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Revisiting Telemetry in Pakistan's Indus Basin Irrigation System

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Received: 31 July 2019; Accepted: 29 October 2019; Published: 6 November 2019

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Abstract: The Indus Basin Irrigation System (IBIS) lacks a system for measuring canal inflows, storages, and outflows that is trusted by all parties, transparent, and accessible. An earlier attempt for telemetering flows in the IBIS did not deliver. There is now renewed interest in revisiting telemetry in Pakistan's IBIS at both national and provincial scales. These investments are typically approached with an emphasis on hardware procurement contracts. This paper describes the experience from field installations of flow measurement instruments and communication technology to make the case that canal flows can be measured at high frequency and displayed remotely to the stakeholders with minimal loss of data and lag time between measurement and display. The authors advocate rolling out the telemetry system across IBIS as a data as a service (DaaS) contract rather than as a hardware procurement contract. This research addresses a key issue of how such a DaaS contract can assure data quality, which is often a concern with such contracts. The research findings inform future telemetry investment decisions in large-scale irrigation systems, particularly the IBIS.

Keywords: Indus Basin Irrigation System; sensors; telemetry; data contract

1. Introduction

Pakistan hosts the world's sixth largest population, estimated at 207.7 million according to the 2017 census [1]. The country consists of four provinces which share water from the Indus Basin Irrigation System (IBIS). The IBIS is the backbone of Pakistan's agricultural economy. The agriculture sector, including crops, livestock, fisheries, and forestry, contributed 18.5 percent to the GDP in 2018–2019 and is a source of livelihood for 38.5 percent of the nation's total labor force [2]. The IBIS is a large, complex system of hydraulic infrastructure that has been developed incrementally over many decades and represents an estimated US$300 billion in investment [3]. It consists of 2 large reservoirs, 16 barrages, 2 headworks, 12 inter-river canals, and 45 canal irrigation systems, and irrigates an area of the order of 17M ha.

A formal agreement on the apportioning of the surface water resources of Pakistan between the four provinces was finally reached in 1991 (herein referred to as the Accord) after long deliberations [4,5]. The Accord, ratified on 21 March 1991, was heralded to remove the biggest hurdle in the way of national unity and cohesion [5]. Unfortunately, the Accord has been unable to deliver this national unity and cohesion, which, in turn, has stymied investment and development in water resources. Mistrust between the provinces and conspiracy theories abound, and at best there is an uneasy peace [4,6]. The lack of trust between the provinces of Pakistan is at the heart of the water issues [7]. The Indus River System Authority Act 1992 followed shortly after the Accord and paved the way for creating the Indus River System Authority (IRSA) as stipulated in Clause 13 of the Accord.

In 2004 the Water and Power Development Authority (WAPDA), a federal government institution of Pakistan, installed an electronic system to measure depth-of-flow at various key locations along the

IBIS and to transmit these data electronically—referred to as the WAPDA Telemetry. The locations where WAPDA installed the telemetry system are shown in Figure 1. This system was installed with an investment of US$5.4 million in 2004 prices [8]. The Government of Pakistan in 2012 commissioned a panel of international experts who authored a seminal report on the water challenges of Pakistan and the way forward. This report, commonly known as the Friends of Democratic Pakistan (FODP) report [6], made the observation that a decade ago, the telemetry system was installed to automate the measurement and reporting process, but it has not worked [6]. The popular press in Pakistan also report that the investment in telemetry has never worked satisfactorily or been accepted by the stakeholders, in particular, IRSA (e.g., [9,10]).

