An integrated approach to improvement of network performance, water loss reduction and energy efficiency in developing countries – case study of Juigalpa, Nicaragua

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ABSTRACT

In developing countries water leakage is usually high due to limited maintenance and rehabilitation strategies, deficient service pressure distribution over the network and intermittent supply conditions. Apparent or commercial losses add to the so-called non-revenue water. In energy-intensive supply systems high water losses are linked to high energy use. However, water loss management and energy efficiency measures are often contemplated separately. Within the Technical Assistance Programme for Water and Sanitation (PROATAS) by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and financed by the German Federal Ministry for Economic Cooperation and Development (BMZ) a combined approach to water loss and energy management is taken to reduce energy costs and water losses as well as to improve pressure distribution of the water supply systems of two medium-sized cities in Nicaragua, Boaco and Juigalpa. This approach includes a holistic assessment of water losses and energy consumption by combining water and energy balance calculations assisted by a hydraulic model. The combined assessment allows for the elaboration and monitoring of an integrated strategy to water loss reduction and energy efficiency. Results of the assessment for the case of Juigalpa are presented as well as the strategy applied to reduce energy consumption and water losses.

KEY WORDS

Energy efficiency, Water loss reduction, Water and energy balance, Integrated approach to water loss and energy management, Water supply in developing countries

INTRODUCTION

Water losses, energy use and network performance of water supply systems are closely linked. Typically all three aspects are not well managed in developing countries. Water leakage is usually high due to limited maintenance and rehabilitation strategies. Tanks are often closed at night as a crude method of pressure management to avoid water losses at night. In the long run this form of water loss management leads to faster deterioration of the network due to the frequent emptying and refilling of pipes and the associated pressure surges. Leakage detection is hampered if the network is not continuously pressurized. The faster than usual deterioration of water meters may lead to an increase in apparent losses.Lee & Schwab (2005), for example, resume the impacts of intermittent water supply. Improved service performance, on the other hand, might require higher energy input and lead to higher absolute water losses, at least in the short term, if service pressures need to be raised. In supply systems where operating costs are not covered by water tariffs this is a luxury a water utility with scarce financial resources is often not able to provide.

In a project within the Technical Assistance Programme for Water and Sanitation (PROATAS) by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) and financed by the German Federal Ministry for Economic Cooperation and Development (BMZ) a combined approach to network, water loss and energy management is taken to reduce energy costs and water losses as well as improving service quality (network performance) of the water supply system of Juigalpa, a medium-sized city in Nicaragua. Several tools are combined to assist in the development of an integrated approach. As the analysed system depends entirely on pumping, pump efficiency was analysed first. A GIS based network register and hydraulic modelling is used to assist in improving network performance. A water balance was calculated as well as an energy balance based on the approach of Cabrera et al., 2010though simplified and modified to include energy consumption in the production step of the supply system and pump system inefficiency. Therefore, a holistic assessment of water losses and energy use is possible and relationship between water losses and energy use can be determined. A strategy to improve service performance, reduce water losses and improve energy efficiency is elaborated based on this assessment.

PRESENTATION OF JUIGALPA WATER SUPPLY SYSTEM

Juigalpa is a medium-sized city (around 70 000 inhabitants) in central Nicaragua. The city's water supply depends on the water resources from Lake Nicaragua. The water is conveyed over a distance of about 35 km and an altitude difference of 125 m by two pumping stations to the treatment plant. The treated water is collected in two tanks of 1.200 m³ each from where the water is distributed mainly by gravity. The northern part of the city is supplied directly by these tanks, but they also supply two storage tanks from where water is delivered to users in the southern low part of town and a small booster station that fills the higher storage tanks that presently only supply a very small portion of the town in the east. The network is divided in four hydraulic sectors, supplied by the above mentioned storage tanks. Figure 1 shows a simplified scheme of the water supply system.

