Development of a Low-Power Smart Water Meter for Discharges in Indus Basin Irrigation Networks[1]

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Abstract. To improve the sampling frequency of water diversion to distributary canals and to improve equity of distribution and data handling we have developed a smart electronic water meter based on ultrasonic sensors and GPRS modem to frequently record and transmit the water diversion data to a centralized server. The server processes the data to extract useful information for example seasonal cumulative water deliveries and discharge time series. The Wireless Sensor Node (WSN) inspired design is extremely low-power, field deployable and scalable with respect to cost and numbers. This paper, reports the first steps towards practical realization of a smart water grid in the Indus river basin, conceptualized by the authors in previous theoretical studies.

1 Introduction

The Indus River Basin in Pakistan has the world's largest contiguous irrigation network, running over 90,000 Km of watercourses and around 25 million acre irrigated area, the overall irrigation infrastructure accounts for approximately US$ 300 billion. Such a large system cannot be managed with high efficiency without using unprecedented levels of automation and usage of decision support systems [1],[3],[13]. Quite contrary, most of the operation is manual which combined with poor management practices have contributed towards acute problems of water scarcity and distribution inequity. See [2] and [6] for an overview of such problems. Therefore, there is a great need to contribute towards agricultural development in Pakistan through the efficient management of surface water in canal networks to enhance food security, reduce poverty and adapt to uncertainties brought about by climate change.

Future irrigation networks as described by [4] and other leading researchers, represent a prime example of *cyber physical systems* (CPS), i.e. physical infrastructures coupled tightly with distributed networks of sensing, computing and control structures. See [7],[12] and [15] for a discussion on CPS. In the context of Indus river basin, the LUMS affiliated authors have conducted a series of theoretical studies to determine the feasibility of a fully automated CPS, envisioned as a *smart water grid* for Pakistan. See [9] and [11] as examples of such case studies. Encouraged by these studies, the group has come into several partnerships in recent years with government

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and non-government organizations to translate the theory into practical systems. The IWMI affiliated authors of this study have similarly been arguing for such automations in the context of wider governance issues related to participatory irrigation management, enforcement of water rights and accountability.

Figure 1(a): Examples of manual gauge readout settings for *pansal nawisi* by Punjab Irrigation Department in Hakra Branch, Bahawalnagar. The water levels are converted to flow using a *rating curve* derived from channel geometry.

This paper focuses on automating the hourly-to-daily measurement of canal water discharges (*pinsal nawisi*) in the network (See Figure 1(a)). This is one of the most critical requirements of automation in the Indus basin due to the following reasons. First, the scale of such measurements, even at a local canal command is very large. The scale enormity when combined with the manual nature of daily flow measurements poses obvious logistical problems in data collection, dissemination and interpretation. Second, the fidelity of manual measurements is questionable due to deteriorating infrastructure and human factors in gauge reading. Third, there is a need to give near real-time picture to basin managers (the provincial irrigation departments, area water boards, farmer organizations) to perform situation assessment and planning, resolve conflicts, ensure transparency and maintain equity amongst users. The manual operation allows no quicker than daily updates. Fourth, automation can enable other operations and services that are not yet feasible such as volumetric metering, demand based delivery, detection of leakages and non-technical losses, structural health monitoring, re-planning under changing scenarios etc. Lastly, automated flow measurements will be the first step towards installing even higher levels of automation such as controlled gates and other active structures.

Keeping in mind these motivations, we have developed a fully functional, field deployable, stand alone and weather proof canal flow measurement system. The design is inspired from wireless sensor network (WSN) technology and most suitable for installation on branch canals and distributaries at irrigation canal networks of the Indus river basin. At the time of writing, 24 nodes are being installed by the authors in Bahawalnagar, Punjab in the Hakra canal command area off the River Sutlej. A full analysis of the networked sensing system with data analysis and interpretation will be reported after testing the system for the upcoming Rabi and Kharif seasons. This paper mostly reports the development of electronics for the wireless sensor node, brief descriptions of the software backbone and supporting civil infrastructure.