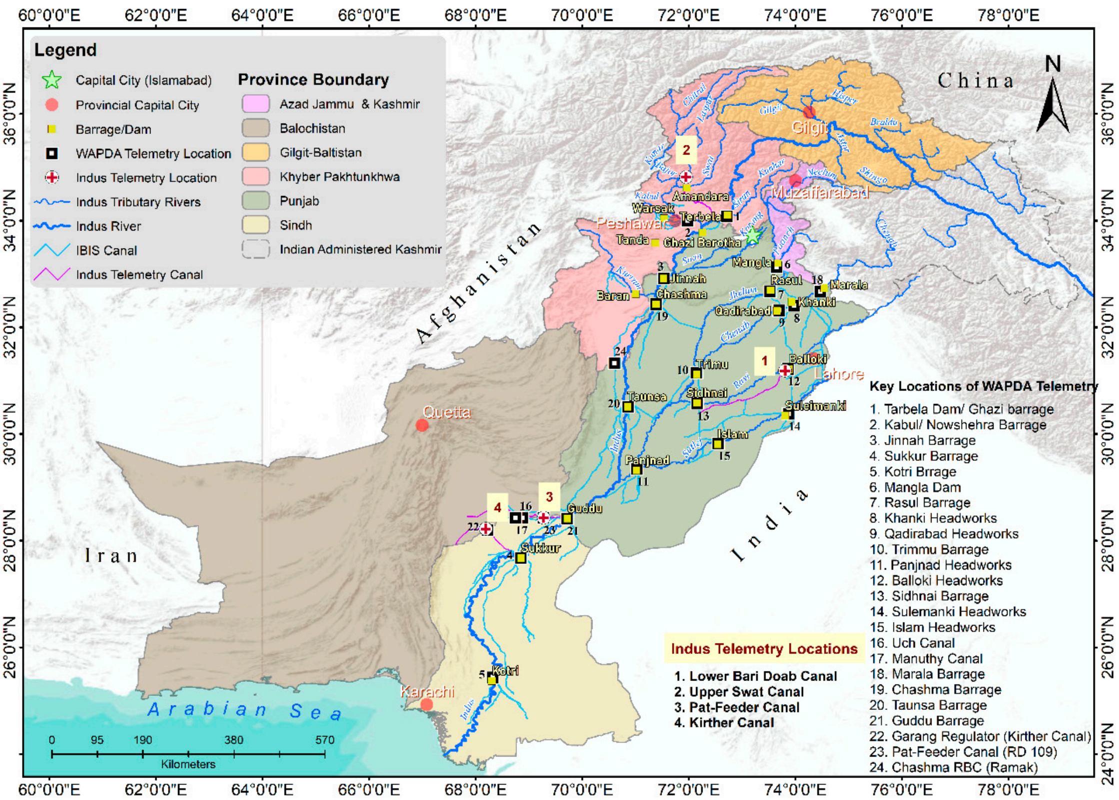


Figure 1. Location map of telemetry locations in the Indus Basin Irrigation System.

Briscoe and Qamar in 2005 [11] suggested the following requirements to implement the Accord in a transparent manner:

1. *"A rigorous, calibrated system for measuring water inflows, storages, and outflows be put in place.*
2. *The measurement system be audited by a party which is not only scrupulously independent and impartial but is seen to be so by all parties.*
3. *Reporting must be totally transparent and available in real time for all parties to scrutinize."*

This sentiment has been expressed in numerous other reports and studies [12–14]. Importantly, the Government of Pakistan has acknowledged the need for automated flow monitoring in its National Water Policy [15], approved in 2018: *"Real-time monitoring of river flows by IRSA is to be ensured through inter alia telemetric monitoring to maintain transparent water accounting system and to check the increasing trend of unaccounted-for water in the Indus System of Rivers. This task should be completed before the end 2021"(sic).*

Some of the clamor for telemetry in the IBIS stems from the fact that IRSA reports large volume balance errors (referred to in the vernacular as losses/gains) every year. The average (1976–2015) annual surface water resource of Pakistan is 178.461 Gm^3/year. The average unaccounted volume for the same period remained 22.474 Gm^3/year; hence, approximately 13% of Pakistan's annual water resource remains unaccounted-for. During 2014–2015, the unaccounted-for volume reached 36.082 Gm^3/year, which was more than twice the national reservoir capacity of Pakistan at that time [16]. This inability to account for water results in recriminations and mistrust between the provinces and in the data and information reported by IRSA [4,6].

The term "unaccounted-for water" is commonly used for public water utilities performance. Large amounts of water supplies to major cities remain unaccounted-for, e.g., in Asia, Latin America, and Africa [17]. In many cases, the data exist with researchers, water users, and local authorities but do not become available to the water accounting authority. The water accounting in the IBIS is based upon the system inflows (the aggregated river inflows) and system outflows (aggregated canal withdrawals). The difference between the system inflows and outflows is referred to as unaccounted-for water or, more commonly, losses and gains. IRSA receives disaggregated data from various line agencies and then processes this to prepare national water accounts. The existing data acquisition, archiving, and reporting system is not robust and the inability to account for potential losses (e.g., evaporation, leaks from river beds, etc.) gives rise to unaccounted volumes. Principle #5 of the Organisation for Economic Co-operation and Development (OECD) Principles on Water Governance states, *"Produce, update, and share timely, consistent, comparable and policy-relevant water and water-related data and information, and use it to guide, assess and improve water policy."* [18,19].

The Government of Pakistan has re-engaged with the issue of water data and information in the recent years. The Government is undertaking a project (World Bank Project identifier P110099; closing date 30 June 2021) that includes an activity for "automation of flow measurement and information system for the IBIS using telemetry system and modern techniques" with the objective that this will scale up efforts to increase transparency in the inter-provincial water allocation system and contribute to water conveyance efficiency in the IBIS [20]. Similarly, the provincial Governments have also invested [21,22] in the installation of hydro-met and real-time flow monitoring.