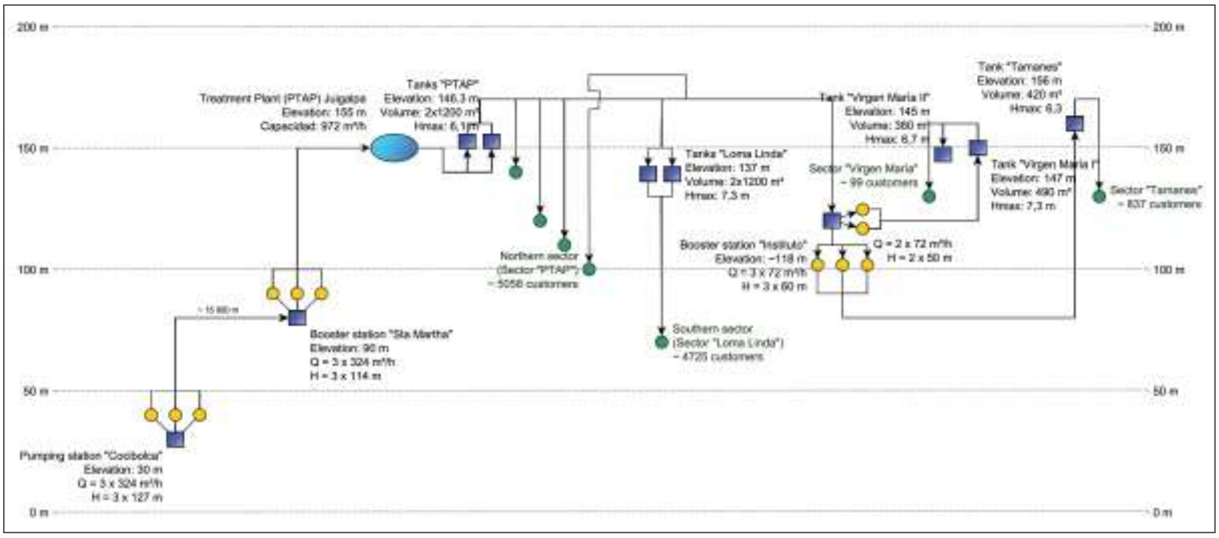

Figure 1: Water supply system of Juigalpa

The population of Juigalpa enjoys a regular, nearly continuous water supply. However, supply conditions are far from optimal. In the southern sector, pressure at night exceeds the maximum allowed pressure of 70 m. Pumping within the network is minimised by reducing the hydraulic sectors supplied by the high storage tanks to a minimum (sector "Tamanes" and sector "Virgen María"). In consequence, the available storage volume is not used to full capacity and pressures in the northern sector are often below the minimum required pressure of 14 m.

Non-revenue water amounts to 44 % (IV. Trimester 2013), real water losses are about 410 litres per connection and day. Measures to reduce real water losses are limited to reparation of reported pipe breaks and cutting the southern sector off supply at night. About 21 km of a total of 140 km pipe length are 50 to 60 year old asbestos cement pipes located mainly in the centre of town.

Due to the altitude difference between water source and city, the water supply depends entirely on external energy to overcome the altitude difference of 125 m between source and treatment plant from where the water is distributed mainly by gravity to the population. Reducing energy costs is one of the main concerns of the water utility as they represent the main percentage of total operating costs. Energy costs could already be reduced from 54 % to 43 % of operating costs, by buying directly from the generator at a far lower price (nearly half). The potential to reduce costs even more by improving energy efficiency is important as a pump energy efficiency study demonstrated (Pedraza & Espino, 2012,2013). Due to the high level of water losses, energy use can further be reduced by reducing water losses in the system.

Low pressures in the system indicate that – at least in some areas – energy input might not be sufficient. Improving network performance might therefore counteract the goal of reducing energy consumption. Considering that water tariffs are low and revenue covers only about 80 % of the operating costs, improving network performance would thus require resources whichare not available. Improving network performance is therefore only feasible if at the same time improvement in energy efficiency and reduction of water losses can be achieved. This requires a holistic assessment of all three aspects combining tools such as a water balance, an energy balance, an energy efficiency study, a GIS based network register and hydraulic modelling.