A high level diagram of the proposed automation is shown in Figure 1(b). A *stilling well* is constructed in close proximity to the canal. At the top of the stilling well is installed a battery powered wireless sensor node that samples the level of water using the principle of ultrasonic distance measurement. The measured water level is time-stamped and then transmitted to a central office at regular intervals using

GPRS/GSM based services. Here, a computer server receives the raw water level data, calibrate them, convert them into discharge (in cubic feet per second, cfs) using a predefined rating curve and then file them in a database. Subsequently, the data is made available for dissemination in the form of graphs, time series and text using various standard web and mobile based services.

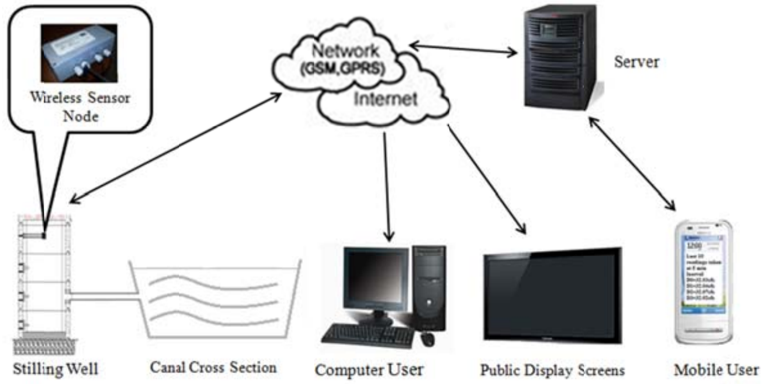


Figure 1(b): System data flow diagram.

The contributions of this article are as follows. Firstly, we achieve extremely low-power battery powered design providing a practical compromise between two extremes: A direct AC mains powered system which is infeasible at remote locations and a solar-powered system which is difficult to secure physically and adds significantly to the cost. Our design guarantees a long-life completely battery powered system only requiring low-cost annual battery replacement. Secondly, we successfully demonstrated usage of maintenance-free ultrasound based sensing instead of conventional mechanical floats or pressure transducers. We have selected extremely accurate, weather proof and narrow beam sensors to overcome installation difficulties within a stilling well. We have taken care to compensate for changes in speed of sound in weather exposed conditions. Thirdly, the unit is field deployable in that we have packaged, tested and calibrated the sensor for all extreme conditions. Though briefly touched in this article, real-world deployment challenges have been systematically tackled in software and civil infrastructure, making our system much more than a laboratory prototype.

2 Wireless Sensor Node Design

In this section, we will mainly focus on Wireless Sensor Node (WSN) (See figure 2(b)). It consists of an ultrasonic range finder as the main sensor for measuring water level and flow. It also has capabilities to interface to auxiliary sensors such as a temperature sensor immersed into the water to calculate its temperature. In the future, we are planning to add other sensors to measure the turbidity and salinity of water. The system is operated with 3.6V, 14000mAH batteries with surge current capabilities. It also has a temperature sensor immersed into the water and calculates the temperature of the water. The WSN calculates the water level in the canal and sends the data to the server through GPRS/GSM at a predefined but configurable interval. Please refer to the block diagram shown in Figure 2(a). The details of each important component are given below.

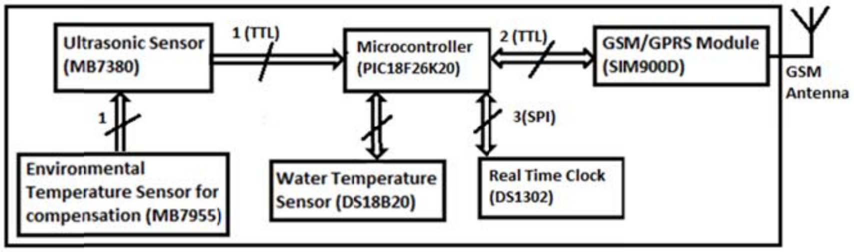


Figure 2(a): Block diagram of Wireless Sensor Node.

Figure 2(b): Photographs of the developed Smart Water Meter.