This paper presents the experience of a pilot study instrumenting canals in the IBIS (herein called the Indus Telemetry) to demonstrate technological choices and, more importantly, how the quality of acquired data can be ensured, particularly when data are supplied as a service. A Data as a Service (DaaS) contract in the water sector, as opposed to more conventional hardware procurement contracts, requires more careful consideration of the data quality. This research offers insight into a data quality process by expanding on its various steps and assesses its attributes or dimensions such as integrity, timeliness, and accuracy. The authors develop and apply a new statistical indicator for data timeliness and also analyze data integrity and accuracy by using appropriate statistical indicators. This research also addresses the question of what should be the statistical limits (upper or lower bounds) for the indicators used to assess data quality. Previous work on this topic is limited; therefore, the present research will lead to new knowledge in the quality assurance of water data and information that, in turn, will foster trust and confidence in the data acquired.

2. Materials and Methods

2.1. The Study Area

Figure 1 shows a map of the Indus Basin Irrigation System (IBIS) indicating the four pilot locations. The figure also identifies 24 key locations where the Water and Power Development Authority (WAPDA) set up a telemetry system in 2004. Notably, many of these key locations are barrages where more than one canal take off from the river. Thus, WAPDA installed at these key locations multiple water level sensors (non-contact ultrasonic range finders): at the rivers, upstream and downstream of the barrage, and at canals, downstream of the head regulator. In addition to the water level sensors, WAPDA also installed sensors to monitor gate openings of the barrages and regulators.

To estimate discharge in open channel flow (rivers and canals), there is a wide range of techniques and instruments to choose from. Jamitco et al. [23] described a system that detects water elevation using an ultrasonic range finder. The data from the range finder can be used to estimate depth-of-flow in the channel, and using a rating curve the velocity and discharge can be estimated. More recently, there has been considerable interest and development in acoustic Doppler current profilers (ADCP) [24] that can estimate velocity directly and avoid the need/use of velocity rating curves. A number of authors, e.g., [25–27], among others, have compared the velocity estimates from ADCPs with more conventional mechanical or electromagnetic current meters and found good agreement.

For automatic data acquisition in the present study (i.e., Indus Telemetry), we selected one main canal from each of four provinces of Pakistan. This selection scheme was deliberate to ensure coverage in all provinces, and the particular canal (and the specific location on each canal) was selected on the advice of the respective provincial irrigation department to ascertain their ownership in the instruments and data. The selected canals originate from three rivers—the Ravi, Swat, and Indus rivers—and irrigate around 1.1 Mha of agricultural land (Table 1). Among the four selected canals, Pat Feeder and Kirther are inter-provincial canals which originate from the Indus River at the Guddu and Sukkur barrages, respectively, in the Sindh province, but supply in the downstream reaches around 72% of Balochistans annual water share (4.774 Gm^3/year). The Lower Bari Doab Canal is a large canal selected in Punjab. This canal irrigates 0.688 Mha of land in Punjab. The Upper Swat Canal was selected in Khyber Pakhtunkhwa province. It originates at the Amandara headworks on River Swat and diverts 68 m^3/s to irrigate over 107,647 ha of land in addition to supplying water for hydropower generation.

Table 1. Selected canals for Indus Telemetry.

Feature	Unit	Lower Bari Doab Canal	Upper Swat Canal	Kirther Canal	Pat Feeder Canal
River (Barrage/Headworks)		Ravi (Balloki)	Swat (Amandara)	Indus (Sukkur)	Indus (Guddu)
Running distance	km	8.99	5.94	35.35	33.22
Discharge Estimation		Flume	Crump Weir	Rating Curve	Rating Curve
Capacity at head	m^3 s^{-1} ft^3 s^{-1}	263.12 (9292)	101.94 (3600)	67.96 (2400)	189.72 (6700)
Geographic coverage	Province(s)	Punjab	Khyber Pakhtunkhwa	Sindh-Balochistan	Sindh-Balochistan
Proportion of total provincial water share	%	8.8	27.7	22.1 *	49.7 *
Length	(km)	201	129	84	171
Irrigated area	(ha)	687,967	111,740	107,647	205,753

* Percent share of Balochistan province only.

The instruments were not installed immediately downstream of canal head regulators. High turbulence and surface waves cause fluctuating readings at such locations. Stilling wells provide a partial solution to this problem by making gauge reading quiescent. However, measuring velocity and discharge in highly turbulent water still remains a challenge, and developing a function between depth-of-flow and discharge—the rating curve—becomes difficult. The instruments were installed at the locations where the provincial irrigation agency reports discharge, i.e., either at the discharge measuring structures (e.g., flume or weir) or a canal cross section where a depth–discharge function (or rating curve) is already available. Pat Feeder and Kirther are inter-provincial canals, and there are no discharge measuring structures at these locations. At these two canals, rating curves are used to estimate discharge from depth-of-flow, but the provincial irrigation agencies do not always agree on the rating curves and the consequent discharge estimates. Table 1 also shows the running distances along the canals where ultrasonic sensors were installed. The instruments were commissioned at these four locations during the second and third quarters of 2018. The data were acquired regularly at 15 min intervals since then. We analyze varying lengths of time series data in subsequent sections of this paper.