TOOLS TO ELABORATE AN INTEGRATED APPROACH

The International Water Association (IWA) developed a relatively simple, standardized and now widely used methodology to calculate the water balance of a supply system as basis for the elaboration of a strategy for reducing water losses and increasing revenue of the utility (Lambert & Hirner, 2000). This so-called top-down balance discriminates all important water flows in the system, allowing for estimating the most important kind of water losses in a specific system (compare table 4). Water losses are categorized into apparent losses (water consumed, but not authorised or billed) and real losses (physical losses leaving the system). Real losses result from the subtraction of consumption and apparent losses from the system input. As not all components are measured, especially apparent losses need to be estimated, the resulting volume of real losses is more or less accurate. It is therefore recommended to combine the water balance with a “bottom-up” approach, which consists of field measurements to determine real losses. However, the water balance represents an appropriate starting point to elaborate strategies for water loss reduction.

Cabrera et al. (2010) present an energy audit that determines energy flows in a water distribution network comparing input energy to energy uses (see table 1). The energy audit is especially useful for systems where water is pumped directly into the network and friction losses impact energy use (see for example Hernández et al., 2010). In systems where pumping is limited to the filling of tanks, as it is the case for the supply system of Juigalpa, the dissipated energy in the network does determine energy output and especially the energy delivered to users, but does not influence energy input of the system. For this reason the energy audit should be combined with a pump efficiency study.

A disadvantage of the approach described by Cabrera et al. is the need for a calibrated hydraulic model making it impractical for many supply systems in the developing world that are characterised by the lack of reliable data and often intermittent supply conditions complicating hydraulic simulations. However, the approach is useful to assess the impacts of improving network performance on energy consumption, as will be shown for the case of Juigalpa.

Table 1: Energy balance in distribution networks as described by Cabrera et al. (2010)

Input energy (natural) E_N	Input energy E_{INPUT}	Energy delivered to users E_U	Energy output E_{OUTPUT}
		Outgoing energy through leaks E_L	
Input energy (shaft work) E_P		Energy dissipation in pipes E_F	Energy dissipated $E_{DISSIPATED}$
		Energy dissipation in valves E_V	

The energy balance as presented by Cabrera et al. does only consider the distribution step, not considering energy used in the treatment process or energy lost due to low pump efficiency. Although the energy balance relies on previous water balance calculation, it does not fully allow for exploring the relationship between water losses and energy efficiency. To overcome this limitation, the approach is modified to include all energy flows in the water supply system (table 2). In the modified approach, the different energy components are, wherever possible, estimated using measured data. A hydraulic model is used to estimate the remaining energy components.

Table 2: Modified energy balance for drinking water supply systems

Input energy* - Natural - Shaft work	Outgoing energy in production step****	Outgoing energy through inefficiencies in pumping**
		Energy used in treatment process*
		Outgoing energy through water losses in treatment plant and transmission mains (previous to distribution)**
	Dissipated energy in distribution step****	Outgoing energy associated to tank filling**
		Energy dissipation in pressure regulating devices**
		Energy dissipation in pipes and valves****
	Outgoing energy through consumption and leakage***	Energy delivered to users (authorised consumption)***
		Outgoing energy associated to apparent losses***
		Outgoing energy through leaks****

*Energy meter readings
**Estimated using flow (Q), elevation and pressure (H) measurements of a determined time period (Δt):
(Hydraulic) Energy $E = \gamma Q H \Delta t$ (with γ = specific weight of water)
***Estimated using flow and pressure data provided by hydraulic model, for details refer to Cabrera et al. (2010).Total outgoing energy through consumption and leakage is determined using a hydraulic model including leakage, energy delivered to users and associated to apparent losses is determined using a hydraulic model of the leak free network.
****Calculated by summing up or subtracting known energy components.

PUMP EFFICIENCY STUDY

The energy balance of the current situation (period October to December 2013) shows that only 32% of all input energy is available in the distribution step. 68% of input energy is consumed or lost in the production step, the greatest energy loss being associated to pump inefficiencies (94% of the energy used in the production step).

Watergy México A.C. performed an energy audit of the two pumping stations of the supply system of Juigalpa as a first step in improving system performance using a methodology developed in 2010 (Watergy México A.C. &Alianza para el Ahorro de Energía, 2010). In the following the results of this study (Pedraza & Espino, 2012,2013) are briefly resumed.

