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Evaluating water delivery systems using continuous objective measurements of supply and demand

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This paper presents preliminary results from a 6 month long study to continuously monitor the performance of piped water delivery systems. Data was collected through the use of pressure transducers which were installed in water storage facilities to record water levels on a ten minute interval. Using data obtained from a rural site in Nicaragua, this paper explores a technique to extrapolate supply and demand flows passing in and out of storage tanks from water level data in order to better estimate actual daily per-capita and peak water demands. A firmer understanding of water supply and demand can lead to more informed design assumptions for water engineering professionals, and can provide a valuable metric for evaluating the performance of water supply infrastructure in rural communities
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Performance, supply, and demand for rural water delivery systems

With the United Nations Millennium Development Goal 7, Target 10, to halve the proportion of the population without "sustainable access to safe drinking water" having reportedly been met ahead of schedule (JMP, 2014), significant investment has undoubtedly been made towards the development of new water supply infrastructure in recent years. Significant resources in time and funding have largely been justified because of expected returns resulting from a reduction in water-borne illness and other health related impacts. However, the dominant paradigm for long-term management of water supply infrastructure, at least in a rural context, has been some variation of community management. In such a paradigm, an expectation exists that the revenue streams necessary for operations and maintenance be derived from user fees, driven by demands not necessarily related to public health objectives. In light of this dichotomy, Nicol (2000) recommends a "sustainable livelihoods" approach to water supply, where water is as a multipurpose part of natural capital and an asset in household economies, suggesting a more comprehensive, nuanced approach to anticipated demand, and better accounting for water uses beyond the "survival level".

In the context of a piped water supply, to evaluate performance with respect to water delivery (both in terms of quantity delivered and reliability of delivery), it may be useful to frame the problem in terms of supply and demand. In other words, performance may be considered satisfactory where the volume of water supplied meets or exceeds demand. Ultimately, supply can be viewed as being a function of environmental constraints at the source and technical constraints of the physical infrastructure in terms of delivery and storage. Furthermore, demand would be viewed as a function of social demographics in terms of population, growth and per-capita consumption of water. This paper explores a methodology that incorporates changes in water storage over time, to extract supply and demand flow-rates by installing water level monitoring equipment within water storage facilities.

An understanding of actual water supply volumes and user demands, which is based on a continuous, physical measurement, has the potential to inform the assumptions made in the development of new water supply infrastructure regarding per-capita daily and peak demands, and may also represent an additional tool existing methods used for benchmarking the performance of water delivery systems. The external factors related to community management that impact both the efficacy of delivery and storage systems as well as modulate demand, thus impacting the long-term sustainability are complex, and have been investigated by Lockwood et al. (2002), among others. This paper postulates that external factors may be better understood in the context of their relation to constraints defined by actual water supply volumes and user demands, insofar as these factors impact supply, demand, and performance, and vice-versa. The results presented in this paper represent a subset of some preliminary findings of a wider 6-month long study currently in progress in 10 sites in Nicaragua. Beyond performance monitoring with respect to water delivery, the overall study also considers water quality and surrounding contextual and management related factors.

Contextual background

For the purposes of this paper, a single water delivery system is highlighted, selected from among the 10 sites considered in the overall study. Given the objective of examining actual water demands beyond the “survival level”, it is important to consider both contextual characteristics specific to the site, as well as institutional frameworks relevant in Nicaragua. The community of Dipina Esperanza is located in the remote municipality of Waslala, in the North Atlantic Autonomous Region (RAAN). Waslala's municipal centre is located within the *Cordillera Central* mountain range and is approximately 8 hours from the capital city of Managua. The municipality has an estimated 63,000 residents, and 80% of the residents live in 67 dispersed rural villages (INIDE, 2012).

