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MODELLING OF AN OPTIMIZED, AUTOMATED WATER SUPPLY SYSTEM WITH LEAK DETECTION FOR OLKARIA GEOTHERMAL AREA, KENYA

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ABSTRACT

The use of water in geothermal operations can be controlled to allow sustained utilisation. The water supply system must be transparent, safe, reliable and controllable. To control the water supply system, monitoring must be introduced. This may be human, physical or remote computerised monitoring. Whatever method is chosen, the same principles must apply. The reliability of supply is key among all principles as it ensures all other principles are met. A reliable system requires that the supply meets the demand both in quality and quantity. Quality is guaranteed when the water reaches its destination at the required pressure and flow. The required quantity must be delivered to the user continuously as and when required. This means that there should not be any losses in the water supply system. However, this is not possible of any system since errors do happen, accidents are at times unpredictable and the response may not be immediate.

This project proposes to replace the manual water supply operation of the Olkaria water supply system with an automated SCADA controlled solution to allow for continuous monitoring and reporting of the water delivery at all points of the network. Since it is impossible to control what is not monitored, pressure and flow sensors must be installed at critical points of the network and the data transmitted to a central location for analysis and control of the tank water levels, booster pump pressure and locations of leaks or bursts when they occur through a supervisory control and data acquisition system (SCADA). This project is restricted to the raw water supply to the three main water reservoir locations. An analysis of the pressure losses along the pipeline is done with the assistance of Engineering Equation Solver (EES) to determine the performance of the system as installed and operated. Models of best operation scenarios are created to simulate a controlled water supply system.

1. INTRODUCTION

1.1. Location

Kenya Electricity Generating Company Limited (KenGen) operates power plants that account for over 75% of the installed electrical capacity in the country. The power plants utilize various sources for electricity production, including hydro, geothermal, thermal and wind. KenGen has the licence to explore and exploit geothermal resources in the Olkaria geothermal field and generate electricity which is distributed through the national grid.

The Olkaria geothermal field is located about 125 km northwest of Nairobi, to the south of Lake Naivasha within the central Kenya segment of the East African Rift System (Figure 1). The field is approximately 204 km^2 and segmented into seven sectors; Olkaria East, Olkaria Northeast, Olkaria Central, Olkaria Southwest, Olkaria Northwest, Olkaria Southeast and Olkaria Domes. The field is largely located within the Hell's Gate National Park, managed by the Kenya Wildlife Service (KWS).

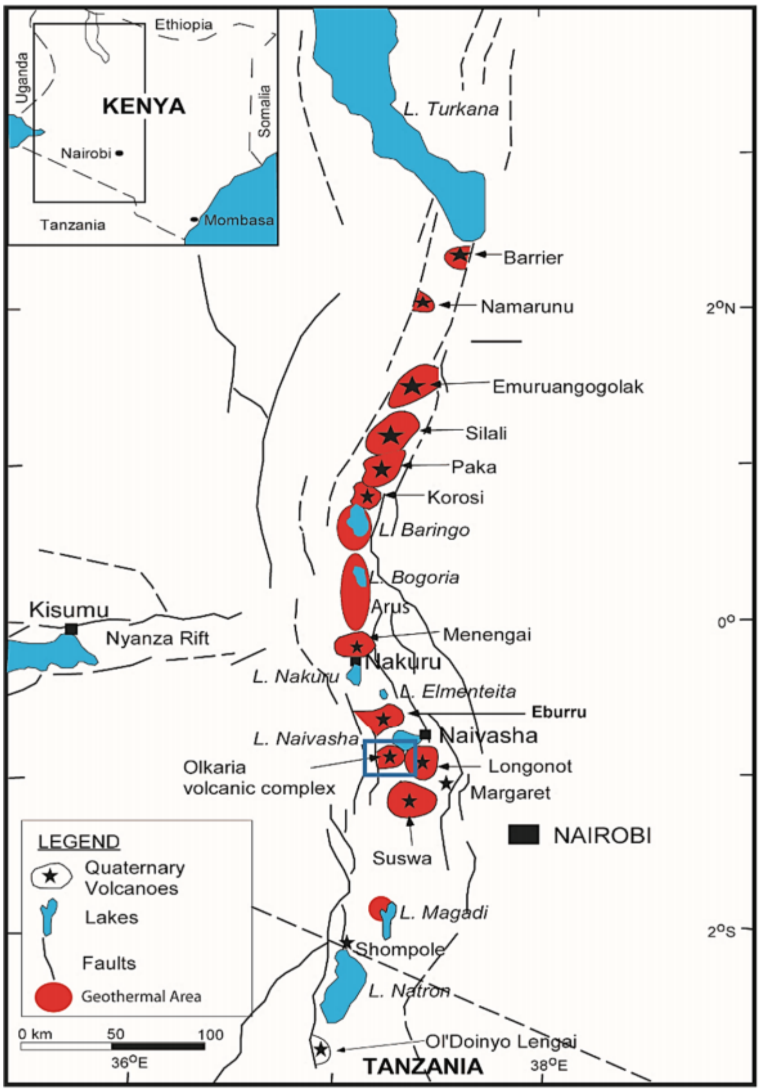

FIGURE 1: Geothermal resource map, Kenyan Rift Valley

Olkaria geothermal field has gently rolling hills, mostly covered with thick layers of pyroclastics and deposits of volcanic ash. Parent soil materials are predominantly volcanic. There is porous volcanic ash derived from lavas, pyroclastic rocks, and lacustrine lake deposits (Clarke et al., 1990, KWS, 1992). The volcanic ashes are very vulnerable to water erosion.

FIGURE 2: Burst fresh water supply line

1.2 Problem statement

KenGen's mission is "to efficiently generate competitively priced electric energy using state-of-the-art technology, skilled and motivated human resource to ensure financial success". Efficient electricity generation requires the reliable supply of inputs through an efficient infrastructure.

An efficient water supply system is therefore a necessity in any geothermal project. At Olkaria geothermal field, Lake Naivasha is the only viable source of water. Considering the restrictions on the abstraction quantities and the high power consumption at the pumping station, the water supply system must be reliable.

Recent studies reveal that the average water loss due to leakages, such as the one shown in Figure 2, along the waterlines is estimated to be

20% of the abstracted raw water which translates to a loss of revenues, delayed project completion, erosion and destruction of vegetation, destruction of infrastructure, and litigations. Water leakage in major supply networks is caused by mismatched parameters such as pressure, quality, diameter and age of the pipes (KenGen, 2015).

It is therefore the responsibility of the engineers to design and operate a pipeline system so that unacceptable conditions do not arise, taking into consideration the normal and the abnormal operation of the system (Thorley, 1991).

1.3 Objectives of the study

The adoption of a centralized, automated water supply and distribution system would not only give an updated and current status of the network, but more importantly guarantee the reliability and efficiency of the system and the service offered to the consumers. The water need within the Olkaria geothermal area is increasing every year and so more water needs to be drawn from the system, it is therefore important to report on every drop of water drawn from Lake Naivasha as a matter of sustainability of the resource. Currently there is a migration from a manual operator-dependant system to one centrally managed with accurate reporting and diagnostics capabilities with the possibility of mitigating water losses due to leakages, pilferage, pipe bursts or wear, through the use of modern leak detection techniques.

Real-time monitoring of the system performance allows the operator to concentrate on more demanding and urgent tasks. This ensures that the resources, tools and personnel are channelled to more pressing tasks. The result is a lean, skilled, dedicated water supply workforce with the capability of handling tasks as they arise. This should result in a reduction of operation costs.

The introduction of modern equipment such as control valves, pressure and flow indicators, controllers and transmitters and backup power supply at critical locations should improve the water line reliability and the lifespan of the pumping equipment. Backup power supply should be installed to ensure that the water supply is not interrupted at any time due to power failure. This should therefore reduce the wear and tear costs of the pumps, cost of electricity consumed at the pumping station and the occurrence of pipe bursts due to abrupt halts in pumping.

A large part of the Olkaria geothermal area is within the Hell´s Gate National Park. Water leaks and bursts result in soil erosion, vegetation destruction, the interference of animal routes and danger to tourists visiting the park. An automated water supply system should accurately and timely indicate the occurrence of abnormal flow or pressures, which are a sign of water loss due to bursts and leakages. Since there is a team readily available to deal with such occurrences, the good relationship between KenGen and the stakeholders and the environment should be maintained.

This study seeks to address the need for an improved, modern water supply system for the Olkaria geothermal area with a view of lowering the generation cost, complying with regulatory requirements and promote the conservation and sustainable use of water from Lake Naivasha. This shall be accomplished by:

i. Assessing the nature of the current water supply system with the intent of locating design gaps;
ii. Developing an optimized water supply system using available tools to address the identified design gaps; and
iii. Designing a water distribution monitoring system to ensure efficient and reliable water supply to the consumers.

2. LITERATURE REVIEW

2.1 Water sources in Kenya

Agricultural and industrial water demands account for 90% of human water use globally (Kundzewicz et al., 2007). The rapid growth in water-intensive activities, especially horticulture, is contributing to Kenya's water stress. Agriculture accounts for 50% of Kenya's water demands. Kenya's vision is to transform into a newly industrialized middle-income country by year 2030 and therefore a clean water supply in sufficient quantity will be critical (Davies and Gustafsson, 2015). Olkaria is under the Naivasha Municipality which is responsible for the domestic water supply in the area. The area has a shallow basin lake situated 80 km northwest of the Kenyan Rift Valley at an altitude of 1,890 m which covers an area of approximately 150 km^2. Naivasha has a population of over 300,000 people settled around the lake. The major land uses are human settlement, intensive commercial horticultural farming, tourism, and geothermal power production (Moseti et al., 2015). These activities close to the lake threaten its existence and pose challenges and risks like over-abstraction, pollution and poor resource management (Davies and Gustafsson, 2015).

Lake Naivasha was therefore declared a RAMSAR site in 1995 in recognition of its global importance to wildlife. It was initially managed by the local property owners under the Lake Naivasha Riparian Association formed in 1927 but is currently being managed by the Water Resource Management Authority (WRMA) (Republic of Kenya, 2012). Lake Naivasha's watershed is largely semi-arid with scarce surface and underground water resources.

The lake water levels gradually decreased from October 2016 to June 2017 due to variations in weather conditions around the lake as shown in Figure 3 (KenGen, 2017). The current level is above the 1,885.3 m a.s.l. limit set by WRMA for lake water abstraction according to the issued permit.

There are few boreholes around the Olkaria geothermal area and at present they are either dry or produce steam (Kerina, 2017; Allen et al. 1989). This makes Lake Naivasha the primary source of water for KenGen's geothermal activities in Olkaria.

The most promising geothermal resources globally, are generally found in fresh-water-stressed areas (Clerk et al., 2011) and Olkaria is not an exception. Therefore, the sustainable management of fresh

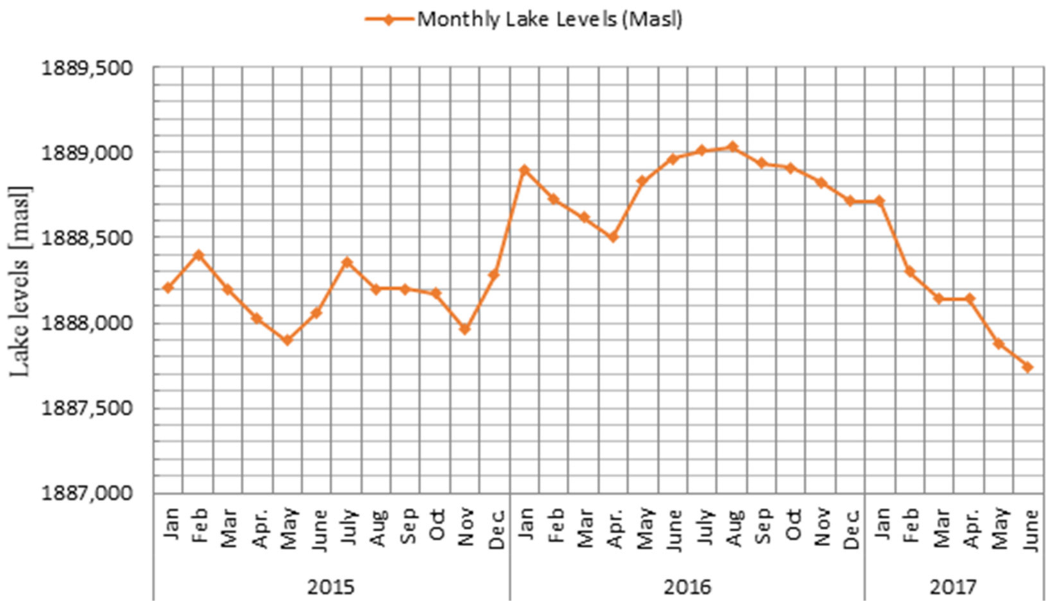

FIGURE 3: Lake Naivasha monthly lake level variation from January 2014 to June 2017 (KenGen, 2017)

water resources is of great importance. In Olkaria, geothermal wells generally produce 75% steam and 25% brine, (Mwangi and Hodgson, 2010). A portion of the brine is collected and distributed to the drilling sites to be used for drilling operations, minimizing the dependence on water from Lake Naivasha.

2.2 Fluid flow analysis

As water flows through a pipe in a steady state, resistance to the flow is normally developed due to friction in the pipe. Energy is therefore required to overcome this friction to enable the delivery of the water to the end of the pipe network. To determine the total energy of the water at any point along the pipeline, Bernoulli's Theorem is applied, (Engineer Educators, 2007) as in Equation 1:

$$H_s = Z + H_p + \frac{V^2}{2g} \tag{1}$$

where H_s = Total system head [m];
Z = Elevation head [m];
H_p = Static head [m]; and
$V^2/2g$ = Velocity head [m].