Both of Juigalpa’s pumping stations are equipped with four pumps; typically two of them are operating with an average pump flow rate of 229 litres per second. All pumps were designed to deliver a far higher head than necessary leading to low efficiency in pump operation. The pumps of the pumping station “Cocibolca”, for example, were designed to deliver a head of 127 m. During typical operating conditions, however, a head of only 84 m is required.

Similarly, at the booster station “Sta Martha”, the installed pumps were designed to deliver a head of 114 m but a maximum head of 89 m is observed. Efficiency is consequently very low for both stations. Figure 2 shows the energy balance for the typical case that two pumps of the pumping station “Cocibolca” are operating in parallel. Only 40,5 % of the input energy are transformed into effective work. The main percentage of energy losses are caused by the pumps itself (44,8 %).

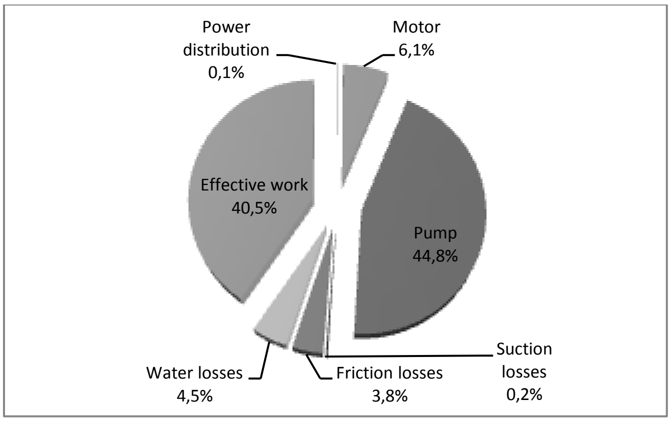

Figure2: Energy balance, pumping station “Cocibolca”. Two pumps operating in parallel.

A low-cost measure to improve pump efficiency is the reduction of the diameter of the pumps‘ impellers to move the pumps’ operating point closer to the optimal operating point. Through the reduction of the impellers‘ diameter of the pumps of the station „Cocibolca“ from 395 mm to 361 mm, it is expected that the pumps‘ power can be reduced from currently 414 kW to 233 kW (two pumps working in parallel). Though this will lead to a reduced pump flow rate and consequently to an increase in operating hours, a significant reduction in energy consumption is to be expected: from currently 7.342 kWh per day to 5.243 kWh per day (see table 3). This corresponds to a reduction in energy use of around 29 %.

Table3: Energy savings by reducing the impellers' diameter, pumping station "Cocibolca"

	Pump operation (Impeller 395 mm)*	**Pump operation (Impeller 361 mm)**
Average daily water production (l/s)	169	169
Average pump flow rate (l/s, 1 Pump)		90.4
Average pump flow rate (l/s, 2 Pumps)	229	181
Average pump flow rate (l/s, 3 Pumps)		267
Operating hours (1 Pump)	0	0
Operating hours (2 Pumps)	17,74	22,5
Operating hours (3 Pumps)	0	0
Total operating hours	17,74	22,5
Average demand (kW, 1 Pump)		114
Average demand (kW, 2 Pumps)	414	233
Average demand (kW, 3 Pumps)		359
Energy consumption (kWh per day)	**7.342**	**5.243**

**Operating data ENACAL, October to December 2013*

Field tests are currently under way. Reducing the impellers' diameter of the booster station "Sta Martha" is expected to lead to further significant reduction in energy consumption and will be implemented once energy savings due to measures taken at the pumping station "Cocibolca" can be observed.

ASSESSMENT OF WATER LOSSES, ENERGY USE AND NETWORK PERFORMANCE

A network register had been elaborated a few years ago, but since then, it was only sporadically updated. Therefore, the network register had to be verified first, using the knowledge of the technical staff. The migration of the register from AutoCAD to the open source geographic information system QGIS facilitates future modifications and allows for better management of infrastructure data than AutoCad. Customer information can be easily imported which facilitates the elaboration of a hydraulic model. QGIS offers a plug-in to export relevant information for hydraulic modelling to the open source simulation programme Epanet. The hydraulic model can thus be easily updated along with the network register.

