IoT Enabled Analysis of Irrigation Rosters in the Indus Basin Irrigation System

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Director, Center for Water Informatics & Technology (WIT)
Lahore University of Management Sciences (LUMS), Pakistan

http://old.lums.edu.pk/wit/

12th International Conference on Hydroinformatics (HIC 2016)
Songdo ConvensiA, Incheon Korea, August 21st -26th, 2016
Cyber Physical Networks & Systems (CYPHYNETS) Lab

**BS.** (Electrical Engineering)

**PhD / MS.** (EE, Math) 2005. Georgia Tech

**Postdocs.** (robotics) Univ. Penn, McGill

Lab Est. 2008.

**Areas**
- Agricultural Automation & Robotics
- Water systems & Hydro-informatics
- Control engineering

**Highlights (2010-2015)**
- Smart Canal Grid Installations in Punjab
- Collaborations with Govt, Industry, Institutes
- Scholarly output in diverse areas

http://cyphynets.lums.edu.pk/
Established January 2016
International advisory board
Faculty Associates across schools
Outreach – conferences, workshops, trainings

Themes
Hydro-informatics, Precision Agriculture
Water Economics, Integrated Systems analysis
Water Science & Technologies

Smart Water Grid Work Featured recently on MIT news
River Basin Management: A complex system of systems

Water

Salt

Silt

Physical Complexity

Center for Water Informatics & Technology
LUMS, Pakistan
River Basin Management: A complex system of systems

A complex historical and cultural process in continuous evolution.

Center for Water Informatics & Technology
LUMS, Pakistan
Managing the World’s Largest Contiguous Irrigation Network

90,000 Km of watercourses
3 reservoirs, 23 barrages
45 canal commands
36 million acre irrigated area

Ref. Muhammad. Managing River Basins with Thinking Machines. 21CW. 2016

Center for Water Informatics & Technology
LUMS, Pakistan
Smarts: Can Informatics Aid Hydraulics?

Key Cybernetics Technologies
- Wireless Sensor Networks
- Internet of Things
- Cyber Physical Systems

Ref. Muhammad. Managing River Basins with Thinking Machines. 21CW. 2016
A Networked Smart Water Grid

Cyber Physical Systems / Internet of Things perspectives

• Physical elements: rivers, watercourses, barrages, weirs, gates, pumps
• Cyber elements: sensors, controllers, communication, services

Ref. Tariq, Nasir, Muhammad. ICCPS 2014
Nasir, Muhammad. IFAC WC 2011, IFAC WC 2014
<table>
<thead>
<tr>
<th>Requirements on tackling</th>
<th>translate to cybernetics (ICT) solutions in</th>
</tr>
</thead>
<tbody>
<tr>
<td>rapid changes</td>
<td>real-time ubiquitous sensing and data collection systems.</td>
</tr>
<tr>
<td>large-scale uncertainties</td>
<td>analysis of large data sets, models for complex systems.</td>
</tr>
<tr>
<td>institutional reforms</td>
<td>new architectures for decision support.</td>
</tr>
<tr>
<td>enforcement of entitlements</td>
<td>monitoring and control technologies.</td>
</tr>
<tr>
<td>accountability and conflict resolution</td>
<td>data preservation and dissemination.</td>
</tr>
</tbody>
</table>
What type of problems can be solved?

- Increase of distribution efficiency
- Demand based delivery
- Control of nontechnical losses
  - Detection of Leak or unauthorized takeoff
  - Detection of unauthorized dumps
- System health monitoring
- Flood/breach security
- Real-time scheduling and planning
- Improvement and enforcement of water rights
Canal Water Accounting (Current PMIU System)

System Architecture (above). Field installations (below).

Project Site: 17 Distributaries in Bahawalnagar.