2.2. The Instruments and Data

Five ultrasonic sensors with ancillary components (data loggers, power supply, and modem) similar to those described by [23] were installed at selected locations of the four canals to measure depth-of-flow in these canals. The Upper Swat Canal splits into two channels at the measurement location; thus, two ultrasonic sensors were installed on this canal. The list of main instruments used in this work is provided in Table A1 (Appendix A). Data were transmitted using General Packet Radio Services (GPRS) technology to a cloud server (Microsoft Azure Data Centre) where they were processed, archived, and disseminated to users.

2.2.1. Data Sampling Period

The data sampling period is the time between samples (measurements). Typically, the data sampling periods can be small, i.e., samples can be taken at high frequency, but the data sampling period may depend on the "warm-up" time of instruments, i.e., some instruments do require a voltage to be applied for a short duration first to allow the circuits to reach normal operating temperatures.

2.2.2. Data Logging Period

The data logging period is the time period at which data is logged (recorded) at the data logger. Data logging is done typically at a higher period—lower frequency—than sampling. Therefore, some aggregate function, i.e., average, sum, maximum, minimum, is applied to the sampled data which are then logged in the data logger. The logged data are also date–time stamped. It is important to note that the date–time stamp is that at which data are logged, rather than that at which they are sampled; therefore, the data must be interpreted accordingly. Data loggers do not normally store any record of the sampled data after they are aggregated.

2.2.3. Data Transmission Period

The data transmission period defines the period at which data that have been logged are transmitted, and this is typically multiples (including one) of the data logging period. In this work, data were transmitted using a modem, cellular phone network, and GPRS technology. The instrument was powered by a modest solar panel (20 W capacity) and a rechargeable battery.

2.3. Calibration and External Parameters

The ultrasonic sensor measures the range from the sensor face to the water surface. These raw data are logged and transmitted to the server where they are post-processed to obtain depth-of-flow. This post-processing requires the instrument elevation and canal bed elevation. The practice to estimate discharge in the IBIS is to assume that the canals behave as wide rectangular channels under uniform flow, and hence, the discharge rating curve is of the form

$$\mathrm{Q} = \mathrm{C}\mathrm{H}^{5/3} \tag{1}$$

where Q is the discharge; C is the rating curve coefficient determined empirically; and H is the depth-of-flow. From L'Hôpital's Rule and the Manning equation, the coefficient in Equation (1) is given by

$$\mathrm{C} = \frac{\mathrm{B}\mathrm{S}^{1/2}}{n_r} \tag{2}$$

where B is the width of the canal; S is the bed slope of the canal; and n_r is the Manning roughness coefficient. Equation (1) is often generalized to

$$\mathrm{Q} = \mathrm{C}\mathrm{H}^{\mathrm{m}} \tag{3}$$

where the coefficient C and m in Equation (3) are determined from flow meter measurements and an ordinary least squares linear regression of a log transformation of Equation (3).

2.4. Data Post-Processing Delay

In this work, once the sampled average range was received at the server, the depth-of-flow and discharge were estimated. However, to avoid what is known in computing as a "race condition" wherein data are being transmitted and processed at the same time (a race between two processes which may lead to instability), a post-processing delay was introduced to allow the data to be transmitted first and then to be post-processed.

2.5. Quality Assurance of Data

A six-step data quality process was suggested by [28] based on best practices from data quality experts. The six steps are definition, assessment, analysis, control, implementation, and improvement. This research adopted the data quality process by [28] and expanded on the first two steps, i.e., the definition step and assessment step, in relation to data from Indus Telemetry.

The definition step sets up the foundation of the data quality process. It includes clarifying what are the business goals, roles, and responsibilities of the parties and data rules in a DaaS contract. Clear, specific, and well-documented definitions enable smooth implementation of DaaS contracts. For example, the goal of Indus Telemetry is to make canal flow data available to the data owner. In Pakistan, the Indus River System Authority (IRSA) is potentially the owner of the flow data. IRSA would be the client awarding the DaaS contract to the contractor. The contractor would be responsible for supplying quality-assured data to the client that comply with the agreed data rules.

The data rules are the essential conditions which data should fulfill to pass the data quality process, e.g., frequency, data integrity, lower bounds of latency, etc. Moreover, the data rules would also feature which statistical tests should be used to check data accuracy and what will be the lower/upper bounds of these statistical tests. We explain the features of data rules in this section and discuss their application (i.e., assessment step) in Section 3.