Based on the available information a hydraulic model was elaborated. Demands in the hydraulic model were assigned to network nodes according to customer density in meter reading zones, for which these data were available. The demand was determined based on the water balance calculated for the period October to December 2013 (See table 4), considering not only authorised consumption but also apparent losses as demand. Real water losses were simulated by assigning an emitter coefficient to each demand node that lead to the real water losses volume calculated by the water balance (the emitter exponent was assumed to equal 1). For the purpose of hydraulic modelling it was assumed that no tank was closed at night. An extra volume of real losses had therefore to be added in the southern sector to account for the losses that would occur during the hours the network is currently not pressurised. This additional volume of real losses is probably overestimated, as an unidentified interconnection between the southern and northern sector maintains part of the southern sector pressurised during the night allowing for leakage to happen.

Table 4: Water Balance Juigalpa, October to December 2013

System Input 1.346.767 m³	Authorised consumption 795.899 m³	Billed authorised consumption 753.679 m³	Billed water exported	0 m³	Revenue water 753.679 m³
			Billed metered consumption	649.691 m³	
			Billed unmetered consumption	103.988 m³	Non-revenue water (NRW) 593.089 m³
		Unbilled authorised consumption 42.221 m³	Unbilled metered consumption	3.342 m³	
			Unbilled unmetered consumption	38.879 m³	
	Water losses 550.868 m³	Apparent losses 103.361 m³	Unauthorised consumption	28.800 m³	
			Metering inaccuracies/Data handling	74.561 m³	
		Real losses 447.507 m³	Water losses in treatment plant	15.298 m³	
			Leakage in distribution network	432.209 m³	

The model was then verified by comparing calculated pressures and flows with field measurements. Pipe roughness was adjusted to achieve a better fit of the model. Pressure measurement also revealed that interconnections between the different sectors exist. These interconnections could not yet be discovered.

Based on hydraulic simulations, a proposal was elaborated to restructure the network to achieve better pressure distribution and better use of storage volumes (see figure 3). Calculations were restricted to current average water consumption. No simulations were done for future increase in demand as at this moment only short term improvements were asked for. Therefore, the current structure of the network was respected as much as possible, moving sector borders mainly by closing and opening existing valves. Improvement can thus be achieved without major investments. Two zones in the southern sector were identified where pressure reduction would lead to important short term reduction of real water losses assuming time based pressure regulation.

As model quality still needs to be improved, the proposed measures will be implemented in a step by step approach accompanied by field measurement that will allow for calibration of the model and continuous verification and adjustment of the proposed measures. This approach is recommendable for all situations with limited information –“improving by doing”.

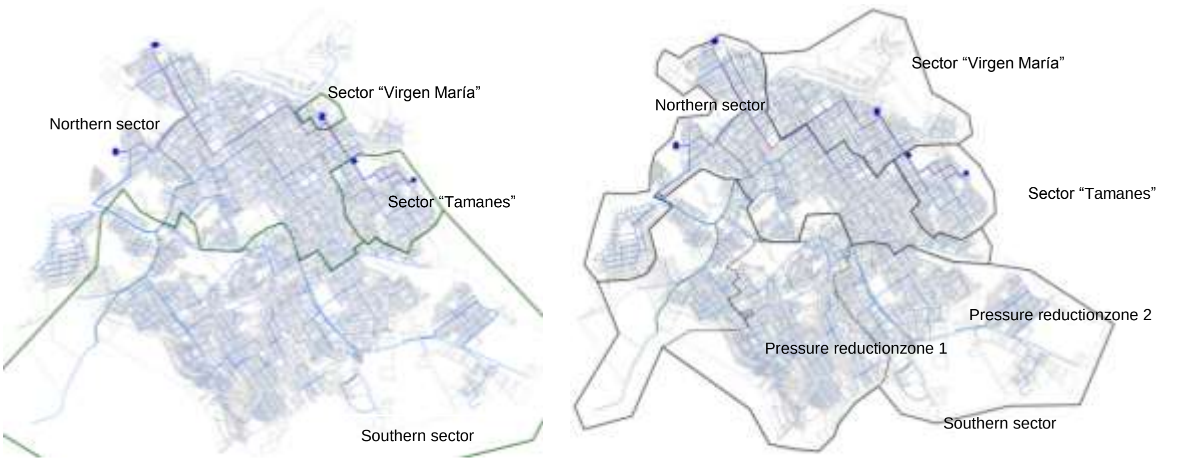

Figure 3: Network Juigalpa, current (left) and proposed (right) sectorisation

Improving network performance is expected to lead to higher energy requirements as raising pressure in the northern sector will require extending the hydraulic sectors supplied by the higher tanks and thus require longer operation hours of the booster station located in the network. Maintaining continuous supply conditions will allow for leakage during the night that currently is avoided by closing the tanks at night. Reducing pressure, on the other hand, will reduce leakage. Therefore, the questions needs to be answered if the reduction of pressure can compensate the additional required energy needed to improve network performance.

