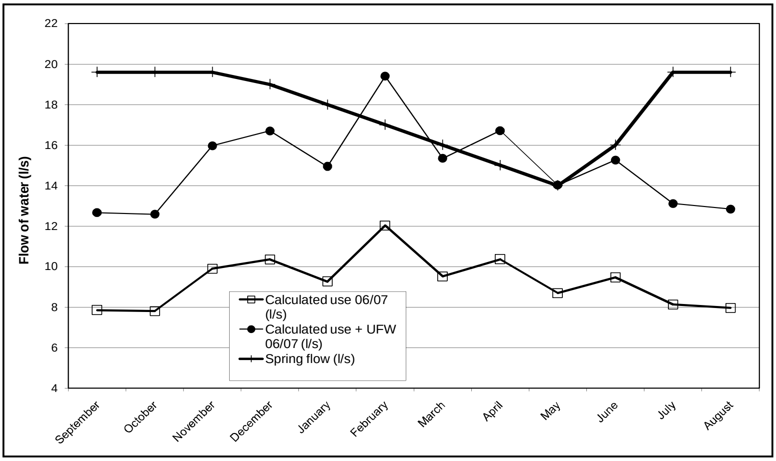

Figure 5. Sketch of the possible balance between water demand and supply

The impact of ageing

Although most system components are in good repair, major items such as tanks and main pipes are beginning to age. The WAO does not have a clear understanding or expectation of the components' lifespan, and with the lack of data collection it does not know in detail how their condition is evolving. This makes it extremely difficult to plan for the potentially major failures that might result in a serious challenge to continued water provision.

This is common to other schemes, such as those in Uganda described by Carter and Rwamanja (2006), who noted that, although gravity-fed projects supported by Kigezi Diocese were well maintained, they now faced the challenge of major repairs or replacement of components. Kleemeier's (2000) study of large Malawian gravity-fed systems similarly found that designers had effectively assumed that components would either last forever or be replaced somehow by community management when they ceased to function.

Designers had effectively assumed that components would either last forever or be replaced somehow by community management

Conclusions

Good water resource management ensures a balance between supply and demand. It becomes critical where demand (in all its forms) threatens to outstrip supply. For this reason it is imperative to understand the supply of water and the demand. Organizations have usually been guilty of assuming that supply is and will remain sufficient to meet demand in domestic water supply systems. The requirement for sustainability is now challenging this assumption in places such as Hitosa.

At the project planning stage it was concluded that there was more than sufficient water for the design population. In actual fact the supply is now lower than believed at that time and the design population has been exceeded, possibly significantly. Extensions and new connections have been made without due consideration of system hydraulics or the volume of available water. The yield has therefore probably been fully utilized already.

Although the installations are in good condition for their age, Hitosa – and probably many similar schemes of this kind of age in Ethiopia and other countries – is a system under stress. While population and demand for water continue to grow, there are new pressures derived from environmental changes and the deterioration of system components over time.

However, with existing evidence it is difficult to confirm with any confidence the reported spring flow reduction, or to determine the causes of problems in maintaining the desired water distribution. While relatively local rainfall figures are available on a monthly basis, data that are either insufficient or absent include the spring flow and flows within the system, the population served, the current layout of the scheme, water losses from overflows and leakage, changes to land use and soil erosion in the catchment, and nearby stream or spring flows that would provide indicators of a changing environment.

The main obstacle to the efficient management of the Hitosa system currently is the absence of data. Without data it is not possible to assess with accuracy the current operation of the system or to make predictions about its future sustainability.

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If (as the authors believe) the case is similar for many other water supply systems built since the 1980s, this represents a serious challenge to the sustainability of the gains made in providing safe water to the world's poorest people. Designers and managers of such systems are therefore called upon to ensure the inclusion of appropriate monitoring and record-keeping in the set-up and design of projects.

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