Dipina Esperanza represents an example of a deep rural or dispersed rural context. The community is located approximately 1.5 hours walking or on horseback from the nearest motor vehicle access at the terminus of an unpaved secondary road, requiring an additional 3 hours travel time to reach the town of Waslala. The distribution network fed by the storage tank studied here consists of 78 private metered connections serving 75 homes and 3 schools, with an estimated population of 225 persons. The households served are arranged into three sectors, corresponding to the school locations, and each is served by its own main pipeline, with a summed length of approximately 12km. The dispersed nature of the community can be partly attributed to cattle ranching for milk production as the predominant economic activity in the area, with homes scattered on individual ranches.

At the time data shown here was taken, the system was fed by a single spring source, which delivered water first to a higher storage tank, directly serving 1 school and 2 additional households, before flowing to the tank considered here. However, some expansion of the system has taken place since then, including aggregation of a second source and installation of a chlorine disinfection system. A third, higher storage tank has also since been installed, serving 17 additional households in a fourth sector of the community. The cylindrical ferrocement storage tank considered here has an effective storage capacity of approximately 29,000 L. The Dipina Esperanza water delivery system was constructed by the US based organisation Water for Waslala in partnership with the Nicaraguan NGO *Asociación de Desarrollo Integral y Sostenible* (ADIS).

On a national level, rural water supply is governed by an institutionalized community management scheme, through a Special Law for Potable Water and Sanitation Committees, passed in 2010, which gives legal status to community water committees, and mandates the establishment of municipal water and sanitation offices, which serve as an external support structure. The national level authority, the Nicaraguan Institute for Aqueducts and Drains (INAA) (2012) has established national design standards for different classes of water supply systems. INAA recommends a design standard of 50-60 L per-capita daily consumption for piped networks with private outdoor connections, but also acknowledges the dependence of the projected consumption level on water uses as well as geographical and cultural factors. For design of distribution networks, INAA recommends designing for a peak flow 2.5 times the average daily flow. Finally, for storage tanks, they recommend a design capacity equal to 35% of average daily consumption, broken down as 15% and 20% to account for peaks and outages respectively. However not every actor working in the development of water supply infrastructure can be assumed to use these standards, and indeed some may apply higher standards, i.e. design for higher projected levels of daily and peak consumption.

Methodology

Water levels were monitored through the installation of In-Situ Rugged Troll® 100 pressure transducers at the bottom of the water storage facility. The data loggers were set to record temperature, pressure, and water level (derived from pressure) every 10 minutes. Because the recorded water level is derived from the total pressure measured, including atmospheric, the recorded water levels were adjusted such that the lowest level recorded was set to zero. Taking the change in water level multiplied by the cross sectional area of the tank, the resulting change in water volume between time steps was used to extract the “net flow” into or out of the tank during the duration. Making an assumption that at some point over a 24 hour period, typically in the middle of the night, there is no water consumed, i.e. no outflow, a reasonable estimation of the effective supply, or inflow entering the tank can be made. Assuming that the inflow, is constant in the short-term, over one to several days, this constant inflow can then be applied to each time step, which when subtracted from the net flow, yields the negative demand, or outflow. Daily peak demand flow was considered to be the highest calculated demand flow for the 24 hour period. Due to fluctuation in atmospheric pressure, tank full was considered to be any water level within 5 cm of "full". To account automatically for possible spikes in daily maximum inflow due to manual removal and reinsertion of the instrument, the constant supply flow for each 24 hour period was set to be the running 7-day median of calculated daily maximum (positive) net flows. An example of the extraction of net, supply, and demand flows is shown for a three day period below in Figure 1. Summing the volume of water consumed for each time step over a 24 hour period, as extracted from the demand flow calculated for each time step, gives a reasonable estimation of total consumption for the period. To facilitate comparison across systems of different sizes, total consumption was divided by the number of households and by the population to give per-household and per-capita consumption respectively. It's important to note that this methodology does not account for losses that could result from leakage within the distribution system. Other trends revealed by water level data were analysed qualitatively by inspection.