2.1 Ultra Sonic Sensor

The Maxbotix MB7380 Ultra Sonic Sensor [8] is a cost-effective solution for applications where precision range-finding, low voltage operation, space saving, low-cost and IP67 weather resistance rating is needed. Each time the sensor takes a range reading, it calibrates itself. The sensor then uses this data to range objects. This sensor line features 1-mm resolution, target-size and operating-voltage compensation for improved accuracy and internal speed-of-sound temperature compensation. To correct power related noise issues we added a 100uF capacitor at the sensor between the V+ and GND pins. The speed of sound in air increases about 0.6 meters per second, per degree centigrade. If the temperature, humidity, or applied voltage changes during sensor operation, the sensor will apply necessary temperature and voltage compensations. Although the MB7380 has an internal temperature sensor; for best accuracy, we used the optional external temperature sensor MB7955 which is detected automatically and compensations are applied for temperature variations in acoustic ranging path.

MB7380 sensor has a calibrated beam pattern. Beam pattern is a 2D representation of the detection area of the sensor. The beam pattern is actually shaped like a 3D cone. Beam pattern is used for a specific target at any given distance to calculate the beam angle for that target at the specific distance. Generally, for shorter distances we need narrower beam angle. Our expected distance to be measured is 1-2 meters. So the cone does not interfere with the walls of the stilling well.

2.2 Microcontroller

Microchip's PIC18F26K20 flash microcontroller with extreme low power (XLP) is used in our embedded design. It is featured with up to 64 kbytes of linear program memory addressing, 1024 bytes of EEPROM data and up to 3936 bytes linear data memory addressing. Each data sample is time stamped which makes it 8 bytes long. We save the most recent 110 records in non-volatile EEPROM and the remaining 500 records in the volatile SRAM. We take the sample after 30 minutes intervals, so we have a total of 48 records daily. Thus, with this much memory we can save 12 days data in case of GPRS/GSM transmission problems.

2.3 GPRS/GSM Module

We used SIMCOM SIM900D Version 1.03 for GPRS/GSM transactions. SIM900D [14] is a quad-band GPRS/GSM engine that works on GSM frequencies. The module is integrated with the TCP/IP protocol; extended TCP/IP AT commands are developed for reliable data transfer applications. The module has GPRS data and transfer of 42.8 kbps. The manufacturer claims the module to be working from 3.1V to 4.8V, but practically we found that the module is not getting itself registered with the network below 3.4V.

2.4 Extreme Low Power Design

As our application require prolonged standalone operation. We are planning our system to last for up to 5 to 10 years, while running from a single battery. To enable applications like these, we selected products with Microchip's nanoWatt XLP Technology, offering the lowest currents for run and sleep. We worked to design the system such that it does not require any maintenance over the lifespan of the application. The designed hardware is spending 98% of its time in sleep. We are powering the circuitry with 3.6V, 14,000mAH Lithium Thionyl Chloride Batteries. Figure 2.4(a) shows typical discharge characteristics at various current levels. A 100µF low ESR tantalum capacitor is placed across the battery, which causes the current spike of 1-2 Amperes (few milliseconds wide) during transmission burst to smooth down to 200-300mA (2 to 3 seconds wide). We cannot run it with normal Lithium Ion Cells, because they have lower surge currents.

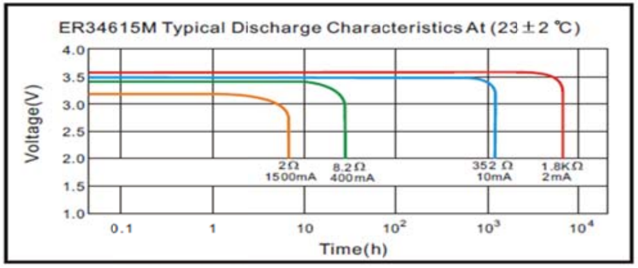


Figure 2.4(a): Battery Discharge Characteristics[5]

GSM/GPRS transactions consume most of the battery power. We turn the GSM module off after every transaction which takes 30uA at shutdown mode. Also the sensors are turned on only at sampling time. In this section, we will highlight the various extreme low-power control features of an embedded microcontroller. The microcontroller might have nothing else to do until the peripheral collects a certain amount of samples. Therefore, the microcontroller enters "sleep" in between each data sample. We evaluated the time×current elements of the energy equation and determined best option is to operate the MCU for longer at low frequency, because the MCU is in running mode during transaction for most of the time. During that time the GSM needs some delays to get registered with the network.