<table>
<thead>
<tr>
<th>Canal</th>
<th>Day</th>
<th>Time and Date</th>
<th>Depth of Flow (ft)</th>
<th>Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahu Shah Distributary</td>
<td>8S</td>
<td>05:40 PM 22/04/2014</td>
<td>1.9</td>
<td>8.05</td>
</tr>
<tr>
<td>Mohar Distributary</td>
<td>1L</td>
<td>02:40 PM 22/04/2014</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mianwala Distributary</td>
<td>2L</td>
<td>06:00 PM 22/04/2014</td>
<td>1.76</td>
<td>21.06</td>
</tr>
<tr>
<td>Malik Distributary</td>
<td>3L</td>
<td>05:50 PM 22/04/2014</td>
<td>2.61</td>
<td>12.17</td>
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<td>17.27</td>
</tr>
<tr>
<td>Dunga Buza Distributary</td>
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<td>3.63</td>
<td>356.64</td>
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<td>Harmenabad Distributary</td>
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<td>06:10 PM 22/04/2014</td>
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</tr>
<tr>
<td>Bhagwan Distributary</td>
<td>5R</td>
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<td>3.49</td>
<td>55.48</td>
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<tr>
<td>Humnum Distributary</td>
<td>6R</td>
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<td>Khichwala Distributary</td>
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<td>4.39</td>
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<tr>
<td>Josar Distributary</td>
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<td>06:00 PM 22/04/2014</td>
<td>2.42</td>
<td>41.65</td>
</tr>
<tr>
<td>Saridawala Distributary</td>
<td>9R</td>
<td>06:00 PM 22/04/2014</td>
<td>5.27</td>
<td>386.48</td>
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<tr>
<td>Hakra Right Distributary</td>
<td>HR</td>
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<td>190.2</td>
</tr>
<tr>
<td>Hakra Left Distributary</td>
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<tr>
<td>Flood Channel Distributary</td>
<td>FC</td>
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<td>2.74</td>
<td>91.6</td>
</tr>
</tbody>
</table>

Laboratory for Cyber Physical Networks & Systems
Dept. of Electrical Engineering, LUMS
Real-time Situation Summary

<table>
<thead>
<tr>
<th>Canal</th>
<th>Day</th>
<th>Time</th>
<th>Date</th>
<th>Depth of flow (ft)</th>
<th>Discharge (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baku Shah Distributary</td>
<td>BS</td>
<td>Tue</td>
<td>05:40 PM</td>
<td>22/04/2014</td>
<td>1.9</td>
</tr>
<tr>
<td>Mubarik Distributary</td>
<td>1L</td>
<td>Tue</td>
<td>03:40 PM</td>
<td>22/04/2014</td>
<td>0</td>
</tr>
<tr>
<td>Mianwala Distributary</td>
<td>2L</td>
<td>Tue</td>
<td>06:00 PM</td>
<td>22/04/2014</td>
<td>1.76</td>
</tr>
<tr>
<td>Malkir Distributary</td>
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<td>22/04/2014</td>
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<tr>
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<td>05:30 PM</td>
<td>22/04/2014</td>
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<tr>
<td>Sundar Distributary</td>
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<td>Tue</td>
<td>06:00 PM</td>
<td>22/04/2014</td>
<td>1.62</td>
</tr>
<tr>
<td>Dunga Bunga Distributary</td>
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<td>Tue</td>
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<td>Khatan Distributary</td>
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<td>22/04/2014</td>
<td>3.03</td>
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<tr>
<td>Haroonabad Distributary</td>
<td>4R</td>
<td>Tue</td>
<td>06:10 PM</td>
<td>22/04/2014</td>
<td>0</td>
</tr>
<tr>
<td>Bhagwan Distributary</td>
<td>5R</td>
<td>Tue</td>
<td>05:20 PM</td>
<td>22/04/2014</td>
<td>3.49</td>
</tr>
<tr>
<td>Mamun Distributary</td>
<td>6R</td>
<td>Tue</td>
<td>05:40 PM</td>
<td>22/04/2014</td>
<td>5.23</td>
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<tr>
<td>Khichiwal Distributary</td>
<td>7R</td>
<td>Tue</td>
<td>06:00 PM</td>
<td>22/04/2014</td>
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<tr>
<td>Josar Distributary</td>
<td>8R</td>
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<td>06:00 PM</td>
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<td>2.42</td>
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<tr>
<td>Sardrewala Distributary</td>
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<td>Tue</td>
<td>06:00 PM</td>
<td>22/04/2014</td>
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</tr>
<tr>
<td>Hakra Right Distributary</td>
<td>HR</td>
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<td>Flood Channel Distributary</td>
<td>FC</td>
<td>Tue</td>
<td>05:20 PM</td>
<td>22/04/2014</td>
<td>2.74</td>
</tr>
</tbody>
</table>
Year Long Monitoring in Hakra Br. Canal Command (2014)