The resistance to flow causes a pressure loss along the pipeline measured as the height of the water column in metres and is commonly referred to as head loss. Many factors contribute to head loss in pipes including: the viscosity of the fluid, the pipe diameter, pipe internal surface roughness, elevations changes within the system and the length of travel of the fluid (PipeFlow, 2017).

There are two principal formulas of determining the friction factor of the pipe: the Darcy-Weisbach and the Hazen-Williams equations, which both take into account the friction factor and the pipe diameter. For steel, cast iron and copper pipes, the Darcy-Weisbach formula is used (Equation 2), while the Hazen-Williams formula is applied for analysis of plastic pipes:

$$\Delta h_f = f \cdot \left(\frac{L}{D}\right) \cdot \left(\frac{V^2}{2g}\right) \tag{2}$$

where Δh_f = Head loss [m];
f = Dimensionless friction factor;
L = Length of pipe work [m];
D = Inner diameter of pipe work [m];
V = Velocity of fluid [m/s]; and
g = Acceleration due to gravity [m/s²].

The Darcy-Weisbach equation has now become the standard equation for calculating head loss in pipes where the flow is turbulent, (PipeFlow, 2017).

Flow in a pipe can be laminar or turbulent. To determine the flow pattern of water in a pipe the Reynolds number, *Re*, must be calculated. The Reynolds number is a dimensionless number that gives a measure of the ratio of inertial forces to viscous forces for given flow conditions and is calculated using the dynamic viscosity and density (μ, ρ) of the fluid, the mean fluid velocity and the hydraulic diameter, as shown by Equations 3 and 4. Pipes that have smooth walls like glass, copper, brass and polyethylene pose less frictional resistance and hence produce a smaller frictional loss than pipes with a greater internal roughness, such as concrete, cast iron and steel. Flow is considered laminar when the computed Reynolds number is less than 2300 and turbulent when the Reynolds number is greater than 4000:

$$Re = \frac{VD}{\vartheta} \tag{3}$$

and

$$\vartheta = \frac{\mu}{\rho} \tag{4}$$

where Re = Dimensionless Reynolds number;
ϑ = Kinematic viscosity [m^2/s];
μ = Dynamic viscosity [kg/ms]; and
ρ = Density [kg/m^3].

The absolute roughness of the pipe, ε, is provided by the pipe manufacturer, and so the relative roughness of the pipe, rr, is calculated as shown in Equation 5:

$$rr = \frac{\varepsilon}{D} \tag{5}$$

where rr = Dimensionless relative roughness; and
ε = Pipe absolute roughness [mm].

For turbulent flow, Colebrook-White equation in Equation 6, is applied to determine the frictional factor:

$$1/\sqrt{f} = 1.14 - 2log_{10}\left(\frac{\varepsilon}{D} + \frac{9.35}{Re\sqrt{f}}\right) \ for\ Re > 4000 \tag{6}$$

where f = Dimensionless frictional factor.

This is an implicit equation and, therefore, it requires mathematical iteration to determine the value of the friction factor, f. Data from the Colebrook-White equation is plotted as a function of the Reynolds number and the relative roughness, so as to accurately determine the correct frictional factor for turbulent flow in circular pipes, in a chart known as the Moody diagram as shown in Appendix I. The friction factor from the Moody diagram is then applied in the Darcy-Weisbach formula to determine the head loss due to friction along the water pipe.

Pipe fittings along the pipeline, such as valves, bends and tees, also have a contribution to the build-up of resistance to flow of the water in the pipe, causing head losses also known as the velocity head of water flowing in a pipe. To obtain the losses due to fittings, loss coefficients or K factors have been developed for various pipe fittings. Equation 7 calculates the velocity head loss:

$$h_s = K\,\frac{V^2}{2g} \tag{7}$$

where h_s = Head loss due to minor losses such as fittings [m];
K = Dimensionless loss coefficient.

We therefore need to calculate the hydraulic head of the water at critical points in the network, especially at junctions, after valves, and at water inlets and outlets. Analysis of the change in the head of the system results in the drawing of the hydraulic grade line which shows the pressure drop in metres along the pipeline. This is important for the design of the pump capacity or design head and is calculated at a no flow scenario, a full flow scenario and the design situation of the system. The pump design head is the sum of the static head, friction head and the difference between the minimum delivery and the supply pressures (Engineer Educators, 2007).

With the advent of computerized solutions for the modelling of water flow systems, carrying out a hydraulic analysis in complex water supply and distribution networks, consisting of several branches, loops, valves, storage tanks and pumps, has been made simpler with software like PipeFlow, EPANET, and KYPIPE, among others. Several equation-solving techniques have been invented such as

Engineering Equation Solver (EES), MATLAB, Scilab, Python and many others, to assist in the analysis.

The incorporation of pump drives like variable frequency drives, VFD, is becoming popular in pumping electronics. VFDs regulate the speed of the motor driving the pump by varying the frequency of the power supply to the motor. The speed is directly proportional to the frequency of the power supply. VFDs are easy to integrate into the pumping control software or SCADA system (Engineer Educator, 2007). The variation allows the control of the pump to efficiently deliver water at the required pressure or head based on the needs.

2.3 Monitoring, control and reporting

"You cannot manage what you do not monitor", goes an old management adage. In order to maintain the quality of the water system throughout the supply network, a monitoring programme has to be in place. The programme can be manual, using human workforce for physical inspection of the network, or remotely monitored through a computerised communication system like a Supervisory Control and Data Acquisition (SCADA) system. SCADA is a computer-based system for gathering and analysing real-time data to monitor and control equipment that deals with critical and time-sensitive materials or events (OleumTech, 2017). Human physical inspection is tedious, slow, inaccurate and expensive and may at times fail to report an incident. On the other hand, computerised remote monitoring of a water supply system is the most efficient way, especially in large field supply networks.

From a remote location, the operator can monitor the entire supply network performance and if needed, control the field devices like control valves and pumps. The operator can display and record logs of data from the sensors deployed along the network measuring parameters like temperature, pressure, storage tank levels and water consumption. These logs can assist in predicting system anomalies like leakages or water bursts, equipment degradation or malfunction, and track system efficiencies and ensure resources are allocated to areas they are needed. Within the communication system, a visual display of the field can be added using closed-circuit television systems installed at specific points of the network.

In some places like California, it is required by law to monitor pressure in the distribution system as a minimum standard for design and construction. Survey reports must contain at least 24 hours of continuous hourly data from two representative points in each pressure zone according to the California Public Utilities Commission (CPUC) General Order 103 (Ferrer et al., 2016).

A SCADA system is a type of industrial control system (ICS) used to control a collection of field equipment and provide an operator at a remote location with enough information to determine the status of a particular piece of equipment or an entire network and cause actions to take place regarding the equipment or network (Stouffer et al., 2006). SCADA has applications in water distribution and wastewater collection and treatment, oil and gas pipelines, electricity generation and distribution and transportation systems (Stouffer et al., 2006). A SCADA system, as shown in Figure 4, consists of field instruments, programmable logic controllers (PLCs) or remote telemetry units (RTUs), communication networks and SCADA host software (Schneider Electric, 2012).

Typically, communication between the RTU/PLC and the field instruments is through a wired connection of a 2-wire 4-20 mA or at times a 4-wire 0-20 mA current loop. Figure 4, however, depicts wireless data communication between the PLC/RTU and the field instruments, which is rarely used. Another rare communication case between the RTU/PLC and the field instruments is Profibus.

Proper instrumentation is therefore key to a safe, reliable and optimised control system. Most field instruments like valves have been fitted with actuators to allow control by a PLC or RTU. These instruments need to comply with the regulatory requirements of the industry. The instrument must be

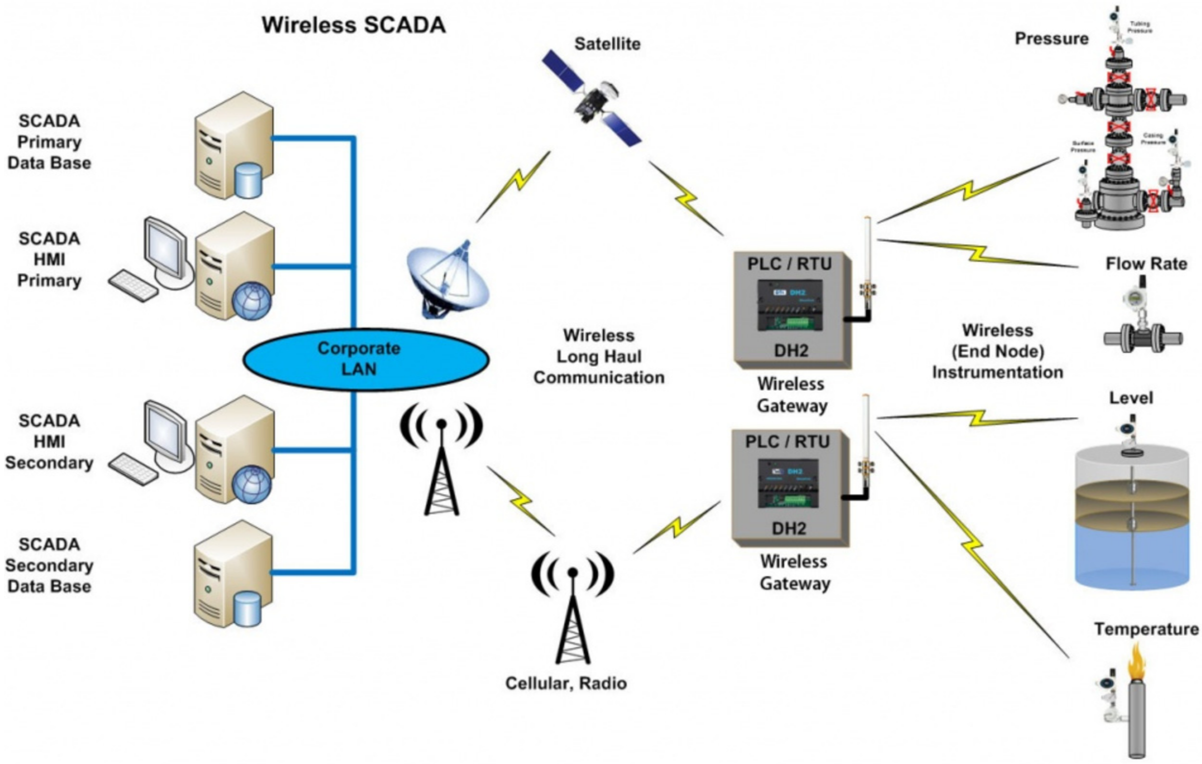

FIGURE 4: Typical SCADA arrangement (OleumTech, 2017)

designed for its particular place to minimise damage to it and risk to the network reliability and safety (Schneider Electric, 2012).

The communication method between the field instruments, the PLC or RTU and the SCADA host is determined according to the environment between the points. This can be via copper cable, fibre optic cable, GSM/cellular, telephone lines, satellite, or radio channels/wireless, (University of Missouri and University of Alabama, 2013).

2.4 Leak detection

A properly designed and maintained water supply system can last indefinitely without leaks. Leaks may occur due to corrosion, sudden pressure changes, weaknesses in couplings or joints, earth movements or sabotage. The detection, location and repair of leaks is therefore of utmost importance, especially in long, complex water supply networks. A leak detection system must be reliable, sensitive, safe, accurate and robust. Several leak detection techniques have been developed over the years and they can be categorized broadly as shown in Figure 5 (Golmohamadi, 2015; Bose and Olson 1993; Zhang, 1996).

Biological leak detection techniques involve the use of experienced personnel and dogs to detect leaks through visual inspection, sounds and odour. This method can only be applied in short pipelines or segments of pipelines.

Hardware based methods are the most common techniques used. Several different devices such as thermal infrared cameras, acoustic sensors, and radars are used to detect and locate leaks in the pipeline. These methods, however, have limitation of detection of smaller leaks and range of detection.

Software based methods analyse fluid characteristics such as pressure, temperature, flow and other data in the pipeline through a SCADA system. For example, flow/pressure change detection, mass/volume balance, a dynamic model-based system, and pressure point analysis are some of the computer based

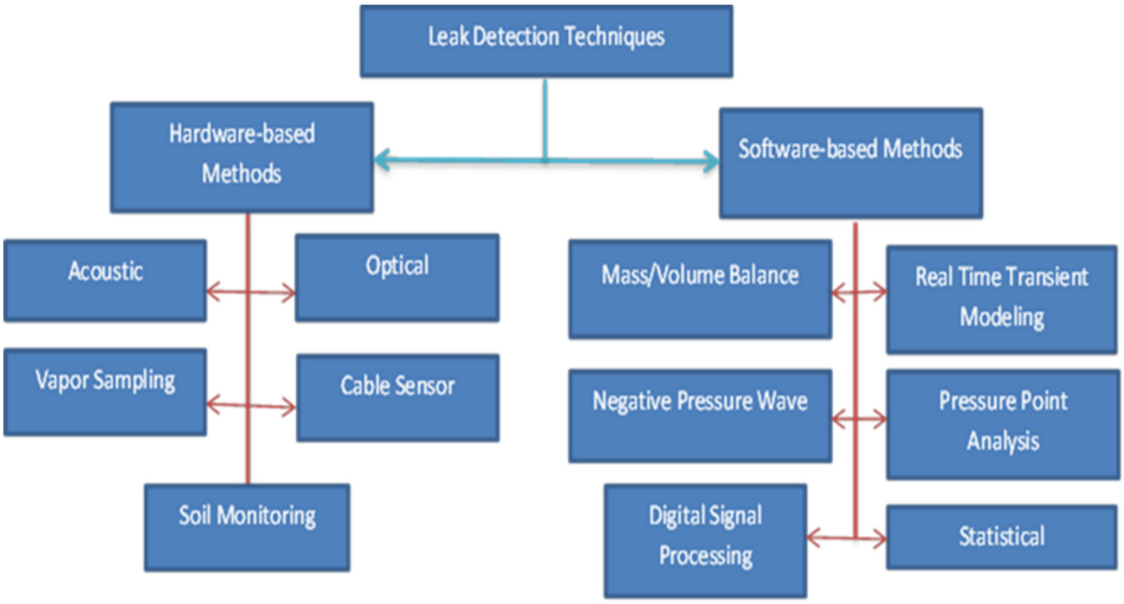

FIGURE 5: Classification of leak detection techniques for pipelines (Golmohamadi, 2015)

solutions for leak detection (Chakraborty et al., 2013). An alarm is normally generated whenever the measured fluid parameter goes beyond an allowable tolerance pre-set in the SCADA software. (Zhang, 1996).