The energy balance was calculated for the current situation and the following three cases:

1) Current sectorisation, but 24h service and no interconnection between northern and southern sectors.
2) New sectorisation without pressure regulation (sectors supplied by high storage tanks extended).
3) New sectorisation with time-based pressure regulation.

For the current sectorisation under continuous supply conditions, an additional volume of real water losses (967 m³/d) is estimated to occur in the southern sector. The additional volume of real water losses leads to an increase in energy consumption (about 972 kWh/d) due to extra energy required to produce and convey the additional water volume and energy leaving the system through additional leakage.Table5 shows the energy balance for case 1. It is assumed that the additional water volume treated will not lead to a significant increase in water used for cleaning and maintenance of treatment units.

Table 5: Energy balance Juigalpa, assumed 24 h service, 3 month period

<table>
<tr><td rowspan="9">Input energy:
1.474.679 kWh
- Pumping station “Cocibolca”: 720.087 kWh
- Booster station “Sta Martha”: 722.673 kWh
- Energy supply at treatment plant: 9.440 kWh
- Booster station in the network: 22.480 kWh</td><td rowspan="3">Outgoing energy in production step:
1.000.668 kWh</td><td>Outgoing energy through inefficiencies in pumping
- Pumping station “Cocibolca”: 460.647 kWh
- Booster station “Sta Martha”: 483.190 kWh</td></tr>
<tr><td>Energy used in treatment process
- Cleaning of treatment units: 8.298 kWh
- Filling of clear water tanks: 33.778 kWh
Energy consumption at treatment plant: 9.440 kWh</td></tr>
<tr><td>Outgoing energy through water losses in treatment plant and transmission mains (previous to distribution)
- Water losses in treatment plant: 5.316 kWh</td></tr>
<tr><td rowspan="3">Dissipated energy in distribution step:
61.789 kWh</td><td>Outgoing energy associated to tank filling:
- Loma Linda: 21.193 kWh
- Tank booster station: 11.959 kWh
- Pumping to high storage tank “Tamanes” and “Virgen María”: 5.574 kWh</td></tr>
<tr><td>Energy dissipation in pressure regulating devices:
0 kWh</td></tr>
<tr><td>Energy dissipation in pipes and valves:
23.062 kWh</td></tr>
<tr><td rowspan="3">Outgoing energy through consumption and leakage:
412.223 kWh</td><td>Energy delivered to users (authorised consumption):
225.422 kWh</td></tr>
<tr><td>Outgoing energy associated to apparent losses:
30.915 kWh</td></tr>
<tr><td>Outgoing energy through leaks:
155.886 kWh</td></tr>
</table>

The same energy balance was carried out for the cases 2 and 3. Table 6 compares the results of all three cases. As can be appreciated in table 6, guaranteeing a continuously pressurised network and guaranteeing service pressures above 14 m at all consumption nodes requires higher energy input and increases real water losses. This effect can be compensated by reducing pressures in the high pressure areas. Careful monitoring of water losses and energy consumption during the implementation of the proposed measures is needed to verify initial estimations and avoid possible unexpected increases in energy consumption and water losses. If needed, the proposed measures have to be adjusted.