The second step of the data quality process is the "assessment step" where acquired data are assessed in accordance with the defined data rules in the first step. The assessment covers multiple dimensions of data quality such as its integrity, timeliness, accuracy, etc. To assess data integrity and accuracy, we considered various statistical indicators as explained in the subsequent subsections. The application and appropriateness of these statistical indicators are discussed in Section 3. We also developed a new statistical indicator to assess data timeliness.

2.5.1. Data Integrity

Data integrity in the context of the DaaS contract explains how complete the data are when compared with the agreed frequencies defined in the definition step. Data integrity is calculated as shown in Equation (4) and expressed as a percentage. The DaaS contract could specify an upper bound for data integrity below which the DaaS contractor may incur a penalty. In this research, the sensor data were logged every 15 min; hence, the maximum possible number of records per day was 96.

$$Data\ Integrity = \frac{\text{count } of\ data\ records\ recieved \text{ during a time interval}}{\text{max. possible data records during a time interval}} \times 100 \tag{4}$$

2.5.2. Data Accuracy

Inaccuracies in electronic data (flow data) may arise due to any one or combination of the following reasons: poor calibration of a sensor; the use of inaccurate parameters in programming the sensor or data logger; the post-processing of raw data into information. When such inaccurate data are presented to the users, it invites critique of the electronic data acquisition methods. This is exactly what happened in the past when WAPDA installed a telemetry system in Pakistan. When the telemetry data were compared with the manual data, they did not match, which raised questions about the accuracy of the electronic data and hampered the ownership of the telemetry system [29,30]. The assessment of data accuracy is therefore very important to develop confidence in electronic data collection techniques.

Conducting an accuracy assessment for any data requires an agreed-upon reference dataset with a high level of accuracy [31]. In this case, it is not clear which of the two sensors has superior accuracy. Therefore, we present our results as a comparison of the level of agreement between the data from the two independent sensors, i.e., ultrasonic sensor and pressure transducer.

The dataset used in the accuracy assessment is depth-of-flow collected with an ultrasonic sensor and pressure transducer. For this we installed pressure transducers in addition to the ultrasonic sensors at the measurement location. Pressure transducers measure liquid levels through a sensor submerged at a fixed level under the water surface. We applied various statistical tests to assess the data accuracy. In the interest of brevity, we present an assessment of the accuracy of data from only one canal (Lower Bari Doab Canal), comparing data from the two independent sensors.

(i) t-*test*

To assess the accuracy of data, we first need to decide whether the data are for a sample or a population. In this case, for each measurement with an ultrasonic sensor we also have the corresponding check measurement with a pressure transducer, and the variable of interest is the difference between the measurement and the check measurement. Therefore, we have data for the entire population of measurements. This implies we are estimating population parameters rather than sample statistics, i.e., population mean, population standard deviation, etc., and not sample mean, sample standard deviation, etc.

Inferential statistics [32] uses a random sample of data taken from a population to describe and make inferences about the whole population. This is valuable when it is not possible to examine each member of an entire population. Student's *t*-test is a commonly used inferential statistical method for hypothesis testing about the mean of a small sample drawn from a normally distributed population. Similarly, the paired *t*-test is applied to statistically determine whether the mean responses are the same. In a particular time period of interest, the count of measurements from both sensors was identical, which depends on the frequency at which the sensors were programmed to log the data (i.e., 15 min). As we were considering all the measurements from both sensors, the data constitute the population rather than a randomly drawn sample.

Since we already know the population mean, we do not need to try to draw inferences (test hypothesis) about the population mean from the sample mean. Furthermore, the aim of comparing the two data sets here is to check the data accuracy and not to draw conclusions about some unknown aspect of a population based on a random sample. Hence, the *t*-test (or other inferential statistics) is not an appropriate method to assess data accuracy; rather, descriptive statistics should be applied.

(ii) Difference Plot and Normality

Borrowing from their wider applications in the medical field, difference plots were used in this work to compare the two methods of measurement, i.e., the ultrasonic sensor and pressure transducer. The detailed procedure of difference plots was first suggested by Bland and Altman [33] in 1986. Bland and Altman, in their publications [34,35], explained in detail their method and also provided a non-parametric approach which is particularly useful in cases when the difference between the methods does not have a normal distribution. The non-parametric approach is similar to the basic approach of the difference plot as explained in [34,35] up to and including the plot of the differences versus the mean values of the two methods. There are then two similar ways of describing such data without assuming a normal distribution of differences. We can calculate the proportion of differences greater than some reference value (such as 3 cm in this case). The reference value can be indicated on the scatter diagram showing the differences versus the mean. Alternatively, we can calculate the values outside which a certain proportion (say 10%) of the observations fall. To do this we order the observations and take the range of values remaining after 5% of the observations are removed from each tail. The centiles can then be superimposed on the scatter diagram. In a DaaS contract, we suggest that when a non-parametric approach to the difference plot is used, the reference values should be agreed upon by the client and contractor and defined at the definition step.