The selection of a leak detection system must always be made while taking into consideration the requirements placed on the application, such as the desired results, the cost of installation, operation, maintenance and servicing of the leak detection system and the installation conditions. In practice, these methods can be combined to improve the accuracy of the system (Fiedler, 2014).

Leak detection using flow and pressure variation in the pipeline started in the early 1940s. A leak causes inlet pressure to decrease and inlet flow to increase simultaneously. To avoid the occurrence of false alarms and operation shutdown, thresholds must be set high enough. Consequently, this system can detect only large leaks. The reduction in pressure results in the pipeline achieving a new balance with the measured pressures changing more rapidly than during normal operating conditions, accompanied by a transient change in the average velocity of the fluid. Statistical methods and digital signal processing techniques are used by a system to identify the pattern of changes in pressure and/or flow (volume balance) that are indicative of a leak in the line. Using the volume balance analysis can improve the leak detection time (Luopa, 2000). The application of statistical methods together with state of the art signal processing technology results in the rapid detection of leaks even over long distances.

The volume-balance leak detection system can be linked to the SCADA system that is receiving the flow rates of water entering and leaving the pipeline. These values are compared after correction to standard conditions using the SCADA received values for meter pressures and temperatures at intervals set in the SCADA (Luopa, 2000). A leak will be identified simply as the difference between the inlet flow rate and the outlet flow rate as shown in Equation 8:

$$\Delta Q = Q_{in} - Q_{out} \tag{8}$$

where ΔQ = Leak flow rate;
Q_{in} = Sum of all inlet flow rates; and
Q_{out} = Sum of all outlet flow rates.

A variation of this method uses a comparison of the corrected integrated flow rates (volumes) that entered and left the pipeline over various time periods. The data is analysed at regular intervals, typically periods of five minutes, one hour or one day. This approach provides a fast response to large leaks and has the potential to identify corrosion leaks as the inlet and outlet integrated flow rates will consistently diverge if the line flow rate is constant (Luopa, 2000). This can be represented by Equation 9:

$$\Delta V = V_{in} - V_{out} \tag{9}$$

where ΔV = Leak volume.
V_{in} = Total volume entering a pipeline.
V_{out} = Total volume leaving a pipeline.

When an anomaly is detected in the system, the SCADA system will automatically close the control valves affected by the leak to prevent further loss.

3. DATA COLLECTION AND ANALYSIS

3.1 Water abstraction and consumption analysis

Fresh water has various uses in a geothermal field including: cooling of steam in the cooling towers, drilling of geothermal wells through drilling rigs, dust suppression, reservoir stimulation and for domestic use by the staff.

The demand for fresh water in Olkaria for geothermal drilling and power plant operations within the field is approximately 200,000 m^3/month for power plant start-ups and drilling operations. Drilling activity requires a continuous water supply of at least 2 m^3/min and preferable 3 m^3/min, (Dumas et al., 2013). At Olkaria currently, there are three drilling rigs. Therefore, approximately 380,000 m^3/month of water is required to adequately supply the drilling rigs.

The allowable Lake Naivasha water abstraction limit for KenGen's Olkaria geothermal field drilling and operation activities set by WRMA is 8,000 m^3/day, or equivalent to 240,000 m^3/month. This deficit of more than 60,000 m^3/month is supplemented by separated water from the power plants collected in a lagoon. In June 2017 91,937 m^3 of separated geothermal water was utilized for drilling to supplement water abstraction from Lake Naivasha (KenGen, 2017).

At the Olkaria geothermal field, there are five main power plants with a total capacity of 676.9 MWe. With plans to increase the generation capacity of the geothermal field by building more power plants and drilling more geothermal boreholes, the demand for fresh water will be greater and the networks will grow.

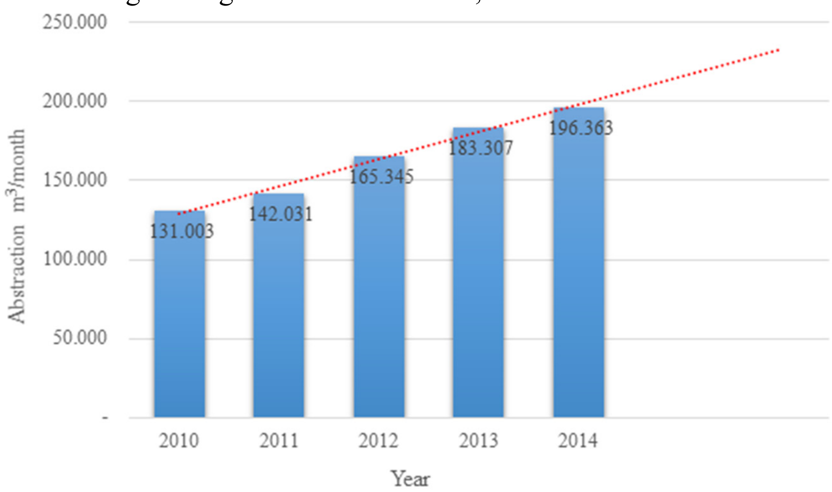

FIGURE 6: Fresh water abstraction from Lake Naivasha between 2010 and 2014

Figure 6 shows the steady increase in water abstraction from Lake Naivasha from 2010 to 2014 (KenGen, 2017). However, some of the abstracted water cannot be accounted for at the user end due to leakages along the supply line and due to poor records from faulty flow meters. Leakage may be caused by corrosion, material defects, faulty connections, high water pressure, water hammer, ground movement and vibrations (Hunaidi, 2000).

Figure 7 shows the water consumption in Olkaria. This chart is derived from the highest recorded water consumption for a single month. An assumption is made that there will be a maximum of eight drilling rigs in operation (as has been recorded in the past) and the water demand is continuous over time.

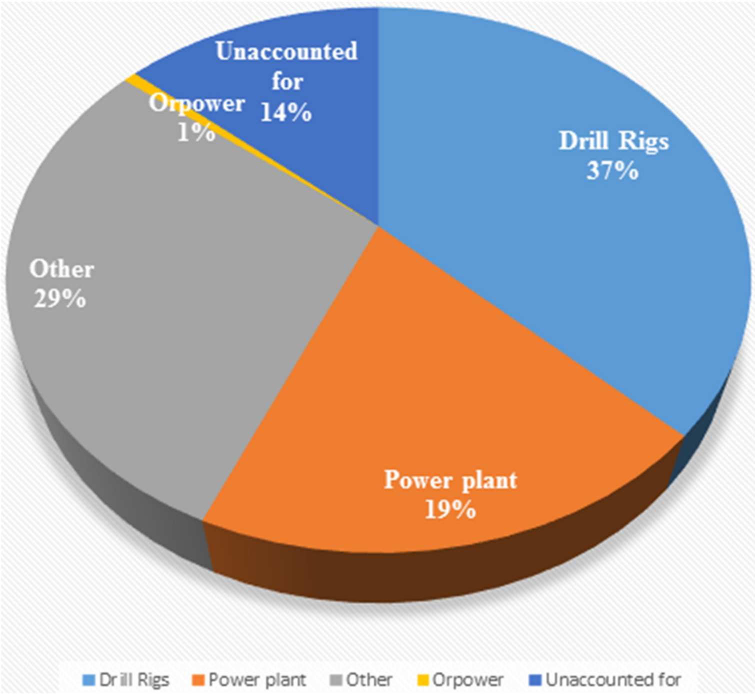

FIGURE 7: Olkaria water consumption data

3.2 Topology and elevation data analysis

A proper water supply system delivers water at the right pressure and capacity at all times to satisfy domestic, industrial, commercial, agricultural, and firefighting demands. The water supply system should consist of pumping, piping, storage, firefighting, metering and monitoring/reporting systems. These systems should meet the challenges of growing water demand, storage strains, undetected leakages along the network and emergencies. The water transmission and distribution layout is dependent on the geographical and geological considerations, degree of development in the area and the location of storage tanks.

It is common that in locations with continuous sharp elevation changes, like Olkaria, the distribution system is divided into two or more service areas as shown by the Google Earth map in Figure 8. The

FIGURE 8: Olkaria 23 km raw water main supply route layout

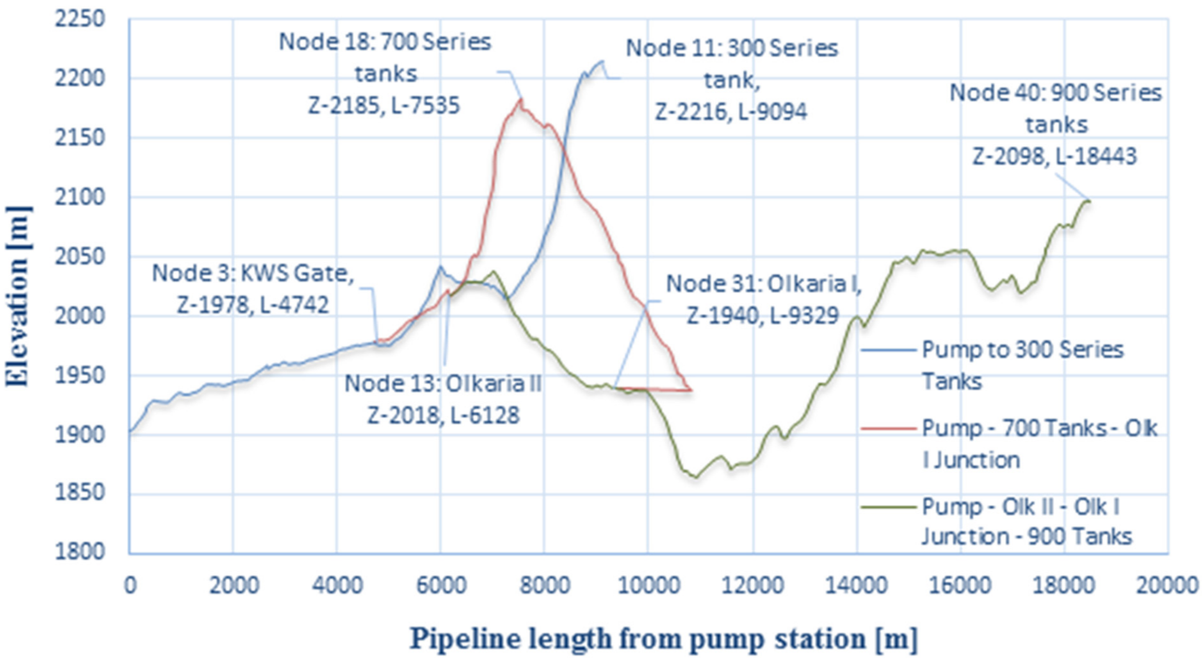

FIGURE 9: Olkaria water pipeline elevation profile

Olkaria water supply system is an open loop system and is divided into three service areas: 300, 700 and 900. Using elevation data from this map, the longitudinal elevation profile of the Olkaria water supply network was developed as shown in Figure 9.

3.3 Water supply system operation review

3.3.1 Pumping station

The high-lift water pumping system in Olkaria was constructed in 1984 near Lake Naivasha for water abstraction and transmission to the storage tanks within the geothermal field. The pump system consists of two submersible intake pumps (duty and standby) 400 m from the pumping station, with a capacity of 1100 m^3/hr and a total head of 30.5 m, and three high-pressure multistage pumps (duty, standby and spare pumps) with a capacity of 300 m^3/hr at 400 m head driven by 573 kW electric motors. The three high-lift multistage centrifugal pumps at the Olkaria high-lift pumping station are started, controlled and stopped manually by an operator at the pumping station. Table 1 gives the details of the pumps and motor assembly installed in Olkaria.

TABLE 1: Pumping equipment information in Olkaria

Item	Type	Manufacturer	Description	Size
Motor	Induction pump	GEC Large Machined Ltd. UK	Rated motor power (kW) Motor efficiency (%) Speed (rpm)	573 77 2960
Booster pump	MMG 4-stage horizontal centrifugal pump	Clyde Union Wier Pumps	Static suction head (m) Static discharge head (m) Pump discharge pressure (m of head) Pump discharge flow rate (m^3/h)	2 317 400 327.6
Submersible pump	Jumbo 600 HD	ABS Pumpen AG	Rated motor power (kW) Maximum discharge head (m) Speed (rpm) Pump discharge flow rate (m^3/h)	60.9 59 1450 1100

Submersible intake pumps are started and stopped by a level switch installed in the storage tank at the pumping station.