Refs. Ahmad, Muhammad et al. IECON 2014, WSN4DC 2013

Legend
- Discharge (cfs) - Canal in 1st Priority
- Discharge (cfs) - Canal in 2nd Priority
- Discharge (cfs) - Canal in 3rd Priority
- Design Discharge (cfs)
System Diagram

Wireless sensor node

Server

GSM/GPRS Network

Public display

Computer user

Mobile user

Sea level

$e_i$

$h = e_i - e_b - d - s$

Water level in the canal

$Q(h) = Kh^{5/3}$

Refs. Ahmad, Muhammad et al. IECON 2014, WSN4DC 2013

Center for Water Informatics & Technology
LUMS, Pakistan
Instruments deployed at different sites
Irrigation Rosters – Warabandi

Warabandi Institute – established during British colonial rule.

Water rationing mechanism.

Irrigation rosters issued by Punjab Irrigation Department to relevant field offices at the start of each cropping season

Irrigation Rosters for Kharif 2014 cropping season
Interpretation of Warabandi

- Distributaries in Hakra Branch are divided into three groups A, B and C which are further divided into sub groups.
- Tables 1 shows the sub groups and distributaries in those sub groups.
- Table 2 shows head names and rotation time at those heads.

### Table 1. Sub groups

<table>
<thead>
<tr>
<th>Sub group</th>
<th>Distributaries in the sub group</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>HR, HL</td>
</tr>
<tr>
<td>A2</td>
<td>4R, 1L</td>
</tr>
<tr>
<td>B1</td>
<td>BS, 1R, 2R, 3R</td>
</tr>
<tr>
<td>B2</td>
<td>5R, 2L, 7R, 3L, 4L, 8R, FC</td>
</tr>
<tr>
<td>C1</td>
<td>6R</td>
</tr>
<tr>
<td>C2</td>
<td>9R</td>
</tr>
</tbody>
</table>

### Table 2. Rotation time at distributary heads

<table>
<thead>
<tr>
<th>Heads name</th>
<th>Rotation time</th>
<th>Distributaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>GA</td>
<td>05:00 AM</td>
<td>BS, 1R, 2R, 3R, 4R, 1L</td>
</tr>
<tr>
<td>6R</td>
<td>10:00 AM</td>
<td>5R, 6R, 2L</td>
</tr>
<tr>
<td>7R</td>
<td>12:00 PM</td>
<td>7R, 3L</td>
</tr>
<tr>
<td>8R</td>
<td>04:00 PM</td>
<td>8R, 4L</td>
</tr>
<tr>
<td>9R</td>
<td>04:00 PM</td>
<td>9R</td>
</tr>
<tr>
<td>TH</td>
<td>07:00 PM</td>
<td>HR, HL, FC</td>
</tr>
</tbody>
</table>
Interpretation of Warabandi

- Table 3 below is an interpretation of irrigation rosters (warabandi) issued by the concerned government department for the first 9 weeks of Kharif (16 April till 14 October) cropping season of 2014.
- For the cropping season Rabi (15 October till 15 April), we have similar warabandi schedule each year.