Bland and Altman also showed in [35] how a grade can be assigned to a method (sensor in our case) based on the proportion of observations in a predefined range of the reference values. In this paper, we developed a criterion and applied it to grade our sensors. Bland and Altman commented that the "*nonparametric method is disarmingly simple yet provides readily interpreted results. Perhaps its simplicity has led to the belief that it is not a proper analysis of the data*".

Bland and Altman responded to the critique on their proposed method in their 2003 publication [31] and concluded,

" … *It (difference plot) can be extended to many more complex situations, when distributions are not normal, when difference is related to magnitude, when there are repeated measurements on the same subject, either paired or not, and when there are varying numbers of observations on subjects*".

It was further stressed in [36] that agreement is a question of estimation, not hypothesis testing. Estimates are usually made with some sampling error, and limits of agreement are no exception.

The common goal usually is to decide whether a new measurement system agrees suitably with an existing one and, hence, whether the two can be used interchangeably [37]. The goal of a comparison of two methods may vary in emphasis by context, as explained by [38], who highlighted four possible goals:

i. Calibration problems, which deal with establishing a relationship between a new system and an existing one that can be used to appropriately adjust the new system's measurements;
ii. Comparison problems, which deal with assessing the level of agreement between two measurement systems whose measurements are on the same scale;
iii. Conversion problems, which deal with the comparison of two systems whose measurements are on different scales; and
iv. Gold-standard comparison problems, which deal with the comparison of a new measurement system with a system that is known to make measurements without error.

The "comparison problem" best defines the goal of comparing two methods of measurement (sensors) in our case, for which we plot and discuss difference plots using the parametric and non-parametric approaches.

(iii) Mean Absolute Percentage Error (MAPE) and Symmetric MAPE (sMAPE)

We also apply statistical tests to estimate the error in the depth-of-flow data collected with the two independent sensors. The mean absolute percentage error (MAPE) is a relative measure that expresses errors as a percentage of the actual data, as shown in Equation (5). Its advantage is that it provides an easy and intuitive way of judging the extent or importance of errors.

$$\text{Mean Absolute Percentage Error (MAPE)} = \frac{100}{n}\frac{\sum x_i - y_i}{x_i} \quad (5)$$

Here, x_i are the actual data, y_i are the forecasted or estimated data, and n is the number of non-missing data points.

However, [39] noted that the formula for the MAPE is not symmetric in the sense that interchanging x_i and y_i does not lead to the same answer, despite the fact that the absolute error is the same before and after the switch. The cause of this asymmetry lies in the denominator of the formula—dividing by y_i instead of the actual x_i leads to a different result.

This issue has been discussed by many researchers ([40,41], among others), with [41] proposing a variation of the MAPE formula to provide symmetry: this is known as the sMAPE (symmetric mean absolute percentage error) and was originally introduced by [42]. The formula suggested by [42] and the later modification by [43] are given in Equations (6) and (7):

$$sMAPE_{Armstrong}\ \frac{1}{n}\ \frac{|x_i - y_i|}{(x_i + y_i) * 0.5} \times 100 \tag{6}$$

$$sMAPE_{Flores} = \frac{1}{n}\ \frac{|y_i - x_i|}{|y_i + x_i|} \times 100. \tag{7}$$

A limitation of sMAPE is that if x_i or y_i is zero, the value of the error will be equal to the upper limit of the error, i.e., 200% for the Armstrong formula and 100% for the Flores formula.

2.5.3. Measurement of External Parameters

Obtaining useful information from telemetry data requires external parameters for processing. The external parameters include the information that is not or cannot easily be measured through instrumentation and telemetry. In the case of flow measurement in the IBIS using ultrasonic sensors, the critical parameters are the bed elevation and the rating curve coefficient in Equation (3). We measured these two critical parameters for 17 tertiary canals of a typical canal system in the Punjab province (i.e., the Hakra Branch Canal system, described in detail in [44–46]). The measurements included a baseline survey of all the canals (at a cross section near a head regulator) in the year 2014 and four subsequent surveys over the year of 2015. An acoustic Doppler current profiler (ADCP) was used to measure discharge during the surveys. The variations in the bed elevation and rating coefficient were then calculated as percent changes from the baseline.

3. Results and Discussion

In this work, the range to the water surface was sampled (measured) every 60 seconds. The data logging period was set to 15 min, and averaging was used as the aggregate function. Hence, the data logger logged the average water surface elevation for the 15 min preceding the date–time stamp.