3.3.2 Pipeline

The water supply line to the three tank locations is approximately 27 km long and consists of 300 mm, 250 mm and 200 mm PN40 seamless carbon steel ASTM A53, grade B, class S, roll-grooved "Victaulic" water pipes at various points of the network. Surface reservoirs have been strategically installed in the three locations to allow distribution by gravity to various consumers downstream.

From the main waterline, the water is distributed downstream to the 200 mm and 150 mm pipes for drilling, power plant operations and domestic uses. Water consumption is the monitored parameter in the supply and distribution network. Water flow meters have been installed along the line to measure consumption for billing and audit purposes. However, not all distribution points are metered.

3.3.3 Tanks

Water levels in the five 4.1 million-litre tanks are manually monitored by field operators to start or stop the pumps, open or close the hand-operated gate valves, read and record flow and consumption data and report on the supply network condition.

3.3.4 Monitoring and control

All aspects of the supply of water from the pumping station are manually monitored. Gate valves are installed at several points in the network to isolate and control the water flow in the pipeline. These gate valves are all manually operated to direct the water flow to the desired location. Referring to Figure 10,

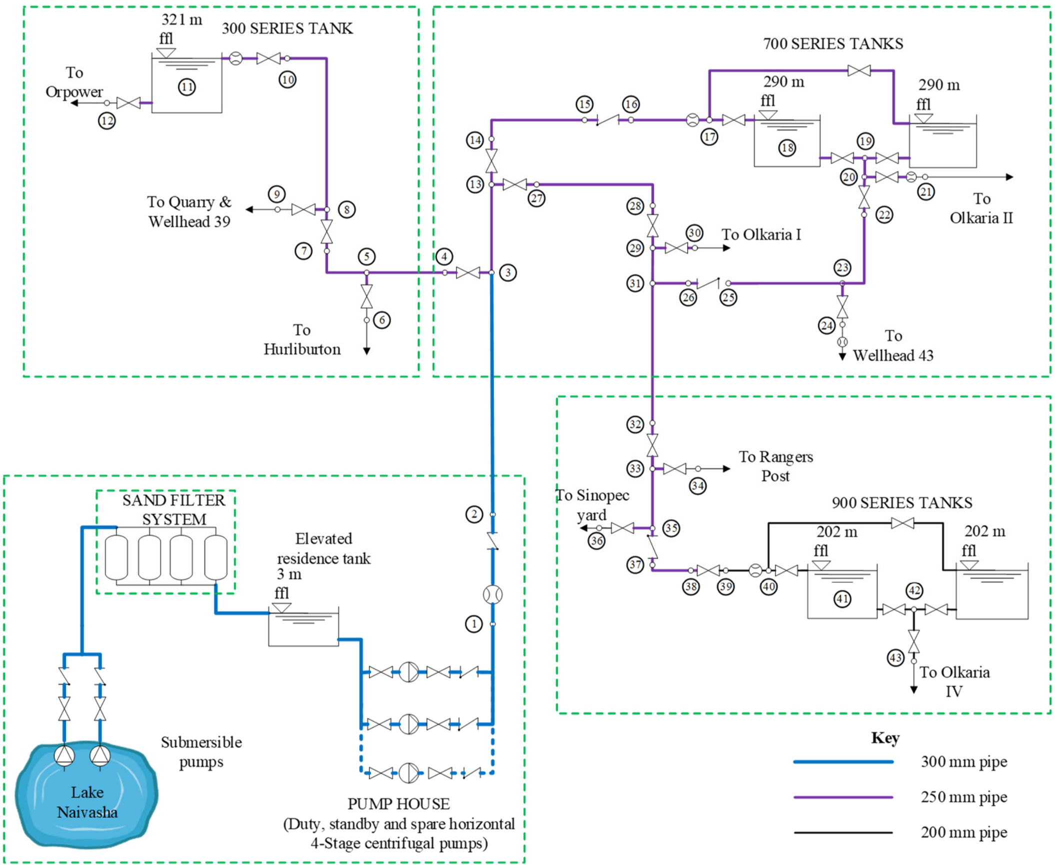

FIGURE 10: Olkaria water supply system process flow diagram

three scenarios of flow control are applied while supplying water to the three tank locations by:

- Partially opening valves 4, 14, 27, 30, 33 and fully opening all other valves, regulated in a way to allow flow to all the tanks;
- Completely closing valves 14 and 27 and fully opening valve 4 to allow water flow to the 300 series tanks;
- Completely closing valve 4, fully opening valve 14, partially opening valves 27 and 33 to allow water flow to the 700 series tanks and the 900 series tanks.

In all the above water supply operation scenarios, operators must drive around inspecting the water flow and collecting data and recording or reporting anomalies. Some parts of the pipeline are buried or located in inaccessible thickets, making it difficult to completely monitor the pipeline condition. The manual operation of the pumping system has been inefficient and requires a lot of resources, human capacity and equipment. Anomalies are not detected in time, leading to losses or damage of the pipeline and the environment. These challenges, therefore, call for an evaluation of the system performance and a redesign if necessary to allow for the automation of the pumping processes from the abstraction to the supply, distribution, maintenance, metering and billing.

All three scenarios were tested with the help of EES to determine the head losses due to friction along the pipe and the losses attributed to the pipe fittings installed in the pipeline network.

4. SYSTEM DESIGN

4.1 Mechanical systems design

4.1.1 Pipeline fluid flow analysis

Table 2 gives the water supply pipeline data.

To calculate the pressure drop of head at each node of the pipeline, the following values were assumed:

Pipe absolute roughness, ε = 0.5 mm;
Atmospheric pressure, P_{atm} = 1 bar;
Pump pressure, P_{in} = 37 bar-a;
Pump head, h_{in} = 377.8 m;
Water temperature at pump, T = 20°C;
Water volumetric flow rate, Q = 360 m^3/hr;
Gravitational acceleration, g = 9.81 m/s^2; and
Reservoir tank height, h_{tank} = 8 m.

From the known water properties, the following were computed:

Water density, ρ = 998.2 kg/m^3;
Dynamic viscosity of water, $\mu = 1.002 \times 10^{-3}$ kg/ms; and
Kinematic viscosity of water, $\upsilon = 1.004 \times 10^{-6}$ m^2/s.

Water mass flow rate and velocity are determined from Equations 10, 11 and 12:

$$\dot{m} = Q \cdot \rho \qquad (10)$$

$$\dot{m} = V \cdot A_{cross} \cdot \rho \qquad (11)$$

Therefore:

TABLE 2: Pipeline naming and information

Pipe name	Nodes		Inner diameter	Cross-sectional area	Pipe length	Distance from pump	Elevation
	Start	End	D, m	A, m²	δL, m	L, m	Z, m a.s.l.
L1	0	1	0.3	0.071	0	0	1903
L2	1	2	0.3	0.071	2560	2560	1953
L3	2	3	0.3	0.071	2155	4715	1978
L4	3	4	0.25	0.049	1	4716	1978
L5	4	5	0.25	0.049	167	4883	1976
L6	5	6	0.25	0.049	1	4884	1976
L7	5	7	0.25	0.049	1121	6004	2035
L8	7	8	0.25	0.049	1	6005	2035
L9	8	9	0.25	0.049	1	6006	2035
L10	8	10	0.25	0.049	3110	9115	2225
L11	10	11	0.25	0.049	1	9116	2225
L12	11	12	0.25	0.049	7	9123	2217
L13	3	13	0.25	0.049	1410	6125	2023
L14	13	14	0.25	0.049	1	6126	2023
L15	14	15	0.25	0.049	701	6827	2122
L16	15	16	0.25	0.049	1	6828	2122
L17	16	17	0.25	0.049	707	7535	2193
L18	17	18	0.25	0.049	1	7536	2193
L19	18	19	0.25	0.049	9	7545	2185
L20	19	20	0.25	0.049	1	7546	2185
L21	20	21	0.25	0.049	1	7547	2185
L22	20	22	0.25	0.049	1	7547	2185
L23	23	24	0.25	0.049	1069	8616	2108
L24	23	25	0.25	0.049	1	8617	2108
L25	25	24	0.25	0.049	600	9216	2060
L26	26	31	0.25	0.049	1	9217	2060
L27	13	27	0.25	0.049	1	6126	2023
L28	27	28	0.25	0.049	3098	9224	1939
L29	28	29	0.25	0.049	1	9225	1939
L30	29	30	0.25	0.049	1	9226	1939
L31	29	31	0.25	0.049	40	9265	1937
L32	31	32	0.25	0.049	1949	11214	1879
L33	32	33	0.25	0.049	1	11215	1879
L34	33	34	0.25	0.049	1	11216	1879
L35	33	35	0.25	0.049	2850	14065	2000
L36	35	36	0.25	0.049	1	14066	2000
L37	35	37	0.25	0.049	1	14066	2000
L38	37	38	0.2	0.031	2389	16455	2024
L39	38	39	0.2	0.031	1	16456	2024
L40	39	40	0.2	0.031	2032	18488	2095
L41	40	41	0.2	0.031	1	18489	2095
L42	41	42	0.2	0.031	10	18499	2097
L43	42	43	0.2	0.031	1	18500	2097

$$V = \frac{\dot{m}}{\rho \cdot A_{cross}} \qquad (12)$$

where $\dot{m}$ = Water mass flow rate [kg/s];
A_{cross} = Cross-sectional area [m^2]; and
V = Water velocity [m/s].

With the estimates of the peak water demand and the type and number of fittings in the water supply network known, these data were subjected to a series of calculations, using EES, to determine the velocity of water, *V,* along each pipe length, the values of the relative roughness factor, *rr,* and the

Reynolds number, *Re*, of each pipe length. The friction factor, *f*, of each pipe length is then determined from the Moody diagram reading. The head loss due to friction, h_f, and minor losses due to fittings h_s, are then calculated at every node using the Darcy-Weisbach equation. Finally, the total hydraulic head at every node is calculated as shown in Equations 13-14:

$$H_i = H_{i-1} - (h_{fi} + h_{si}) \tag{13}$$

$$H_1 = P_{in} + Z_1 \tag{14}$$

where H_i = Hydraulic head at node i [m];
H_{i-1} = Hydraulic head at node i-1 [m];
h_{fi} = Head losses due to friction at node i [m];
h_{si} = Head losses due to minor losses at node i [m];
H_1 = Hydraulic head at pump node 1 [m];
P_{in} = Pump discharge pressure [m]; and
Z_1 = Pipeline elevation at first node [m].

The hydraulic head at pump node H_1 must be greater than the static head (elevation of the highest point in the pipeline network) so as to deliver water to it after overcoming the losses along the pipeline. In the cases that this is not achieved, a vacuum is formed in the line as the atmospheric pressure is now higher than the pipeline pressure. Therefore, a booster pump is needed to aid the delivery to the destination at that point. The results from the EES calculations are as tabulated in Appendix II, Tables 1-5.

A plot of elevation, *Z*, and hydraulic head, *H*, against the pipe length, *L*, was drawn to determine the hydraulic grade line (HGL) along the pipeline to each water tank location considering the three pumping operation scenarios.

Scenario 1

Figure 11 represent the scenario 1 pumping operation where all the valves are open to allow maximum flow across them. Valve 14 is restricted to allow flow equivalent to downstream demand. The result shows that water is delivered to the tanks, when the valves are well regulated, to allow only the demanded water flow through them.

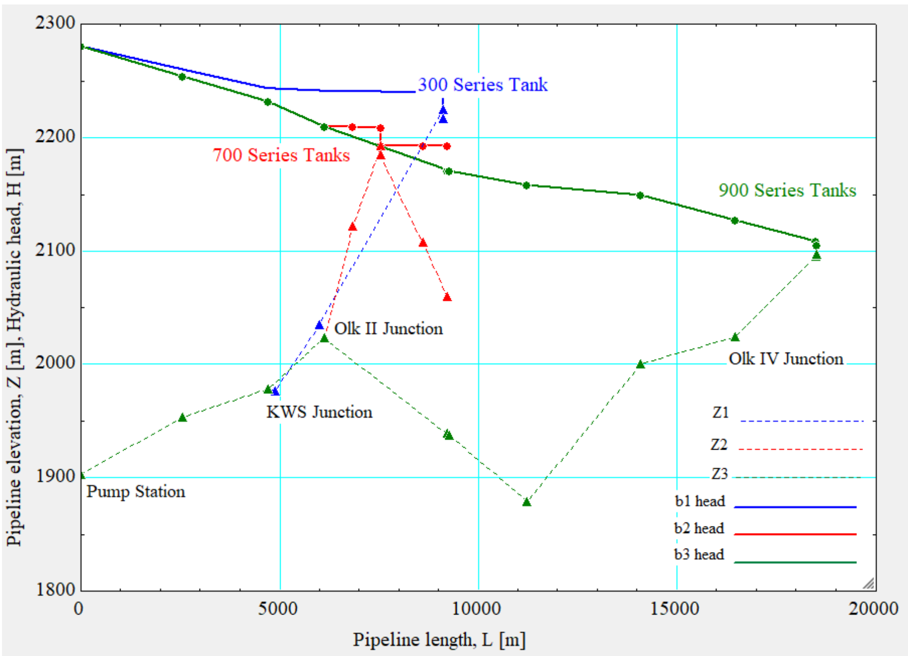

FIGURE 11: Scenario 1 HGL Plot

Scenario 2
This scenario requires that water only flows to the 300 series tank through valve 4. The HGL plot in Figure 12 shows that the water cannot be delivered to the tanks as vacuum forms in the pipeline after 8000 m at an elevation of 2150 m a.s.l. The flow rate at L10, when all the valves are open is 0.094m^3/s (Appendix II Table 2)