Figure 2.4(c) shows current consumed for a single GPRS transaction. It would be worth mentioning here that currents consumed during GPRS transactions, varies greatly with RF signal strength. At low signal level WSN will consume more current during the transmission burst (See Figure 2.4(d)). While the GSM module is shut down for about one hour it takes 1-2 mA current. The sensors are on for only 2 seconds and take not more than 2mA current, so we are ignoring those currents and only consider currents consumed by GSM part of WSN. The graph specifies that the GSM module turns on at 7th second and after doing the transaction turns off after 100 seconds. At 16th second WSN registers itself with the GSM network. For the next 40 seconds it waits for an incoming text message. At 65th second the system brings up wireless connection with GPRS. After 74 seconds, WSN starts up a TCP connection. It makes two tries to get connected. At 85th second it sends the data successfully. It waits for an incoming data from the server and then shuts down the GSM part. Currents consumed by the microcontroller PIC18F26K20 (at 2.9V) in various modes boast sleep currents below 100 nA, Watch-dog Timer down to 1μA and Run-currents down to 100 μA/MHz. This essentially means that the GSM module should be the main focus of our design from the point of view of power consumption.

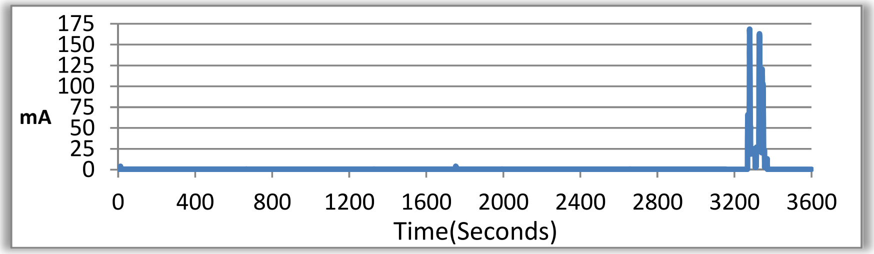


Figure 2.4(b): Current vs. time plot for one transmission cycle (~one hour).

At sleep mode, WSN consumes 0.5-0.6 mA of current. Let us integrate the curve shown in figure 2.4 (b) for an hour interval. We are using two batteries in parallel, so we have a total of 28AH charge.

$$q(T) = \int_0^T i(t)dt. \approx \sum_{n=0}^{3600} i(n)\,.\Delta t = 6077mC = 6.077Coulomb.$$

Thus expected battery life = (28*60*60)/6.077=16,587Hours= 691 days. Please find the below results for burst transmission during various signal strength. The signal strength was varied by placing conductor materials around WSN. In each of the below results the current samples are taken at 0.5 seconds interval. The below results show that at strong signal strength, WSN consumes low current during the transmission burst.

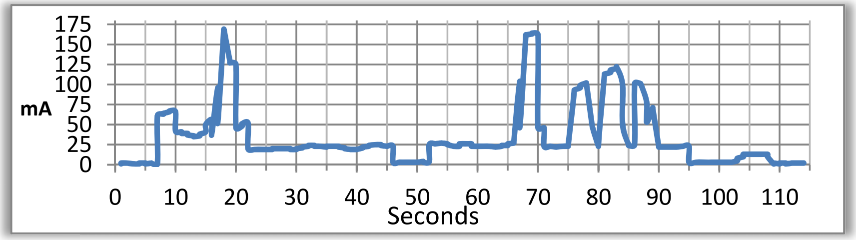


Figure 2.4(c): Current vs. time plot for one transmission burst.