Data transmission from all canal locations was scheduled three times each day at 0745, 1145, and 1545, Pakistan Standard Time. This means that all transmissions were made during daylight hours, and the datalogger was programmed such that the system does not attempt to transmit data if the battery voltage is below a threshold value (in this case set at 11 V). Further, if the battery voltage falls below a critical value (i.e., 9 V) the sensor stops recording data. Although it is tempting to transmit data frequently, data transmission is the most power-consuming process of an automated data acquisition system. This is not an issue during daylight hours when the solar panels can generate power, but excessively frequent data transmission can drain the battery and lead to system shut-down at night-time or during overcast winter days with shorter day lengths. A post-processing delay of 10 min was used in this work.

The sampling period was set through appropriate programming of the data logger which excites the sensor—in this work, 1 min. Sampled data points are only stored temporarily in a data logger until an aggregate function is applied to the sampled data. In a DaaS contract, it would be difficult to specify or validate/verify sampled data. However, when the aggregate function is applied to the data, a count of the sample size that is aggregated can be recorded. Sample size is given by

$$N_S = \frac{T_D}{T_S} \tag{8}$$

where N_S is the sample size aggregated at the data logging period; T_D is the data logging period; and T_S is the data sampling period. Hence, Equation (8) provides the maximum or upper bound on the sample size that is aggregated. The actual sample size may be less than this due to hardware/software failures. Hence, a DaaS contract could specify a threshold value, and a contractor in response could adjust the data logging period and data sampling period to exceed the threshold value while allowing for occasional hardware/software failures. For the parameters used in this work, the sample size was 15.

3.1. Data Integrity

Table 2 shows the data integrity for all four canals during the reporting period. The table shows that data integrity was more than 90 percent in all cases. The Pat Feeder and Kirther canals showed the highest data integrity of above 99 percent. A low value of data integrity indicates that the data from the sensor were not recorded in the data logger. Other than physical damage to the system and/or components, this normally happens due to manual power shut down for troubleshooting or low voltage at the sensor/data logger. In our experience, during long spells of rain, overcast, or fog, the solar panels do not supply enough energy to charge the battery and the system shuts down if the battery voltage drops below 9 V.

Table 2. Data integrity and timeliness.

Canals		**Lower Bari Doab Canal**	**Kirther Canal**	**Pat Feeder Canal**	**Upper Swat Canal**
Reporting period during 2018		31 May to 10 Dec	15 Aug to 10 Dec	07 Sept to 10 Dec	09 July to 10 Dec
Average Latency per day	hr	17.10	13.33	8.09	8.37
Data records received	#	17,057	11,296	8818	29,281
Max possible records	#	18,528	11,328	8832	29,952
Data Integrity	%	92.1	99.7	99.8	97.8

Note: Lower bound of latency with current transmission frequency is 6.21 h.

3.2. Data Timeliness

Latency is defined as the time that elapses between when a sample is taken and when those data and derived information from post-processing are accessible to a user. However as defined earlier, the sampled data are not retained in the data logger; rather, only an aggregation is applied to the sample. Furthermore, the date–time stamp is that at which the aggregate function is applied rather than the date–time at which it is sampled. Hence in this work, latency is the time that elapses from when the aggregate function is applied to when the data and derived information become accessible to a user. Latency is a function of the data logging period, data transmission period, and data post processing delay and is given by

$$\mathcal{L} = \frac{\sum_{i=1}^{\frac{T_T}{T_D}-1} (\Delta + iT_D)}{\left(\frac{T_T}{T_D}\right)} \tag{9}$$

where $\mathcal{L}$ is the latency; T_T is the data transmission period; i is an index (0,1,2, …); and Δ is the data processing delay. The data transmission period is expressed as any multiple (including one) of the data logging period. The expression in Equation (9) determines the lower bound of latency. The observed latency will be equal to or higher than this lower bound if there are hardware or software failures. For the parameters selected in this work, the lower bound of the latency was 6.21 h.

Table 2 shows the observed latency of the data from all four canals during the specified reporting period. The data from Lower Bari Doab Canal had the highest average latency per day (17.10 h) followed by Kirther Canal (13.33 h). Data from Pat Feeder and Upper Swat Canals showed slightly higher latency than the lower bound of latency (6.21 h). High latency values indicate delays in transmission that are due to any number of reasons, including but not limited to poor Internet connectivity and inadequate power to start up the modem.

Figure 2 provides some further insight into the data integrity and latency for the Lower Bari Doab Canal. The figure presents a daily count of records and latency for the reporting period. The upper bound of the record count per day was 96 (as explained in Section 2.5.1) and the lower bound of latency was 6.21 h. Ideally the record count per day should be 96, but if data are lost, the record count falls below 96 and, hence, data integrity decreases. Similarly, if the data are received without any failure, the latency will be identical to the lower bound of 6.21 h, but where there are transmission failure(s), the latency increases above 6.21 h. Figure 2 shows that data integrity and latency were not interdependent upon each other.