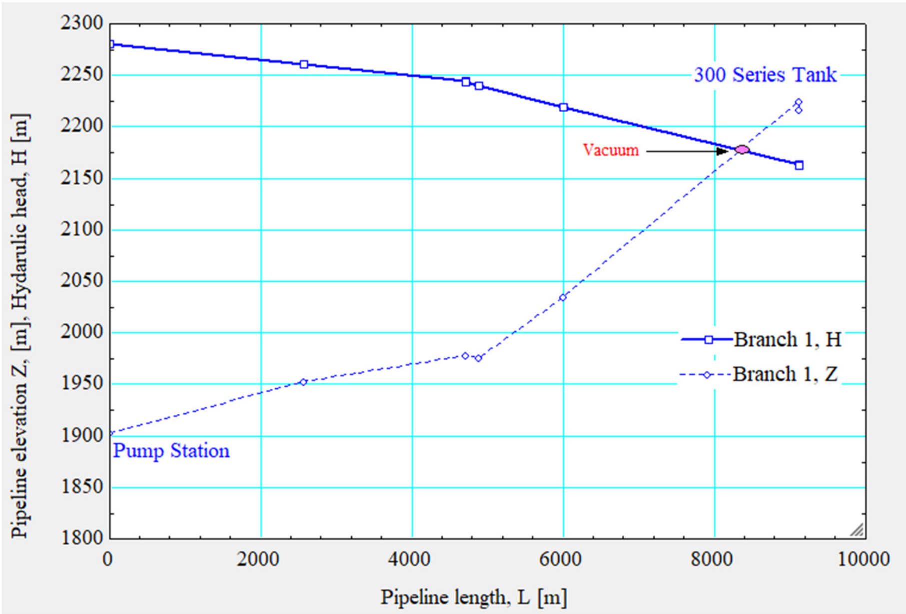

FIGURE 12: Scenario 2a HGL plot when all the valves towards 300 series tank are fully open

To avoid the formation of vacuum in the line, valve 4 is partially open (¼ way) to reduce the head losses in the pipeline. This results in a residual head of 1 m at the 300 series tank, as shown in Figure 13. The flow rate at L10 for this scenario is 0.019 m^3/s (Appendix II Table 3).

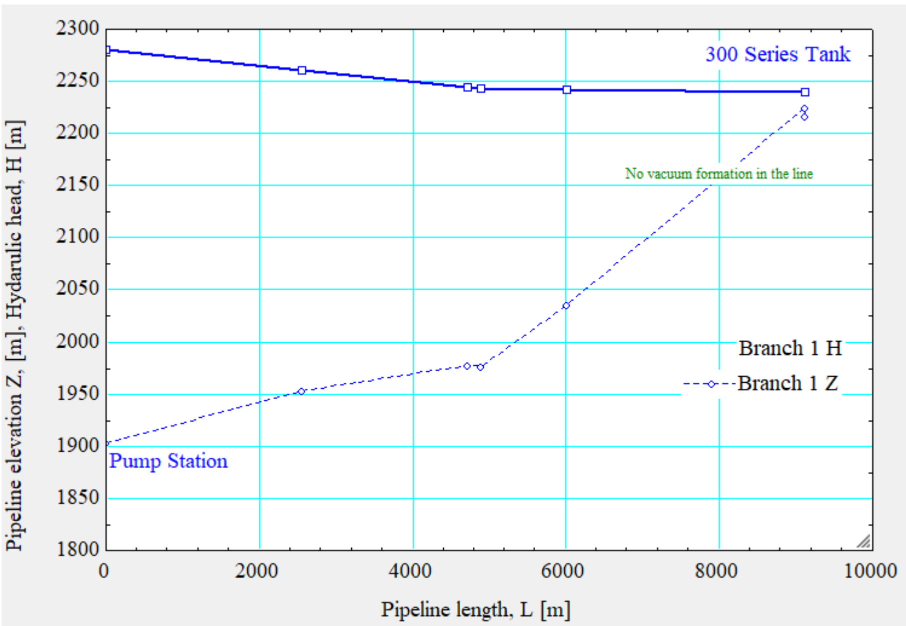

FIGURE 13: Scenario 2b HGL plot when valve 4 is open ¼ way towards the 300 series tank

Scenario 3
Here, no water is delivered to the 300 series tank. One operation scenario analysed was by fully opening all the valves leading to the 700 and 900 series tanks. Figure 14 shows that the water will not be delivered at 900 series tank location since the hydraulic head is lower than the static head at the tank.

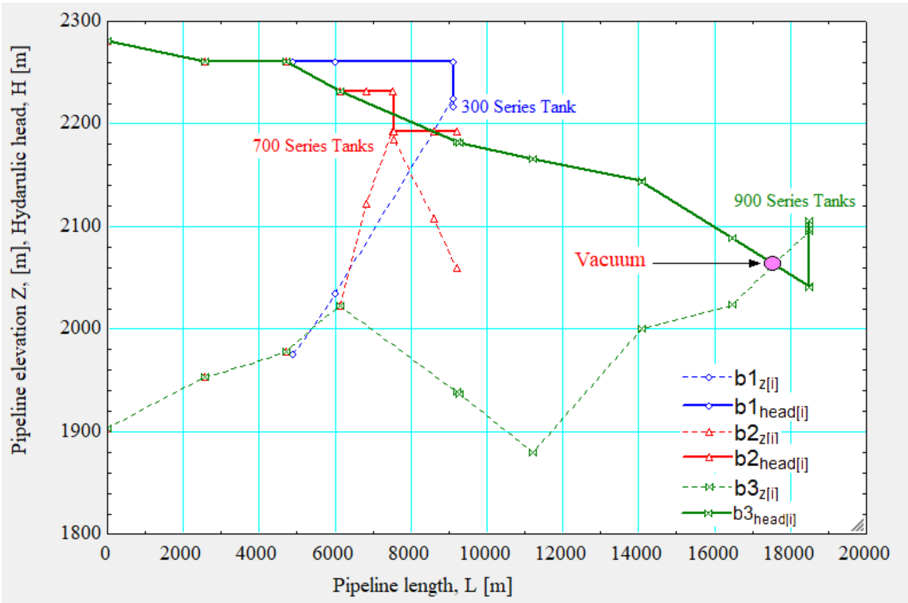

FIGURE 14: Scenario 3a HGL plot when all the valves towards the 700 and 900 series tanks are fully open

To avoid anomalies, restriction and control of flow is necessary at various points in the network. The water flow is therefore wholly diverted to the 700 and 900 series tanks. Valve 4 is completely closed, valve 14 fully open, valves 27 is ¾-way open while valve 33 is ¼-way open. This allows water flow to the 700 series tanks and 900 series tanks without any vacuum formation in the line. Figure 15 shows the HGL plot of scenario 3b with a positive residual head at both tanks.

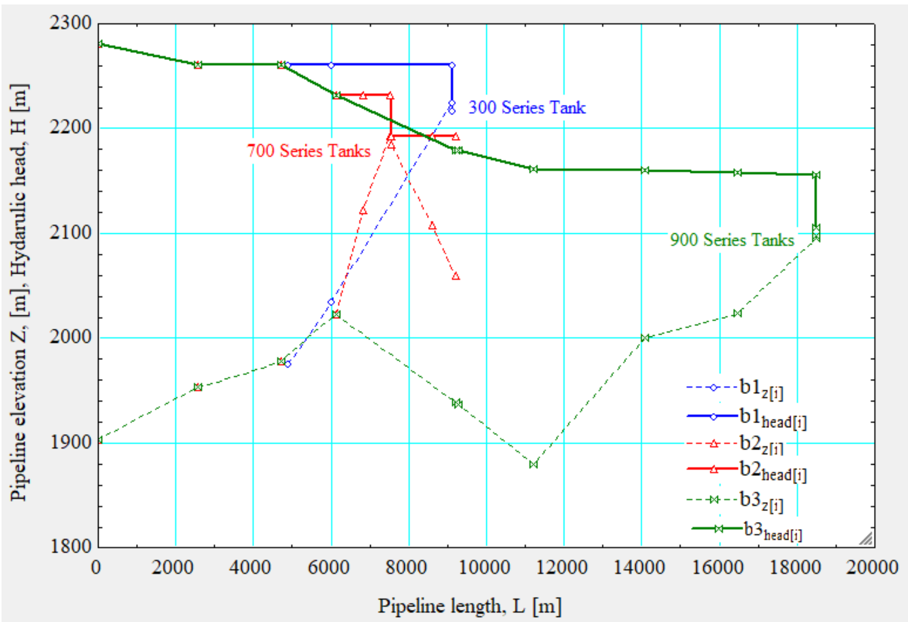

FIGURE 15: Scenario 3b HGL plot when valves 27 and 33 are restricted towards 900 series tanks

4.1.2 Flow control design

Power supply

In order to lower the initial pumping costs and improve the reliability and efficiency of the pumps, a speed controlled pumping system using variable frequency drives (VFD) can to be introduced. The booster pumps are started using a soft starter system to protect the motor from electrical stresses during starting, thereby increasing the lifespan of the motor. The use of VFD and soft starter systems requires reliable electricity supply. For this reason, a standby generator should be installed to pick up the load in case of an electricity supply outage. The quality of electricity supply shall be continuously monitored and transmitted to the central control room for logging and reporting. Field measuring equipment, flow transmitters, pressure transmitters and the telemetry units (PLCs and/or RTUs), should be powered using solar power supply systems with battery backup.

Security

To enhance the security of equipment and personnel at the pumping station, CCTV surveillance cameras should be mounted at critical locations. The images will be transmitted to the central control and security room for viewing and storage. Similar CCTV equipment should be deployed to the tank locations to monitor the control panels and critical equipment at the sites. Further, automated switching of the security lighting systems, using photocells and/or PLCs, at all critical installations should be introduced.

Water pipeline

a. Control valves. From the fluid flow analysis, it is established that valves 4, 14, 27, 30 and 33 have to be varied to ensure the delivery of water to the tanks. These valves have to be monitored and controlled in a manner prescribed in scenarios 1, 2 and 3 of the pumping system operation. Therefore, motor driven control valves should be installed at nodes 4, 14, 27, 30, and 33. These valves should be flow controlled based on the demand situation for water delivery to the reservoir tanks. The valves will control the flow of water to ensure that there is no vacuum formed in the line during pumping, and they should be operated to open and shut slowly to minimise surges in the water line.

At the tank inlets, motorized control valves should be installed at nodes 10, 17 and 40 to control the water delivery into the tanks. These valves will be controlled by the water level in the reservoir tanks. A level transmitter will send a signal to the level controller to variably close the valves when the tank is full to avoid an overflow and open when the level is low. An alarm shall be sent to the control room to alert the operators of the tank level.

In order to control the flow out of the tanks and avoid air entering the pipeline when the water level is low, motor driven on/off valves should be installed at nodes 12, 19 and 42. The on/off valves should be pressure controlled so that when the pressure in the tanks falls below the critical level, the pressure switch sends a signal to the pressure controller to close the valve until the pressure is normalized. An alarm will then be sent to the central control room showing critically low water levels in the reservoir tanks.

b. Flow indicators, transmitters and leak detection. A total of 38 flow transmitters should be installed along the pipeline, from the intake station to the three tank locations. Out of these, 23 turbine flow transmitters should be installed along the main line for flow monitoring and leak detection. They should be spaced a kilometre apart. Twelve orifice flow indicating transmitters should be installed at all outlets from the main line and reservoir tanks. Three magnetic flow indicating transmitters should be installed at key points of the water supply line, that is the pump outlet, after node 4 towards the 300 series tank and after node 3 leading to the 700 and 900 series tanks.

A leak causes inlet pressure to decrease and inlet flow to increase simultaneously. Therefore, several flow and pressure transmitters will be installed along the pipeline to measure and transmit the water flow rate, volume and pressure levels. This data will provide real-time input for the control analysis for the detection of leaks. The detectors are sometimes used to close line valves automatically. Figure 16 shows the proposed water supply system piping and the instrumentation diagram (P&ID).