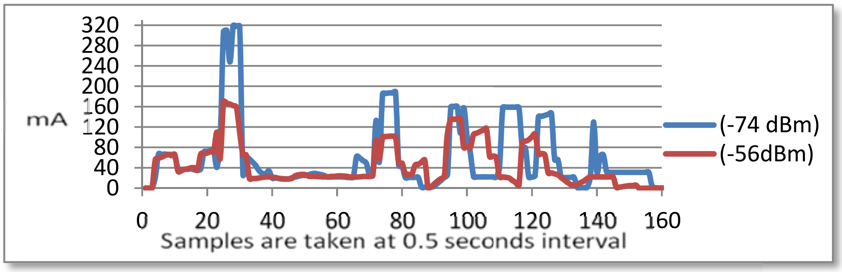


Figure 2.4(d): Currents consumed at -74dBm and -56dBm signal levels

2.5 Hardware Enclosure

The electronic Circuitry is protected against the environmental factors with IP67 (dust tight and protected against immersion) Ingress Protection standards die cast Aluminum Box of 180mmx80mmx60mm. Die cast Aluminum is selected because it is not corroded even if immersed in water. It has the capability to withstand harsh environmental conditions. The moisture and dust cannot enter inside the electronic circuitry. If the device is immersed into the water in case of flooding, the electronics will be protected. As GSM/GPRS signals do not work properly inside a metal housing. Four IP67 standard connectors are provided for antenna, two external temperature sensors (environment and water) and turbidity sensor in the future. The connectors are made of ABS plastic and are corrosion free with a special seal filled inside.

RoHS (Restriction of Hazardous Substances) Directive essentially states that electrical and electronic products put on the market shall not contain Lead, Cadmium, Mercury, Hexavalent Chromium, Poly brominated biphenyls and Poly brominated diphenylethers. All components and packing materials used in the design fulfill the requirement of RoHS.

2.6 Real Time Clock

Implementation of Real Time Clock (RTC) was necessary for Smart Water Meter to put a time stamp while take the reading. Dallas DS1302 was selected for its ease of availability and reliability. It consumes less than 500nA in battery backup and is operated with separate 3.3V 40mAH cell.

Thus, RTC cell backup time= (40mAH/500nA=80,000 hours=9 years). The RTC time can be checked and reset remotely from server side. RTC counts seconds, minutes, hours, date of the month, month, day of the week, and year with leap-year compensation valid up to 2100. It has three wire SPI interface and 8-pin SOIC package is used in our embedded design.

2.7 Design Problems and their Solutions

Since Wireless Sensor Node is likely to be installed at locations with limited GSM/GPRS coverage. It is provided with an external antenna mounted at highest point inside the Stilling well. The device sends data on GPRS and in case of low RF signals it will initiate and SMS to the server, as SMS requires less signal strength.

Being operated from 3.6V battery, we are quite close to the minimum voltage ratings of SIM900D i.e., 3.4V.The copper traces from battery to the GSM module are 3.2 mm wide in the PCB design to reduce the voltage drop for situations, where the circuit consumes high currents like 1-2A during transmission burst. Note that $Resistance = (Resistivity * Length\ of\ wire)/Area$. Also, wide tracks sink heat to the environment instantly. Narrow tracks result in high energy dissipation, which further increases the resistance in the absence of heat sink. Thus for best performance during transmission bursts we need to reduce the length of wire as well as widen copper traces on PCB from battery terminal to the GSM module. To appreciate the importance of this, note that SIM900D does not work below 3.4V. At high currents the voltage across the battery terminal decreases due to the internal resistance of the battery as shown in the Figure 2.4(a) above. If the resistance from battery terminal to the GSM module is 0.3 Ohm and we have a transmission burst of say 1.0A, then voltage drop across the wire, $V = IR = 1 * .3 = 0.3V$.So voltage at SIM900D will be 3.6V-0.3V=3.3V and will be powered down due to these drops.

The GSM part of WSN is protected against electro static discharge (ESD) with SMF05C, a 5 line transient voltage suppressor array, having a peak power dissipation of 100W (8 x 20 µS waveform) [10]. It has ESD rating of class 3B (exceeding 8 kV) per human body model and Class C (exceeding 400 V) per machine Model. Human body interaction with the circuitry is possible during SIM replacement. During assembling, we have ensured proper handling against electrostatic discharge. Anti-static Wrist Straps, are used to prevent ESD by safely grounding the technician working with electronic equipment. It consists of a band of fabric with fine conductive fibers woven into it.