![Table 3. An interpretation of warabandi schedule issued by Punjab Irrigation Department for first nine weeks of Kharif 2014.](image)
Analysis of *Warabandi (Irrigation Rosters)*

- Irrigation rosters for distributaries in Hakra Branch are overlaid on measurements as color codes in the plots on the next three slides for group A, B and C.
- The designed discharge for each distributary is represented by a red horizontal line.
- A grid on horizontal axis represents one week time span.
- Distributaries in a group for a particular week are either in the first (green color), second (blue color) or third (red color) priority according to the annual irrigation roster issued by the irrigation department.
- If a group is in the first priority for a week, all distributaries in this group get water. If still more water is available, it is provided to the distributaries with second and then third priority for that week.
Warabandi for group A for the year 2014-2015.
Warabandi for group B.

Center for Water Informatics & Technology, LUMS, Pakistan
Warabandi for group C for the year 2014-2015.
Water delivered per acre to 17 distributary canals in Hakra Branch (sequenced in decreasing order of design discharge from left to right) for the cropping season Kharif 2014 (15th April 2014 till 15th October 2014).
Conclusions – Talk 1

- Smart water metering with high sampling / transmission frequencies and backend services can aid in equitable distribution of water resources amongst stakeholders and improve management practices.
- Data collection can lead to deeper network level analysis and provide insights at new temporal scales.
- There is (small) operational inequity in inter-distributary deliveries considering only larger distributaries.
- The deployment also validates the potential of large scale deployment of smart water metering for surface water management in the Indus basin.
- The major concerns like cost and scalability could be resolved with the proposed solution.
A Smart Metering Approach towards Measuring Flows in Small Irrigation Outlets

Waqas Riaz, Zahoor Ahmad, **Abubakr Muhammad**

*Associate Professor of Electrical Engineering, SBASSE
Director, Center for Water Informatics & Technology (WIT)
Lahore University of Management Sciences (LUMS), Pakistan

http://old.lums.edu.pk/wit/

12th International Conference on Hydroinformatics (HIC 2016)
Songdo ConvensiA, Incheon Korea, August 21st -26th, 2016
Indus Basin Irrigation Hierarchy (Recalled)

Center for Water Informatics & Technology
LUMS, Pakistan

Ref. Absar, Gardezi, Muhammad, Shah. DPRC, 2011
Drawbacks of manual monitoring method

- Human error while taking reading
- Discharge computation error while using hydraulic relations
- Chances of corruption
- Water theft
- In-efficient data collection system for strategy planning
- Requires lot of human resource, time and movability for taking reading
Flow measurement in open channels

- Timed Gravimetric method, Tracer-Dilution method, Area-Velocity method, Manning’s Equation and by the use of Hydraulic Structures [8,9].

- Timed Gravimetric method and Tracer-Dilution method are usually practiced for instantaneous measurement of flow rate. Whereas, Area-Velocity method, Manning’s Equation and Hydraulic structure can be used both for instantaneous and continuous flow measurement.

- Hydraulic structure method is found most appropriate for flow measurement at outlet level because:
  - It offers most accurate measurement (+/- 10%) and requires least number of parameters to be required for flow measurement. Only upstream head is required to be measured for discharge computation in free-flow state [8,9].
  - Hydraulic structure can be designed and manufactured in many materials like steel, wood, reinforced plastic, glass and concrete etc. This enables them to be cost flexible.
Flow measurement in open channels

- Long throat flume/broad crested weir is being chosen as flow measurement primary structure as they offer:
  - High Modular Limit (ML), therefore 0.7-0.95.
  - Flume and weirs are computer amenable which makes them easy to design using open source software like WinFlume.
  - Long throat flume/broad crested weirs are simple in design.
  - Requires less skills to construct and operate flume structure.
  - Less costly
Proposed smart water monitoring system for small irrigation water courses

- Hydraulic structure technique was chosen to measure flow rate as they are less costly. A long throated flume/broad crested weir is used as a primary device for flow measurement because of their high submergence ratio (0.7-0.9).