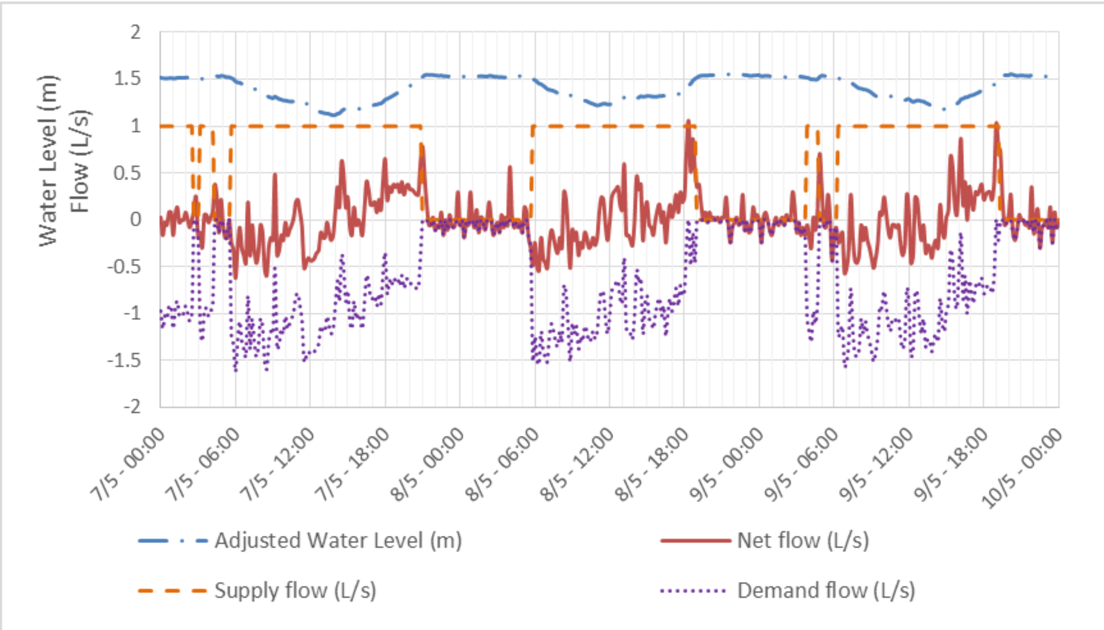

Figure 1. Tank levels and corresponding net, supply and demand flows Dipina Esperanza, May 7th – 9th, 2014

Results and discussion

For the purposes of this paper, a one month period was chosen, facilitating a time scale long enough to reveal trends, but short enough to present in detail. Data here is presented for May 2014, at the tail end of what's normally considered a dry period in the region. During this period, 218 mm of rainfall were measured at a rain gauge in the nearby community of Yaro, but only 17.3 and 16.5 mm were measured respectively for March and April. Figure 2 shows water levels for the Dipina Esperanza storage tank and corresponding per-capita daily consumption over the course of May 2014, while Figure 3 shows the corresponding supply and demand flow curves for the period. On a typical day, the water level begins to drop early in morning, close to 6:00 AM, and continues to drop until sometime in the later morning or early afternoon, at which time the water level begins to rise again. Sometime in the evening the tank fills, and then remains full or near-full until the peak demand period begins again the following morning. During the month-long period the Dipina Esperanza storage tank never emptied. The trends shown in the Dipina Esperanza water level data indicate that the system operates 24-7 and that the volume of water supplied more than satisfies demands.

The estimated daily supply flows, as a 7 day running median of daily maximum flows, range from 0.62 L/s to 1.00 L/s, representing a difference of 47%. The overall median of daily maximum flows for the period was 0.76 L/s. This would equate to approximately 175 L/p/d, but because the tank fills daily, not all this should be considered useful supply. The average level of per-capita daily consumption calculated was 121 L/p/d, double the INAA recommended design figure of projected demand. The figure may seem surprising, given the deep rural character of Dipina Esperanza, but the situation is likely more complex, and would require consideration of modulating factors, such as cost to the user and availability of water from other sources. The median peak demand flow for the period was calculated to be 1.47 L/s, or 1.9 times the 0.76 L/s considered the average daily flow.