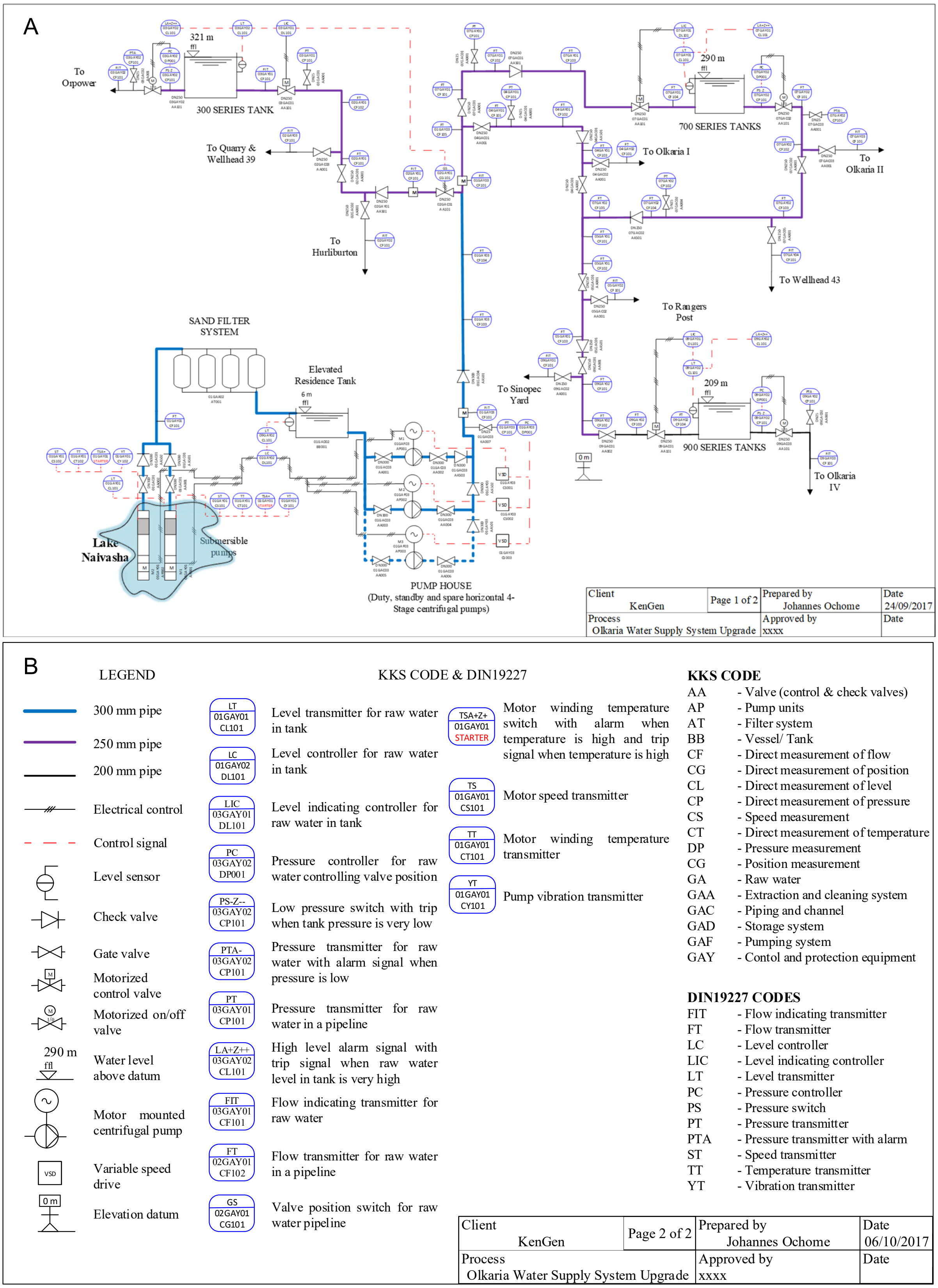

FIGURE 16: a) Proposed Olkaria water supply system P&ID; and b) Symbols and codes

4.2 Electrical systems and SCADA design

4.2.1 SCADA design philosophy

In the design of a SCADA system several aspects have to be considered including: security, communication protocol, scalability, portability, flexibility, compatibility with existing hardware, availability or redundancy, risk and reliability, total cost of ownership and life cycle cost and the available budget.

To improve the availability of the remote communication, redundant interfaces or media may be used such as a self-healing fibre optic Ethernet ring, radio or a telephone modem. To provide a high availability of the process, the use of redundant controllers, IO and power supplies may be used in areas where a failure of a critical component, equipment or module is foreseen. The use of power management solutions like surge controllers, intelligent uninterruptible power supply systems (UPS), backup power supply options, and lightning protection systems will be critical given the low power quality in the local electricity grid. However, the cost and system complexity can rapidly escalate when redundancy is a requirement (DiNanno and Changy, 2005).

To avoid unwanted access or malicious penetration into the SCADA system and other cyber threats, it is important to limit access to the system data and functionality by users depending on their levels. Password control and firewall installation can assist with preventing unauthorized system access.

The SCADA system designed should be able to support a variety of remote stations, which may vary in size and configuration. Future demand changes need to be incorporated within the design to allow for easy connectivity.

The capability to support multi-port communications and protocols is critical since remote data acquisition and control can be communication intensive, requiring many communication ports and remote access options (DiNanno and Changy, 2005).

The ease of integrating the system with the existing varied hardware is a big consideration in the design and choice of a SCADA system, especially the communications interfaces that have varied protocols, come from different vendors and have an array of cabling interfaces. This may impact integration efforts due to some inconsistencies in signal interfaces and protocols. The risk in both development and in operation is minimized by choosing pre-tested and highly integrated solutions and using well proven hardware and software designs.

An analysis of the total cost of a SCADA project has to be done to see the financial viability of the project. In order to do this, all costs of development, installation and maintenance of the system have to be considered through the project life cycle. This includes the cost of specification development, design and drawings, procurement and implementation, documentation, start-up/commissioning, maintenance and licencing, operation and downtime, evolutions, and end of life or disposal. Selecting hardware and software solutions that offer multiple and pre-engineered functions often saves substantial development and integration costs on the project (DiNanno and Changy, 2005). Above all, the budget guided by the implementation strategy restricts the level and mode of development.

Figure 17 shows the typical topology of the proposed SCADA system for the Olkaria water supply for the connection and communication to one reservoir tank location. It assumes the use of radio/ microwave links for communication between the RTUs and the master station.

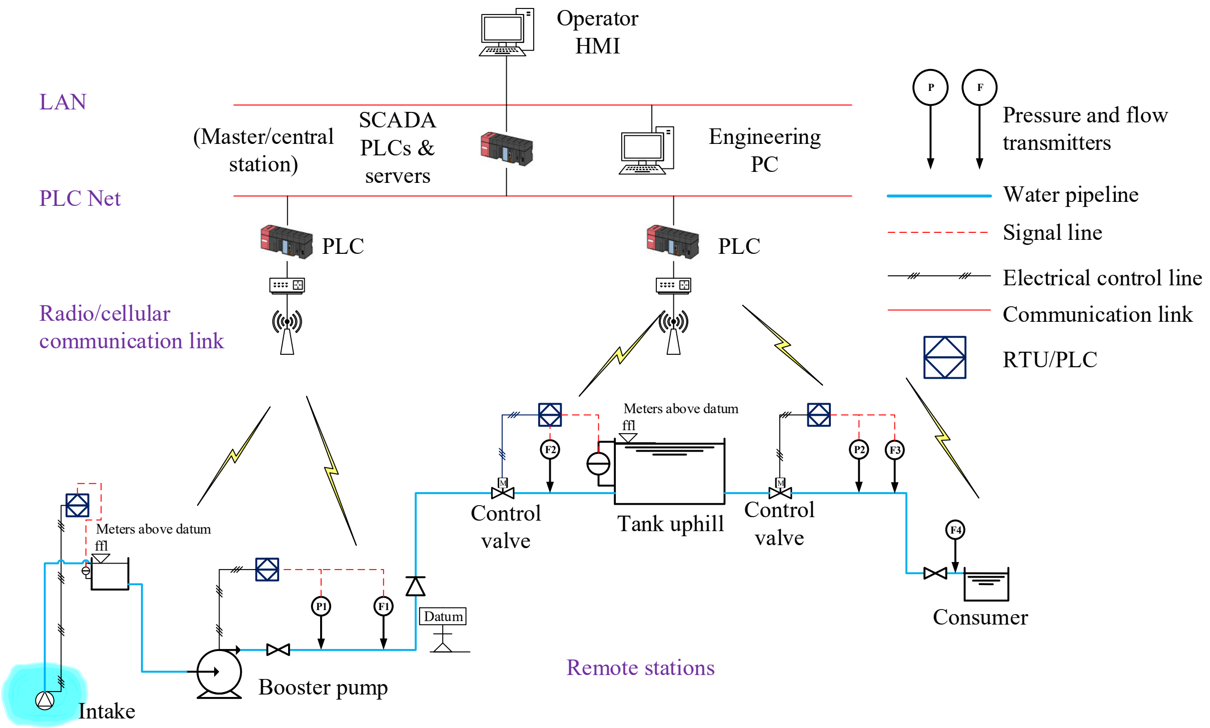

FIGURE 17: Typical SCADA topology to one reservoir tank

4.2.2 RTU/PLC communication

An RTU (remote telemetry unit or remote terminal unit) is a microprocessor based, stand-alone data acquisition and control unit. A PLC is a device used to automate the monitoring and control of industrial facilities. It can be used as a stand-alone or in conjunction with a SCADA or other systems. PLCs connect directly to field data interface devices and incorporate programmed intelligence in the form of logical procedures that will be executed in the event of certain field conditions. The line between PLCs and RTUs is thin and the terminology is virtually interchangeable. The term RTU will refer to a remote field data interface device which may include automation programming (Barr and Fonash, 2004).

Each station should have an RTU hardware module that includes a control processor and associated memory, analogue inputs and outputs, counter inputs, digital inputs and outputs, communication interface(s), power supply, as well as an RTU rack and enclosure, (Clark et al., 2004). It will control and acquire data from field equipment (pressure sensors, level sensors, flow meters, photocells, power meters and switches) installed at the four sites as shown in Figure 18 for transfer to a central station (dispatcher). Appendix III shows the list of digital/analogue input and output signals for SCADA and the expected alarms.

The electrical equipment associated with control, instrumentation and protection is vulnerable to corrosion and failure due to hydrogen sulphide (H_2S). H_2S is a very corrosive gas, especially in combination with high humidity, and it is advisable to minimize the adverse effects by making a careful selection of materials and maintain the appropriate environmental conditions (Apiyo, 2016; and Rivera, 2007).

Communication network options

The field devices and sensors should be hardwired (Current loop 4-20 mA, on/off, PROFIBUS or RS485 protocols) or wirelessly connected to the RTU for communication and data transfer to the master station. A hardwired 4-20 mA communication connection between the RTU/PLC and the sensors/transducers is the most common with a shielded twisted pair cable for signals. Overvoltage protection of the sensors

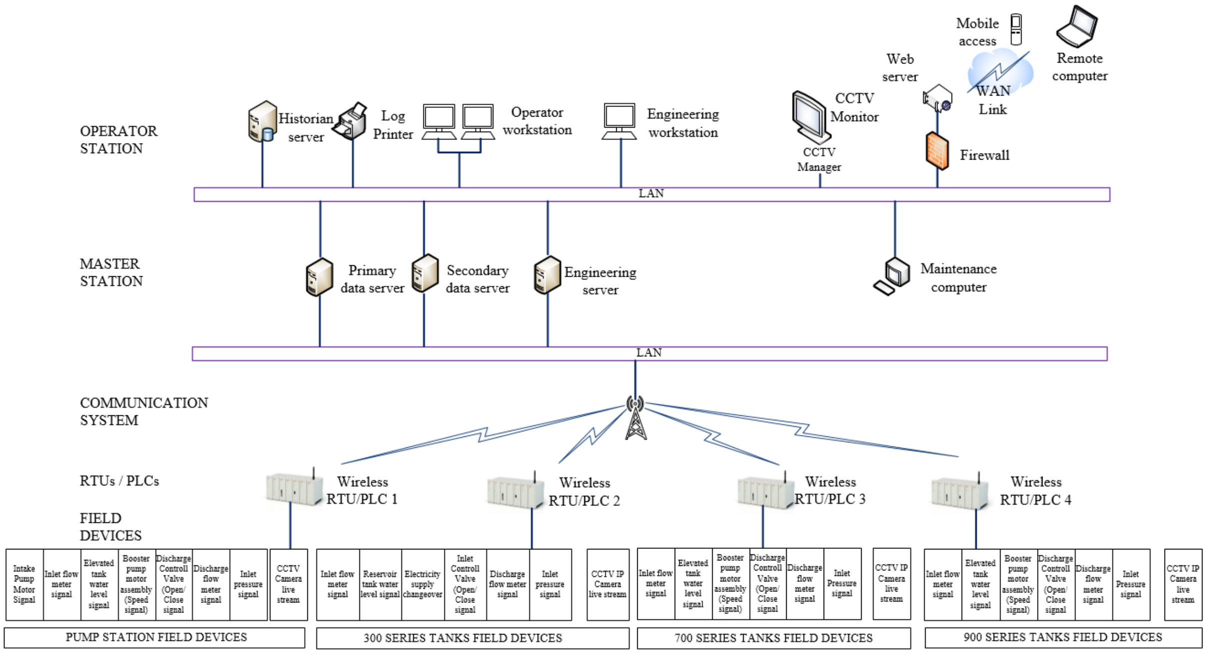

FIGURE 18: Olkaria water supply SCADA schematic drawing

and the RTU/PLC at ends must be done. To avoid damage by rodents, all the cables must be laid in pipes/conduits. A master station has two main functions: to obtain field data by periodically polling the RTUs and to control the field devices through the operator station. Without a properly designed communication system the SCADA system will not work since this is the only way to acquire data and issue control instructions to remote devices. A good communication network should be reliable and highly available. At Olkaria the following options need to be explored:

- Fibre optic;
- Ethernet;
- Power Line Carrier (PLC) links;
- Wireless/radio links;
- Microwave radio links; and
- Cellular.

a. Fibre optic
This is best direct communication option with the fastest data transfer rates with the help of electromagnetic waves in the optical frequency range. The large bandwidth will allow the transmission of video and speech signals from the security cameras installed at the remote sites as a part of the SCADA system. Transmission can be done over long distances without the need for repeaters along the line. Communication is not affected by the topography, weather or interference by other communication systems. Fibre optic communication systems are immune to lightning overvoltage, especially if a non-metal sheath is used. It is not possible or very difficult to eavesdrop a fibre optic communication. However, the downside to this technology is the initial high installation cost which is proportional to the transmission distance. It is worth noting that the cost of fibre optics systems has been decreasing. This system is therefore, the most suitable for connecting the RTUs to the master station.