- Whereas, our own in-lab manufactured ultrasonic based low power smart water meter was used as secondary device for head measurement.
Proposed smart water monitoring system for small irrigation water courses

- Long throat flume is designed and deployed in an open channel water course upon which wireless sensor node (WSN) are mounted.

- Two ultrasonic sensors measure empty space range $r_1, r_2$ above water level, which are than converted into depths of water above the crest level of flume $h_1, h_2$ using Eq. 2.
Proposed smart water monitoring system for small irrigation water courses

Following is the system architecture for data recording and dissemination:
System Highlights

- Ultrasonic sensors can measure depth from 30cm to 5m with an accuracy of ± 1 mm. [10]
- System is operated with 3.6v, 14 AH battery with surge current capability which can run meter up to 1 year due to its low-power design.
- In the absence of GSM/GPRS network, meter can store up to 510 records and in the absence of power can retain up to 110 records [11].
- Two ultrasonic sensors can be connected.
- Send data recorded to server via GSM module using GPRS mode at a predefined but configurable interval.
- IP67 weather resistant rated.
- State estimation of flume structure, therefore, free flow or submerged.
- Less head loss is required for flow measurement
Design details of the smart water metering test unit deployed at LUMS

- A long throat flume was designed and deployed for flow measurement in a storm water drain channel in LUMS.

- The flume was designed using an open source windows based software known as WinFlume.
Design details of the smart water metering test unit deployed at LUMS

Dimensions and assembling can be seen here:
## Design details of the smart water metering test unit deployed at LUMS

<table>
<thead>
<tr>
<th>Design constraints</th>
<th>Design criteria</th>
<th>Values evaluated using WinFlume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure type</td>
<td>Stationary crest</td>
<td>-</td>
</tr>
<tr>
<td>Freeboard</td>
<td>( \geq 20% \text{ of } h_{\text{max}, \text{min}} \text{ required at } Q_{\text{max}} = 17.164 \text{ mm} )</td>
<td>473.179 mm</td>
</tr>
<tr>
<td>Froude number</td>
<td>( \leq 0.5 )</td>
<td>0.219</td>
</tr>
<tr>
<td>Allowable discharge measurement error at single measurement:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>At maximum discharge ( Q_{\text{max}} )</td>
<td>( \pm 4 % )</td>
<td>( \pm 2.58 % )</td>
</tr>
<tr>
<td>At minimum discharge ( Q_{\text{min}} )</td>
<td>( \pm 8 % )</td>
<td>( \pm 3.65 % )</td>
</tr>
<tr>
<td>Head detection method</td>
<td>Ultrasonic sensor without stilling well</td>
<td>-</td>
</tr>
<tr>
<td>Measurement uncertainty by head detection method</td>
<td>1 % or better [10]</td>
<td>-</td>
</tr>
<tr>
<td>( Q_{\text{max}} ) to be measured</td>
<td>1 cu. Ft/s</td>
<td>-</td>
</tr>
<tr>
<td>( y_{2_{\text{max}}} ) (max. tail-water depth)</td>
<td>-</td>
<td>113.201 mm</td>
</tr>
<tr>
<td>( Q_{\text{min}} ) to be measured</td>
<td>0.4 cu. Ft/s</td>
<td>-</td>
</tr>
<tr>
<td>( y_{2_{\text{min}}} ) (min. tail-water depth)</td>
<td>-</td>
<td>62.108 mm</td>
</tr>
<tr>
<td>Tail-water calculation method</td>
<td>Manning’s equation using ( n ) and ( s )</td>
<td></td>
</tr>
<tr>
<td>Manning’s ( n )</td>
<td>-</td>
<td>0.030</td>
</tr>
<tr>
<td>Hydraulic gradient ( s )</td>
<td>0.003830 mm/mm</td>
<td>-</td>
</tr>
<tr>
<td>Modular Limit (ML) at ( Q_{\text{min}} )</td>
<td>( &gt; 0.7 )</td>
<td>0.782</td>
</tr>
</tbody>
</table>
Design details of the smart water metering test unit deployed at LUMS