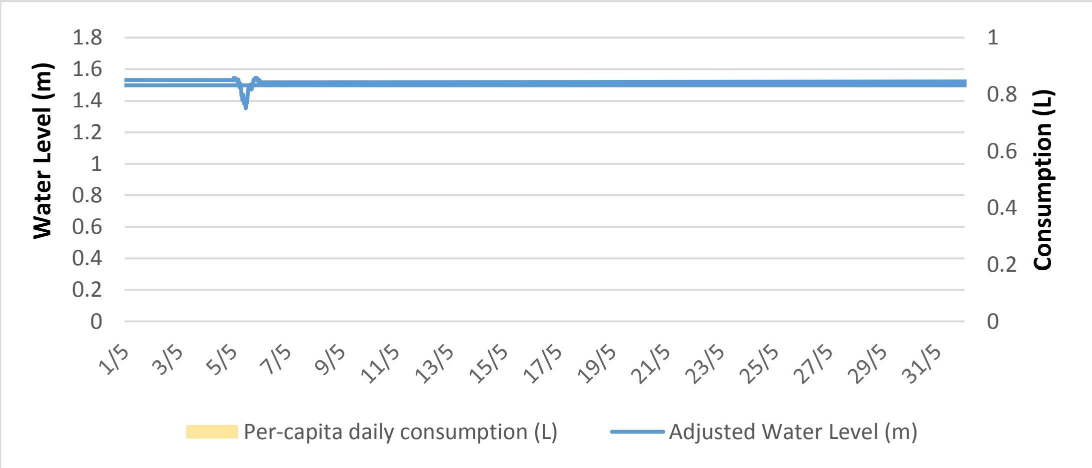

Figure 2. Tank water levels and corresponding per-capita daily consumption Dipina Esperanza, May 2014

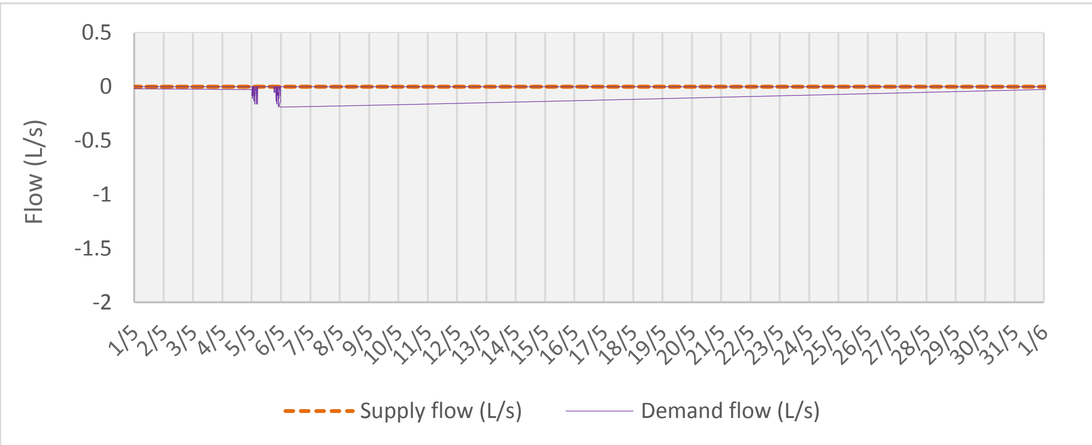

Figure 3. Estimated supply and demand flows Dipina Esperanza, May 2014

Limitations to approach

Application of the methodology described here requires several assumptions that imply some unknown margin of error. In the case presented here, the 47% difference in the range of calculated daily supply flows reveals significant variation in inflows. With the existence of 3 connections prior to the tank analysed here, some disruption of supply should indeed be expected, meaning the numbers calculated here could err on the high side. The upper storage tank, too, provides extra storage meaning some of the supply flow presumed lost at tank full conditions was actually still available elsewhere. In cases of systems with multiple tanks, a more complex approach taking into account all tanks may be necessary. The common presence of connections prior to storage tanks, too, presents complications.