b. Ethernet
This is the most widely used LAN (Local Area Network) because it is cheap and easy to use. The connection of LAN to the SCADA network allows users within the company with the right software and access rights to view the system. This will be important for connection to the HMI (Human-machine interfaces) and other computers that may access the SCADA.

c. Power line carrier links
This is achieved by using the electrical power distribution facilities as a carrier of the data. Their performance is determined by the sound/noise ratio and the attenuation characteristics of the lines. It is however unaffected by the topography. The main disadvantage to this communication option is that the system suffers from electromagnetic interference and interference from adjacent channels. This system is hardly recommended today because of interference from machines that can appear suddenly, and because power lines are not intended for high frequency use. This can result in unpredictable standing waves, reflections, data loss, etc. It has been tried in Reykjavik around the year 2000 for internet distribution but with bad results.

d. Wireless / Radio links
This system uses radio transmitters and receivers to send data over short distances on VHF or UHF frequency bands. Normally, it requires line of sight for best application. This may be the best alternative for areas without cellular coverage, which are far from the fibre optic connection. Such UHF radio links are available to transmit low-speed ethernet over considerable line-of-sight distances, using high gain Yagi antennas. Some vendors such as Satel (who manufacture UHF communication links, repeaters and accessories for Profibus like the "Satelline" UHF radio modem with a dedicated network management system) can supply digital repeaters that can be installed on mountain tops. The typical frequency band for UHF radio links is around 450 MHz with a typical data rate of 9600 baud. The system, however, does not support video transmission. The use of some frequencies require a licence application for authorization by the Communication Authority, CA, of Kenya.

e. Microwave radio links
Within the broader spectrum of radio frequency (RF) communications, point-to-point communications are usually carried out using microwave frequencies between 1 GHz and 100 GHz (frequencies higher than 10 GHz are, for practical purposes, not used for industrial data communication) along line-of-sight (LOS) paths called links. These frequencies and their propagation characteristics allow the transmission of vast amounts of data, speech and video between RTUs and the master station without the need to lay cables between them. When propagated through the atmosphere, poor environmental conditions can disrupt microwave links, as signal reflection or refraction greatly reduces the power levels of received signals, especially higher-frequency transmissions, thereby requiring the installation of repeater stations. Adjacent-link interference could be a problem if there is not sufficient LOS clearance. One must also avoid the use of the common "free" shared microwave Wi-Fi bands on 2.4 and 5.8 GHz because of possible interference in these sometimes crowded bands. Just like the radio frequencies, microwave radio frequencies require licencing by the CA of Kenya.

f. Cellular
Kenya currently has three main GSM service providers with good coverage all around the country. The cellular system is based on the cellular phone technology to transmit data, regardless of distance, but it is dependent on cellular signal coverage. This transmission technology is quickly gaining in popularity in areas that may not have strong radio signals or line-of-sight conditions, especially now that cost per minute continues to decline. It is good to consider a redundancy in case of failure of the GSM connectivity by using dual multi-SIM GSM modems allowing connections to more than one GSM service. Most parts of the Olkaria geothermal area have good cellular coverage. This therefore, becomes the most feasible redundant communication method after fibre optic communication links.

A new and very promising system for interconnecting equipment with the cellular GSM 4G network is called M2M, meaning Machine-to-Machine, sometimes called the Internet of Things (IoT). M2M is a global infrastructure for the information society which enables advanced services by interconnecting (physical and virtual) things based on existing and evolving interoperable information and communication technologies (Vermesan and Friess, 2013). M2M is rapidly gaining popularity since it allows communication of devices and performance of actions without the manual assistance of humans especially for remote monitoring and control. Currently, M2M does not have a standardized connected device platform and many M2M systems are built to be task- or device-specific. It is expected that as

M2M becomes more pervasive, vendors will need to agree upon standards for device-to-device communications (TechTarget, 2017).

4. CONCLUSIONS

The choice to automate the water supply system at Olkaria is a time dependent one. Since its commissioning, the water supply system at Olkaria has been able to deliver required services to its customers. However, as projects keep demanding more flow from the system, it is time to consider more efficient water operation and management techniques, using state-of-the-art technologies. SCADA systems have been deployed at the Olkaria power plants and by extension should be improved to manage other facilities in the area such as the water supply system. This way, KenGen benefits from reduced water losses due to leakages and bursts, reduced machine downtime, up-to-date reporting, efficient pipeline data analysis and above all, efficient use of its skilled human resource. In order to achieve these, elaborate training programmes need to be initiated to give skills to the staff on modern water management techniques, instrumentation design and specification development and modern plant maintenance strategies.

The application of SCADA solutions for water systems combined with leak detection and use of control valves will significantly improve the service delivery. These techniques have to be complemented with adapted water conservation programmes aimed at minimizing water wastage. These initiatives should combine to form a "water strategy" for conserving this valuable resource and making it available for future development.

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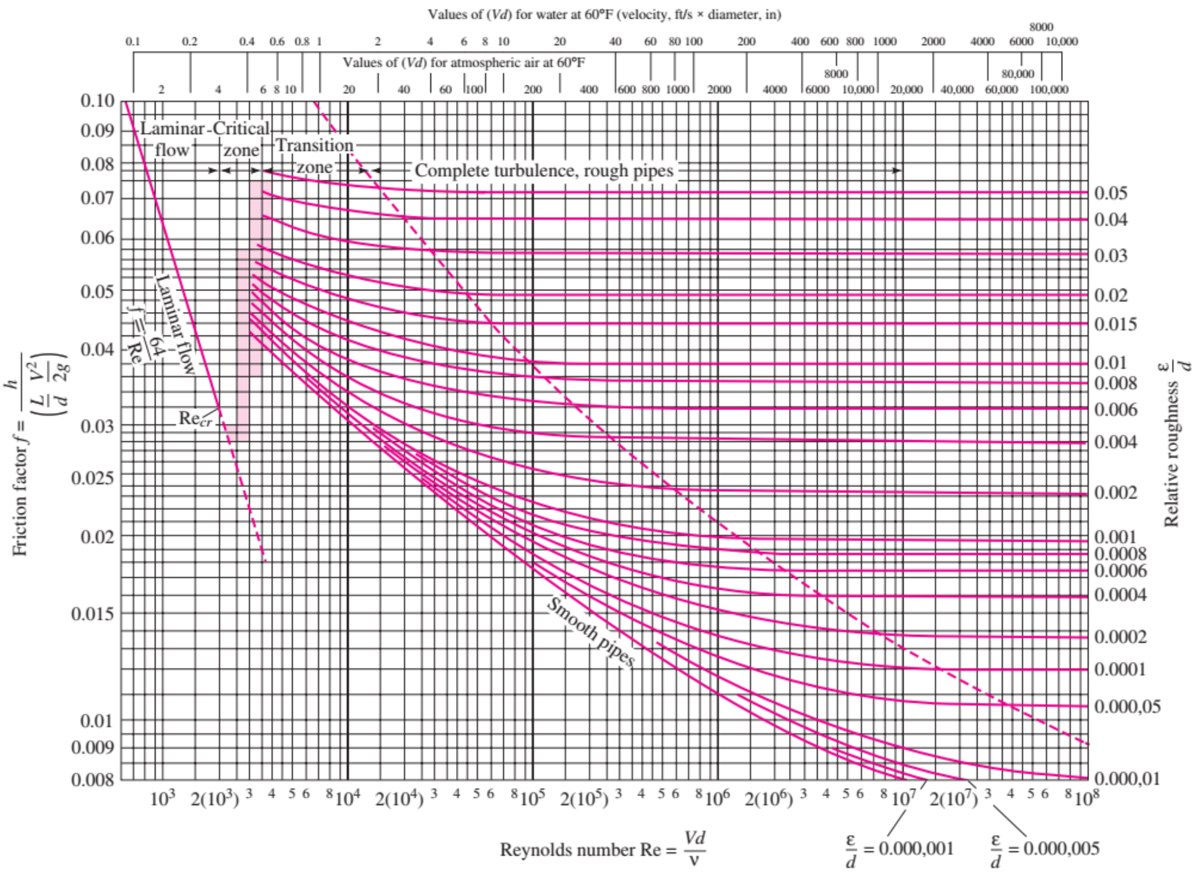
APPENDIX I: Moody diagram (White, 2011)



APPENDIX II: Calculation results of fluid flow analyses

TABLE 1: Calculation results of fluid flow analysis for scenario 1

Pipe	Friction factor	K factor	Reynolds number	Relative roughness	Mass flow rate	Volumetric flow rate	Velocity	Elevation	Head loss	Hydraulic head
	f	K	Re	rr	ṁ, kg/s	Q, m3/s	V, m/s	Z, m	h_f, m	H, m
L1	0.0229	4.17	422755	0.002	99.82	0.100	1.415	1903	0.43	2281
L2	0.0229	2.00	422755	0.002	99.82	0.100	1.415	1953	20.17	2261
L3	0.0229	0.00	422755	0.002	99.82	0.100	1.415	1978	16.81	2244
L4	0.0250	1.67	125135	0.002	24.62	0.025	0.503	1978	0.02	2244
L5	0.0250	0.00	125135	0.002	24.62	0.025	0.503	1976	0.21	2244
L6	0.0319	1.67	14374	0.002	2.83	0.003	0.058	1976	0.00	2244
L7	0.0252	0.00	110762	0.002	21.79	0.022	0.445	2035	1.14	2242
L8	0.0252	0.17	110762	0.002	21.79	0.022	0.445	2035	0.00	2242
L9	0.0311	1.67	16487	0.002	3.24	0.003	0.066	2035	0.00	2242
L10	0.0254	0.17	94274	0.002	18.55	0.019	0.379	2225	2.31	2240
L11	0.0254	1.50	94274	0.002	18.55	0.019	0.379	2225	0.01	2240
L12	0.0254	1.17	94274	0.002	18.55	0.019	0.379	2217	0.01	2225
L13	0.0240	0.17	382171	0.002	75.20	0.075	1.535	2023	16.28	2228
L14	0.0265	0.17	55663	0.002	10.95	0.011	0.224	2023	0.00	2228
L15	0.0265	0.00	55663	0.002	10.95	0.011	0.224	2122	0.19	2227
L16	0.0265	2.00	55663	0.002	10.95	0.011	0.224	2122	0.01	2227
L17	0.0265	1.00	55663	0.002	10.95	0.011	0.224	2193	0.19	2227
L18	0.0265	0.34	55663	0.002	10.95	0.011	0.224	2193	0.00	2227
L19	0.0265	0.34	55663	0.002	10.95	0.011	0.224	2185	0.00	2193
L20	0.0265	1.00	55663	0.002	10.95	0.011	0.224	2185	0.00	2193
L21	0.0283	1.67	30438	0.002	5.99	0.006	0.122	2185	0.00	2193
L22	0.0291	0.17	25224	0.002	4.96	0.005	0.101	2185	0.00	2193
L23	0.0291	0.00	25224	0.002	4.96	0.005	0.101	2108	0.07	2193
L24	0.0291	1.67	25224	0.002	4.96	0.005	0.101	2108	0.00	2193
L25	2.979×10^{16}	0.00	2.15×10^{15}	0.002	0.00	0.000	0.000	2060	0.00	2193
L26	2.979×10^{16}	2.00	2.15×10^{15}	0.002	0.00	0.000	0.000	2060	0.00	2193
L27	0.0241	1.17	326508	0.002	64.25	0.064	1.311	2023	0.11	2227
L28	0.0241	0.00	326508	0.002	64.25	0.064	1.311	1939	26.18	2201
L29	0.0241	0.17	326508	0.002	64.25	0.064	1.311	1939	0.02	2201
L30	0.0249	1.67	131900	0.002	25.95	0.026	0.530	1939	0.03	2201
L31	0.0245	0.00	194608	0.002	38.29	0.038	0.782	1937	0.12	2201
L32	0.0245	0.00	194608	0.002	38.29	0.038	0.782	1879	5.95	2195
L33	0.0245	0.17	194608	0.002	38.29	0.038	0.782	1879	0.01	2195
L34	0.0358	1.67	8173	0.002	1.61	0.002	0.033	1879	0.00	2195
L35	0.0246	0.00	186435	0.002	36.68	0.037	0.749	2000	7.99	2187
L36	0.0336	1.67	10992	0.002	2.16	0.002	0.044	2000	0.00	2187
L37	0.0246	2.00	175443	0.002	34.52	0.035	0.705	2000	0.05	2187
L38	0.0257	0.00	219304	0.003	34.52	0.035	1.101	2024	18.99	2168
L39	0.0257	0.67	219304	0.003	34.52	0.035	1.101	2024	0.05	2168
L40	0.0257	4.00	219304	0.003	34.52	0.035	1.101	2095	16.40	2152
L41	0.0257	1.84	219304	0.003	34.52	0.035	1.101	2095	0.12	2152
L42	0.0257	0.34	219304	0.003	34.52	0.035	1.101	2097	0.10	2105
L43	0.0261	1.67	148088	0.003	23.31	0.023	0.743	2097	0.05	2105