- Equation for discharge computation of long throat flume in free flow state

\[ Q = k_1 (h_1 + k_2)^u \]  

Eq. 1

Where,
\( Q \) = discharge rate in cu. Ft/s.
\( h_1 \) = depth of water above flume crest on upstream side.
\( k_1, k_2, u \) = are empirical coefficients and their value depends upon dimensions, material and geometry type of flume and channel.

- For existing test unit channel, value of empirical coefficient computed using WinFlume are:
\[ k_1 = 0.0007699 \]
\[ k_2 = 1.023 \]
\[ u = 1.606. \]
Design details of the smart water metering test unit deployed at LUMS

Rating curve computed using WinFlume
Estimation of state of hydraulic structure

- By using an additional ultrasonic sensor at the tail water section of the channel, state of hydraulic structure can be estimated when used in combination with upstream ultrasonic sensor measurement.

- These range readings $r_1$, $r_2$ can be used to compute $h_1$, $h_2$, $y_1$, $y_2$ and $ML$ using the following equations:

$$h_1 = (R_{\text{max}} - r_1) - p_1,$$
$$h_2 = (R_{\text{max}} - r_2) - p_1.$$

$$y_1 = h_1 + p_1,$$
$$y_2 = h_2 + p_1.$$

$$SR = h_2 / h_1.$$

where,

- $r_1$ = range of ultrasonic sensor on upstream side
- $r_2$ = range of ultrasonic sensor on downstream side
- $R_{\text{max}}$ = maximum range ultrasonic sensor are expected to give on a measuring site
- $h_1$ = depth of water above flume crest on upstream side
- $h_2$ = depth of water above flume crest on downstream side
- $y_1$ = depth of water above bed of water course on upstream side
- $y_2$ = depth of water above bed of water course on downstream side
- $p_1$ = sill height of flume
- $SR$ = submergence ratio
Estimation of state of hydraulic structure

Start

IF \((y_2 > y_1) \text{ AND } (y_2 > p_1)\)

False

Stagnant

True

Backward Flow

IF \((y_1 < p_1) \text{ AND } (y_2 < p_1)\)

True

Zero flow

False

IF \((y_1 > y_2) \text{ AND } (y_1 > p_1)\)

False

IF \((h_2/h_1 < ML)\)

True

Forward & Free-Flow

False

Submerged state
Test Run

- A 60 min test run was conducted by pumping water into storm water drain channel at LUMS campus.
- The channel was a 25 x 25 (inch) rectangular type masonry channel and was initially dry before the test was conducted.
- The equipment was tested to identify state of flume structure during run and to be able to measure discharge in free flow state.
- WSN was configured at a sampling frequency of 1 min and transmission frequency of 10 min.
- Following scenario was adopted for the test run:

<table>
<thead>
<tr>
<th>Duration</th>
<th>State</th>
</tr>
</thead>
<tbody>
<tr>
<td>First 5 minutes</td>
<td>Zero/no flow</td>
</tr>
<tr>
<td>Next 35 minutes</td>
<td>Free flow</td>
</tr>
<tr>
<td>Next 20 minutes</td>
<td>Submerged state</td>
</tr>
</tbody>
</table>
Conclusions – Talk 2

- Flow measurement in small water courses (outlets) and state estimation of hydraulic structure has been successfully demonstrated.
- A long throat flume is found suitable hydraulic structure for small flows.
- An automated measurement unit has been demonstrated.
- The proposed solution is viable for continuous flow measurement where GSM/GPRS network is available.
- Since no components are in contact with liquid, the device is applicable to a variety of situations.
Thank you!