2.8 Wireless Sensor Node Budget

The cost breakdown of the wireless sensor node has been given below from current list prices. Note, mainly that the absence of the solar panels have significantly reduced the unit price. Moreover, the maintenance is only annual replacement of batteries. We believe that this (low) cost has made the deployment of these units feasible at practical scales of deployment. See table 2.8 below for budgeting details.

S.No.	ITEM	PRICE (USD)
1	MB7380 with temperature Sensor	114
2	SIM900D	20
3	Batteries	16
4	Die cast Aluminum Enclosure	26
5	Miscellaneous parts	14
	Total	$190 / PKR. 19,000

Table 2.8: WSN Budget

3 Software Design

3.1 Working

The WSNs installed at different canals send Water level readings on server. After the server receives the strings of data, it processes the data string and extracts the required parameters i.e., date, time, temperature, and level readings. These readings are then stored in the database with their respective date and time, which are then used to compute the seasonal cumulative water deliveries and discharge in average cubic feet per second (cfs). The data is displayed as CSV files with graphs depicting seasonal and yearly variations on a website. The whole software design consists of Server and Client side designs.

3.2 Server-Side Software design

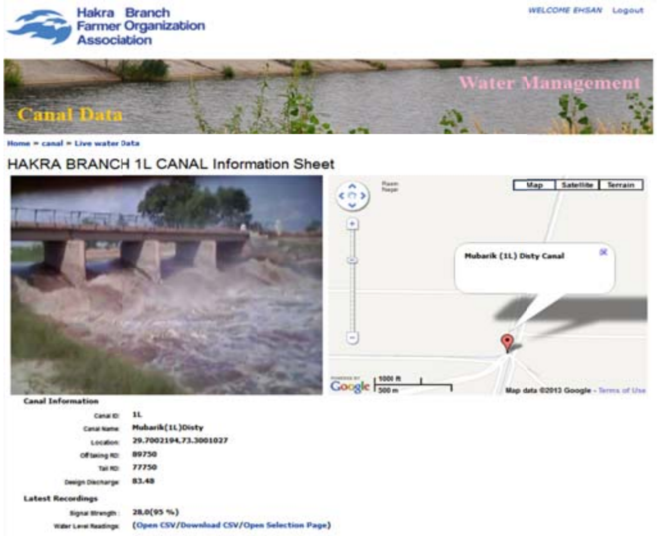
The Server side design comprises of Web Server, Server-side script, Operating System and a Database for storing the required data. Our choice for Server is the Microsoft Internet Information Services (IIS). We are using Microsoft server-side Web application framework (ASP.NET). For Relational Database Management System (RDBMS), we are using Microsoft SQL in web applications. The server is running on the Microsoft Window Server 2008 R2 Operating System.

The important aspects of the software design include:

1. **Security.** Common types of software flaws that lead to vulnerabilities include: SQL injection, Cross-site scripting and some others. MSSQL and Asp.net provides sufficient extensions and options to avoid such type of vulnerabilities.
2. **Replication and Back Up.** Replication of MSSQL database can be a solution to various problems like Scale-out problems, Data Security, Analytics, Long-distance data distribution and the Backup taken from slaves rather than from master, which result in no load on the production Master machine for this task. If the Slave node is down, this is not a problem since replication is performed asynchronously and when the Slave Node is up and Live after a downtime, it continues replication from the point it has been paused.

3.3 Client-Side Software Design

The design of the website is quite user-friendly and it provides users with an ease to check out the canal readings with the seasonal water discharge per unit area for different canals with other parameters like turbidity and temperature (See figure 3.3(a)). The website is designed using the Hypertext markup language (HTML), Cascaded style sheet (CSS) for displaying and styling web pages. JavaScript, a commonly implemented as a part of a web browser, is used to create enhanced user interfaces and addition of some other features like Google map for showing the location of all the canals, drop down menu lists etc. Comma Separated Values (CSV) files is used to display the level readings. CSV files are practical for importing level readings into a spreadsheet programs like MS Excel. Figure 3.3(b) shows a plot of the received readings from a test site (See Figure 4.1) over 19 hours, sampled at 10 minutes and transmitted from WSN at an interval of 1 hour.