TABLE 2: Calculation results of fluid flow analysis for scenario 2a

Pipe	Friction factor	K factor	Reynolds number	Relative roughness	Mass flow rate	Volumetric flow rate	Velocity	Elevation	Head loss	Hydraulic head
	f	K	Re	rr	ṁ, kg/s	Q, m3/s	V, m/s	Z, m	hf, m	H, m
L1	0.0229	4.17	422755	0.002	99.82	0.100	1.415	1903	0.43	2281
L2	0.0229	2.00	422755	0.002	99.82	0.100	1.415	1953	20.17	2261
L3	0.0229	0.00	422755	0.002	99.82	0.100	1.415	1978	16.81	2244
L4	0.0239	1.67	507306	0.002	99.82	0.100	2.037	1978	0.37	2243
L5	0.0239	0.00	507306	0.002	99.82	0.100	2.037	1976	3.38	2240
L6	0.0319	1.67	14374	0.002	2.83	0.003	0.058	1976	0.00	2240
L7	0.0239	0.00	492932	0.002	96.99	0.097	1.979	2035	21.40	2219
L8	0.0239	0.17	492932	0.002	96.99	0.097	1.979	2035	0.05	2219
L9	0.0311	1.67	16487	0.002	3.24	0.003	0.066	2035	0.00	2219
L10	0.0239	0.17	476445	0.002	93.75	0.094	1.913	2225	55.53	2163
L11	0.0239	1.50	476445	0.002	93.75	0.094	1.913	2225	0.30	2163
L12	0.0254	1.17	94274	0.002	18.55	0.019	0.379	2217	0.01	2225

TABLE 3: Calculation results of fluid flow analysis for scenario 2b

Pipe	Friction factor	K factor	Reynolds number	Relative roughness	Mass flow rate	Volumetric flow rate	Velocity	Elevation	Head loss	Hydraulic head
	f	K	Re	rr	ṁ, kg/s	Q, m3/s	V, m/s	Z, m	h_f, m	H, m
L1	0.0229	4.17	422755	0.002	99.82	0.100	1.415	1903	0.43	2281
L2	0.0229	2.00	422755	0.002	99.82	0.100	1.415	1953	20.17	2261
L3	0.0229	0.00	422755	0.002	99.82	0.100	1.415	1978	16.81	2244
L4	0.0250	1.67	126827	0.002	24.96	0.025	0.509	1978	0.02	2244
L5	0.0250	0.00	126827	0.002	24.96	0.025	0.509	1976	0.22	2244
L6	0.0319	1.67	14374	0.002	2.83	0.003	0.058	1976	0.00	2244
L7	0.0252	0.00	112453	0.002	22.13	0.022	0.452	2035	1.17	2242
L8	0.0252	0.17	112453	0.002	22.13	0.022	0.452	2035	0.00	2242
L9	0.0311	1.67	16487	0.002	3.24	0.003	0.066	2035	0.00	2242
L10	0.0254	0.17	95965	0.002	18.88	0.019	0.385	2225	2.39	2240
L11	0.0254	1.50	95965	0.002	18.88	0.019	0.385	2225	0.01	2240
L12	0.0254	1.17	94274	0.002	18.55	0.019	0.379	2217	0.01	2225

TABLE 4: Calculation results of fluid flow analysis for scenario 3a

Pipe	Friction factor	K factor	Reynolds number	Relative roughness	Mass flow rate	Volumetric flow rate	Velocity	Elevation	Head loss	Hydraulic head
	f	K	Re	rr	ṁ, kg/s	Q, m3/s	V, m/s	Z, m	h_f, m	H, m
L1	0.0229	4.17	422755	0.002	99.82	0.100	1.415	1903	0.43	2281
L2	0.0229	2.00	422755	0.002	99.82	0.100	1.415	1953	20.17	2261
L3	0.0229	0.00	422755	0.002	99.82	0.100	1.415	1978	16.81	2244
L4	8.54×10^{31}	1.67	0	0.002	0.00	0.000	0.000	1978	0.00	2244
L5	8.54×10^{31}	0.00	0	0.002	0.00	0.000	0.000	1976	0.00	2244
L6	8.54×10^{31}	1.67	0	0.002	0.00	0.000	0.000	1976	0.00	2244
L7	8.54×10^{31}	0.00	0	0.002	0.00	0.000	0.000	2035	0.00	2242
L8	8.54×10^{31}	0.17	0	0.002	0.00	0.000	0.000	2035	0.00	2242
L9	8.54×10^{31}	1.67	0	0.002	0.00	0.000	0.000	2035	0.00	2242
L10	8.54×10^{31}	0.17	0	0.002	0.00	0.000	0.000	2225	0.00	2240
L11	8.54×10^{31}	1.50	0	0.002	0.00	0.000	0.000	2225	0.00	2240
L12	8.54×10^{31}	1.17	0	0.002	0.00	0.000	0.000	2217	0.00	2225
L13	0.0239	0.17	507306	0.002	99.82	0.100	2.037	2023	28.53	2228
L14	0.0265	0.17	55663	0.002	10.95	0.011	0.224	2023	0.00	2228
L15	0.0265	0.00	55663	0.002	10.95	0.011	0.224	2122	0.19	2227
L16	0.0265	2.00	55663	0.002	10.95	0.011	0.224	2122	0.01	2227
L17	0.0265	1.00	55663	0.002	10.95	0.011	0.224	2193	0.19	2227
L18	0.0265	0.34	55663	0.002	10.95	0.011	0.224	2193	0.00	2227
L19	0.0265	0.34	55663	0.002	10.95	0.011	0.224	2185	0.00	2193
L20	0.0265	1.00	55663	0.002	10.95	0.011	0.224	2185	0.00	2193
L21	0.0283	1.67	30438	0.002	5.99	0.006	0.122	2185	0.00	2193
L22	0.0291	0.17	25224	0.002	4.96	0.005	0.101	2185	0.00	2193
L23	0.0291	0.00	25224	0.002	4.96	0.005	0.101	2108	0.07	2193
L24	0.0291	1.67	25224	0.002	4.96	0.005	0.101	2108	0.00	2193
L25	2.98×10^{16}	0.00	0	0.002	0.00	0.000	0.000	2060	0.00	2193
L26	2.98×10^{16}	2.00	0	0.002	0.00	0.000	0.000	2060	0.00	2193
L27	0.0239	1.17	451643	0.002	88.87	0.089	1.814	2023	0.21	2227
L28	0.0239	0.00	451643	0.002	88.87	0.089	1.814	1939	49.73	2201
L29	0.0239	0.17	451643	0.002	88.87	0.089	1.814	1939	0.04	2201
L30	0.0249	1.67	131900	0.002	25.95	0.026	0.530	1939	0.03	2201
L31	0.0241	0.00	319744	0.002	62.91	0.063	1.284	1937	0.32	2201
L32	0.0241	0.00	319744	0.002	62.91	0.063	1.284	1879	15.80	2195
L33	0.0241	0.17	319744	0.002	62.91	0.063	1.284	1879	0.02	2195
L34	0.0358	1.67	8173	0.002	1.61	0.002	0.033	1879	0.00	2195
L35	0.0241	0.00	311570	0.002	61.31	0.061	1.251	2000	21.96	2187
L36	0.0336	1.67	10992	0.002	2.16	0.002	0.044	2000	0.00	2187
L37	0.0242	2.00	300579	0.002	59.14	0.059	1.207	2000	0.16	2187
L38	0.0254	0.00	375724	0.003	59.14	0.059	1.886	2024	55.02	2168
L39	0.0254	0.67	375724	0.003	59.14	0.059	1.886	2024	0.14	2168
L40	0.0254	4.00	375724	0.003	59.14	0.059	1.886	2095	47.52	2152
L41	0.0254	1.84	375724	0.003	59.14	0.059	1.886	2095	0.36	2152
L42	0.0254	0.34	375724	0.003	59.14	0.059	1.886	2097	0.29	2105
L43	0.0261	1.67	148088	0.003	23.31	0.023	0.743	2097	0.05	2105

TABLE 5: Calculation results of fluid flow analysis for scenario 3b

Pipe	Friction factor	K factor	Reynolds number	Relative roughness	Mass flow rate	Volumetric flow rate	Velocity	Elevation	Head loss	Hydraulic head
	f	K	Re	rr	ṁ, kg/s	Q, m3/s	V, m/s	Z, m	h_f, m	H, m
L1	0.0229	4.17	422755	0.002	99.82	0.100	1.415	1903	0.43	2281
L2	0.0229	2.00	422755	0.002	99.82	0.100	1.415	1953	20.17	2261
L3	0.0229	0.00	422755	0.002	99.82	0.100	1.415	1978	16.81	2261
L4	8.54×10^{31}	1.67	0	0.002	0.00	0.000	0.000	1978	0.00	2261
L5	8.54×10^{31}	0.00	0	0.002	0.00	0.000	0.000	1976	0.00	2261
L6	8.54×10^{31}	1.67	0	0.002	0.00	0.000	0.000	1976	0.00	2261
L7	8.54×10^{31}	0.00	0	0.002	0.00	0.000	0.000	2035	0.00	2261
L8	8.54×10^{31}	0.17	0	0.002	0.00	0.000	0.000	2035	0.00	2261
L9	8.54×10^{31}	1.67	0	0.002	0.00	0.000	0.000	2035	0.00	2261
L10	8.54×10^{31}	0.17	0	0.002	0.00	0.000	0.000	2225	0.00	2261
L11	8.54×10^{31}	1.50	0	0.002	0.00	0.000	0.000	2225	0.00	2261
L12	8.54×10^{31}	1.17	0	0.002	0.00	0.000	0.000	2217	0.00	2225
L13	0.0239	0.17	507306	0.002	99.82	0.100	2.037	2023	28.53	2232
L14	0.0265	0.17	55663	0.002	10.95	0.011	0.224	2023	0.00	2232
L15	0.0265	0.00	55663	0.002	10.95	0.011	0.224	2122	0.19	2232
L16	0.0265	2.00	55663	0.002	10.95	0.011	0.224	2122	0.01	2232
L17	0.0265	1.00	55663	0.002	10.95	0.011	0.224	2193	0.19	2232
L18	0.0265	0.34	55663	0.002	10.95	0.011	0.224	2193	0.00	2232
L19	0.0265	0.34	55663	0.002	10.95	0.011	0.224	2185	0.00	2193
L20	0.0265	1.00	55663	0.002	10.95	0.011	0.224	2185	0.00	2193
L21	0.0283	1.67	30438	0.002	5.99	0.006	0.122	2185	0.00	2193
L22	0.0291	0.17	25224	0.002	4.96	0.005	0.101	2185	0.00	2193
L23	0.0291	0.00	25224	0.002	4.96	0.005	0.101	2108	0.07	2193
L24	0.0291	1.67	25224	0.002	4.96	0.005	0.101	2108	0.00	2193
L25	2.98×10^{16}	0.00	0	0.002	0.00	0.000	0.000	2060	0.00	2193
L26	2.98×10^{16}	2.00	0	0.002	0.00	0.000	0.000	2060	0.00	2193
L27	0.0239	1.17	465559	0.002	91.61	0.092	1.870	2023	0.23	2232
L28	0.0239	0.00	465559	0.002	91.61	0.092	1.870	1939	52.81	2179
L29	0.0239	0.17	465559	0.002	91.61	0.092	1.870	1939	0.05	2179
L30	0.0249	1.67	131900	0.002	25.95	0.026	0.530	1939	0.03	2179
L31	0.0241	0.00	333659	0.002	65.65	0.066	1.340	1937	0.35	2179
L32	0.0241	0.00	333659	0.002	65.65	0.066	1.340	1879	17.19	2162
L33	0.0256	0.17	83415	0.002	16.41	0.016	0.335	1879	0.00	2162
L34	0.0358	1.67	8173	0.002	1.61	0.002	0.033	1879	0.00	2162
L35	0.0258	0.00	75242	0.002	14.80	0.015	0.302	2000	1.37	2160
L36	0.0336	1.67	10992	0.002	2.16	0.002	0.044	2000	0.00	2160
L37	0.0262	2.00	64250	0.002	12.64	0.013	0.258	2000	0.01	2160
L38	0.0269	0.00	80312	0.003	12.64	0.013	0.403	2024	2.66	2157
L39	0.0269	0.67	80312	0.003	12.64	0.013	0.403	2024	0.01	2157
L40	0.0269	4.00	80312	0.003	12.64	0.013	0.403	2095	2.30	2155
L41	0.0269	1.84	80312	0.003	12.64	0.013	0.403	2095	0.02	2155
L42	0.0269	0.34	80312	0.003	12.64	0.013	0.403	2097	0.01	2105
L43	0.0261	1.67	148088	0.003	23.31	0.023	0.743	2097	0.05	2105

Appendix III: List of digital and analogue inputs and outputs for SCADAL

Instrument	Digital input	Analog input	Digital output	Analog output	Alarm
Mains supply					
Status			√		OFF
Automation box power supply			√		OFF
Automation box battery power	√				LOW
Solar charging units		√			
Phase monitoring			√		OFF
Frequency		√			
Voltage		√			
Current		√			
Consumption				√	
Submersible pump					
Status		√			
Speed		√			
Elevated tank					
Water level	√				HH, LL
Standby generator					
Status			√		OFF
ATS Function mode	√				
Fuel Level		√			
Oil level		√			
Battery level		√			
Engine speed		√			
Frequency		√			
Output power		√			
Load factor		√			
Running time		√			
Failure count		√			
Booster pumps					
Status	√				OFF
Function mode	√				
Discharge pressure		√			
Running time		√			
Bearing Temp			√		HIGH
Speed		√			
Vibration			√		HIGH
Maintenance record		√			
Booster pump motors					
VSD				√	
RPM		√			
Winding Temp		√			
Emergency stop	√				ON
Pressure Sensors					
Status		√	√		
Flow meters					
Status		√			
Control valves					
Status (open/closed)	√				
Reservoir tanks					
Water level	√		√		HH, LL
Photocells					
Status	√				OFF
CCTV					
Power supply	√				OFF