Also, the dataset presented includes points (or subsets of points) that deviate from the overall trend. On two dates, May 23rd and 27th, the tank was shown to remain full for the entire 24 hour period. In order to verify if the anomalous tank full state was maintained during these days because of a shutting down of the distribution network for maintenance, repairs, or other reasons would require validation from operators and/or users. It is worth noting that qualitative validation from the relevant stakeholders mentioned is indeed a component of the overall study in progress. Tank full conditions for a longer period of time could also be interpreted differently, as having an available supply exceeding even peak demands. However, this case, too, requires validation. Furthermore, as it represents a situation where no distinct changes in tank water level occur over time, estimating supply and demand using the technique described here is not possible in this case.

In the scope of the broader study still in progress, changes in barometric pressure over time is being accounted for by the installation of Rugged Baro Troll ® pressure transducers at locations near to storage tanks. Losses in the distribution system may be less easily accounted for, and it may be reasonable to apply a loss factor as a fixed percentage to adjust consumption calculations. In a system where all connections are metered, and meter readings are well documented, the method may be more directly verified and losses more directly accounted for. Finally, the approach outlined here is limited in that it only considers the system as a whole, and even if the data indicates that supply meets or exceeds demand and that the system reliably functions on a continuous basis, it does not necessarily follow that water reliably reaches all points in the distribution network on a continuous basis. Again, qualitative validation is necessary in this case.

Conclusions

Quoting the commonly used adage *you can't manage what you don't measure*, the installation of pressure transducers in storage tanks represents a relatively simple, low-cost method requiring minimal effort and disruption to users to continuously monitor the performance of piped water systems. At a high level, using raw tank level data can be used to evaluate system performance by the PE25 method developed by Ermilio, et al. (2014) considering the proportion of time over a given period the tank is empty or near empty (below 25% full), and thus without the reserves necessary to satisfy ongoing demands. Tank level data can also be used to dissect more specific behaviour over time, such as the rate that water rises and falls and at what times during the day these rises and falls occur. Extracting quantitative estimates of real supply and demand requires the making of assumptions, which each entail some margin of error, and is best applied in situations where effective supply can be reasonably assumed to be constant over periods of several days, and where supply does not exceed peak demand making water level changes unobservable. While the method is empirical and does entail assumptions, it remains physically based, quantitative, and continuous. Results do require validation from operators and users. Thus the method is not proposed simply as a replacement for qualitative assessment through stakeholder engagement, but rather as a means to inform and facilitate this engagement.

The extraction of actual demands from currently functioning systems is relevant to the reconsideration of design assumptions made regarding projected per-capita daily and peak demands. The limited results shown here indicate that projected demand assumptions may need to be more carefully considered, and that minimum demand projections designed for meeting public health objectives may be lower actual demands that should be met to ensure long-term sustainability. In cases where projected demand is underestimated, an installed delivery system that falls short of satisfying demand may run the risk of having an adverse effect on community willingness to pay and efficacy of system management, operations, and maintenance, and hence long-term project sustainability. Alternatively, user demand may be further modulated through planned intermittency, thus altering peak demands and necessitating household level storage, which may pose a threat to water quality and sanitary conditions and thus meeting of desired public health objectives. However, important questions of causality remain. The relatively high demands extrapolated from the tank level data here could possibly be artificially high, due either to losses or insufficient demand modulation on the part operational and management structures, for example transparent and well-enforced consumption based payment structures. Undoubtedly the relationships between system performance with respect to water delivery, supply, demand, demand modulation, and management are complex and contain feedback loops. Nevertheless, the facility to continuously and physically measure a reasonable proxy to system performance in tank water levels has potential as a valuable tool to both evaluate the degree of system success or failure and to more deeply dissect system behaviour over time.

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