Table 6: Energy consumption and water losses for case 1 to 3 over a period of 3 month

	Current situation	Case 1	Case 2	Case 3
Real water losses (m³)	432.209	521.192	559.624	467.895
Outgoing energy in production step (kWh)	940.020	1.000.668	1.062.862	964.342
Dissipated energy in distribution step (kWh)	undetermined	61.789	58.008	72.125
Dissipated energy due to pressure reduction	0	0	0	23.460
Energy delivered to users (kWh)	undetermined	225.422	231.584	222.829
Outgoing energy through apparent losses (kWh)	undetermined	30.915	31.760	30.559
Outgoing energy through leaks (kWh)	undetermined	155.886	171.956	138.335
Total energy input (kWh)	1.385.262	1.474.679	1.520.170	1.428.190
Energy use / authorised consumption (kWh/m³)	1,74	1,85	1,91	1,79
Energy use / authorised consumption, improved pump efficiency (kWh/m³)		1,59	1,64	1,54

It needs to be highlighted, that although network performance could be improved, no or only a slight reduction in water losses or energy consumption might be achieved which conflicts with the utility's main objectives, reduction of energy use and reduction of non-revenue water in the short term. In the long term, however, the improved network performance should result in fewer pipe breaks and slower deterioration of the network and hence a lower level of water losses. The implementation of a statistic of pipe breaks will help to visualise this effect in the future. It needs to be emphasised that pressure reduction is a measure to achieve short term results and to help to improve network performance of a supply system working in intermittent supply conditions. Pressure reduction will also contribute to prolong the pipes' service life by reducing pipe breaks. Reduced water losses through pressure management are entirely achieved by reducing flow through existing pipe leaks, but these leaks still exist. Therefore, a programme for continuous active leakage control needs to be implemented.

The energy balances resumed in table 6 do not yet consider the energy savings expected by improving pump efficiency which will reduce the outgoing energy in the production step. The last line in table 6 compares the energy efficiency of the system for the three modelled cases assuming improved efficiency of the pumping station "Cocibolca" through the reduction of the impellers' diameter (29% reduction in energy consumption). It becomes clear, that even the restructured system without pressure reduction requires less energy than is currently needed to operate the system.

CONCLUSIONS

The water utility of Juigalpa is dealing with a series of problems typical of water supply systems in developing countries such as scarce economic resources, high level of water losses and low efficiency in energy use. Measures taken to tackle these problems, such as closing tanks at night creating intermittent supply conditions or allowing for inadequately low service pressures to reduce energy requirement, are inappropriate and prone to worsen the problem in the future by contributing to faster deterioration of the infrastructure or by contributing to the dissatisfaction of the customers and reducing their willingness to pay. Juigalpa water utility's main preoccupation is reducing water losses and energy costs. Improving network performance, guaranteeing adequate service pressure 24 hours a day, is seen as a luxury. However, improving pump efficiency first will mobilise resources that can be reinvested in measures to improve network performance.

With the assistance of a hydraulic model it could be shown that pressure distribution in the network could be improved without the need for major investments. However, as expected, raising service pressures and service hours, requires higher energy input due to higher level of water losses as revealed by the energy balance calculated for the simulated restructured network. But the energy balance also revealed that the implementation of two pressure regulated hydraulic sectors can compensate the increase in water losses and energy requirement due to improved network performance. This shows the importance of pressure reduction as short term measure to reduce water losses and associated energy use in deficient systems. Continuous water supply will slow down pipe deterioration in the long term and facilitate active leakage control.

The study indicates that it is possible to achieve better performance and service quality in the short term maintaining the operational costs and by this enhancing energy efficiency, customer satisfaction and willingness to pay.

The hydraulic model is based on data that are not always reliable, further verification and calibration of the model is required. Estimations of water losses and energy uses of the restructured system are subject to error. But as field measurement indicate rough concordance of model and reality and the proposed measures do not require major interventions in the infrastructure, a step by step implementation is considered the appropriate way to proceed ("improving by doing"). The delivery of a calibrated but outdated model can thus be avoided. It is, however, necessary to accompany the restructuring of the network with field measurements (pressure, flow, consumption) for continuous verification and correction of the hydraulic model and initial estimations and if necessary adjust initial assumptions and proposed improvement measures.At the end a calibrated hydraulic model will be available that can be used to assist in further optimisation of operation of the network and / or to analyse future needs for network extension or restructuring. Monitoring data will also permit to verify initial estimations of water losses and energy use of the restructured system and to develop an easy to use method to calculate the energy balance of a system based entirely on empiric data without the assistance of hydraulic modelling.

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