HAKRA BRANCH 1L CANAL Information Sheet

Canal Information

Canal ID: 1L
Canal Name: Mubarik(1L)Disty
Location: 29.7002194,73.3001027
Offtaking RD: 89750
Tail RD: 77750
Design Discharge: 83.48

Latest Recordings

Signal Strength: 28.0(95 %)
Water Level Readings: (Open CSV/Download CSV/Open Selection Page)

Figure 3.3(a): Website User Interface for accessing the canal Information

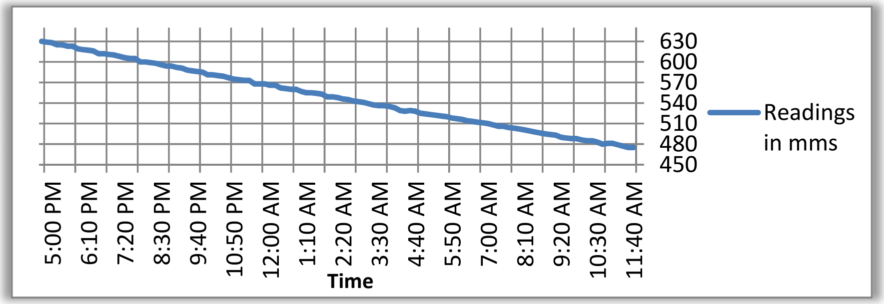


Figure 3.3(b): Water level measurements from stilling well at a test site with a small controlled leakage for 19 hours

4 Stilling Well and Civil Infrastructure

To protect WSN against harsh outdoor environment and to provide a relatively stable water surface to be read by the ultrasonic sensor we have designed the infrastructure to achieve these objectives. In hydraulic engineering this type of structure is called a stilling well (See figure 4.1) which necessarily consists a concrete lined box installed on either side of a channel and is hydraulically connected to the channel through a conduit. A reinforced concrete wall is composed of a square steel grid immersed in a dielectric slab (concrete). This structure offers a resonant behavior when the signal reaches the wall and, due to this phenomenon, an FSS (Frequency Selective Surface) reflector appears. FSS reflector may act as band stop filter for GSM frequencies. Thus, steel reinforcement is avoided in the civil structure.

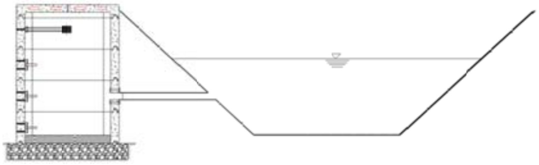


Figure 4.1(a): Cross section of stilling well across canal.

Figure 4.1(b): Instrument installations, alignment and leveling. (c): Installed Unit

While designing the stilling well, we considered several important matters. Pre-cast segments were used in construction to achieve uniformity and cost effectiveness. The stilling well is wide enough that it could not interfere with the cone of ultrasonic signal and to enable personal access to its base for annual cleaning. An arrangement has been made for leveling the WSN; with nuts on the side wall we can align the instrument properly. WSN is installed on a metal frame. The stilling well is assembled strong enough to bear the harsh out door environment; therefore it is constructed of high strength PCC concrete. The structure is constructed in segments of 1 foot to facilitate handling and transportation. The segments are joined together with high strength 2-part thixotropic epoxy adhesive to eliminate seepage and to provide significant strength while in tension from lateral force.

5 Conclusions

A low-power water discharge measurement has been developed which is suitable, affordable and ready for wide-scale deployments in irrigation canal networks of the

Indus river basin. GSM/GPRS based transmission is chosen as a suitable technology for communication whereas ultrasound based ranging is found suitable for sensing water levels. Power requirements, packaging, installation and system integration issues have been addressed and resolved.

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