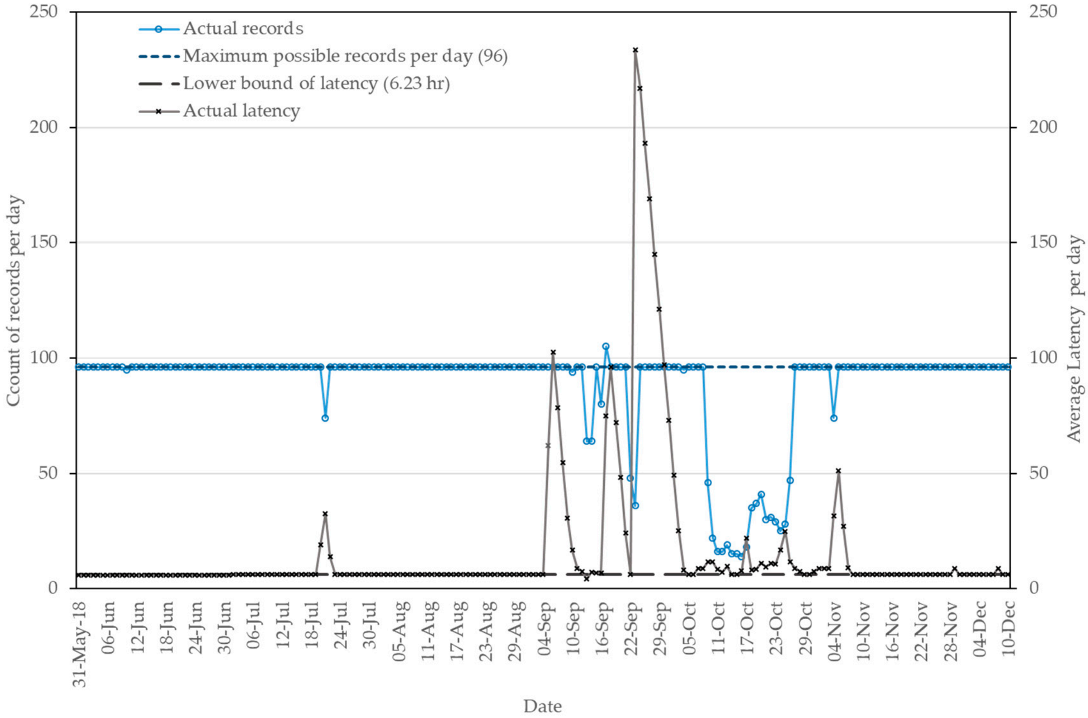


Figure 2. Observed data records and latency per day for the Lower Bari Doab Canal.

In Figure 2, a high fluctuation is observed in the latency (black continuous line), but the record count (blue continuous line) remained relatively stable over the period 4 September 2018 to 8 October 2018. The high fluctuation in latency is primarily due to poor Internet connectivity in the area where instruments were installed. The system experienced power issues from 9 to 27 October 2018, and hence there was a substantial decrease in the record count (data loss) during this period. Interestingly, the Internet connectivity improved in this period, resulting in an improvement in the latency. A couple of instances of high latency were observed during November and December but with no drop in the record count. This occurred due to occasional network failure at the time of transmission. It can be inferred from Figure 2 that the average latency and record count were not inversely proportional but rather behaved independently.

This discussion on latency leads into the broader question of what constitutes "real-time" flow data, as advocated by Briscoe and Qamar [11]. One interpretation of real time is zero latency, which would be near impossible, expensive to achieve, and probably unnecessary. It would be more realistic to specify quasi-real-time flow data by specifying the latency in a data as a service (DaaS) contract. A pragmatic approach can be to specify separate day-time and night-time latency. Hence, a DaaS contract could specify an upper bound on latency (the lower bound is a value calculated by using Equation (9)). By way of example, if an upper bound of 12 hours is specified, then latency must not exceed 12 hours or this will incur a penalty. The configuration as shown in Figure 2 does not fulfil the terms of this specification for 15 percent of the time, which would incur the penalty and encourage the DaaS contractor to find a solution to this problem. Again, a DaaS contract would specify the record count, and it would be up to the contractor to program a data logger to ensure that the actual record count equals or exceeds the specified threshold.

3.3. Data Accuracy

To analyze the accuracy of data, we analyzed the depth-of-flow in the Lower Bari Doab Canal measured with an ultrasonic sensor and pressure transducer at 15 min frequency. Normality tests were applied to the difference between the measurements (d-b-m). While plotting the difference plots, limits of agreement (LoAs) were calculated using the mean and standard deviation when the data followed a normal distribution. If this was not the case, a non-parametric version of the difference plot was used to calculate the limits. Table 3 shows the results of various normality tests applied on the d-b-m. The results suggest that the data were not normally distributed.

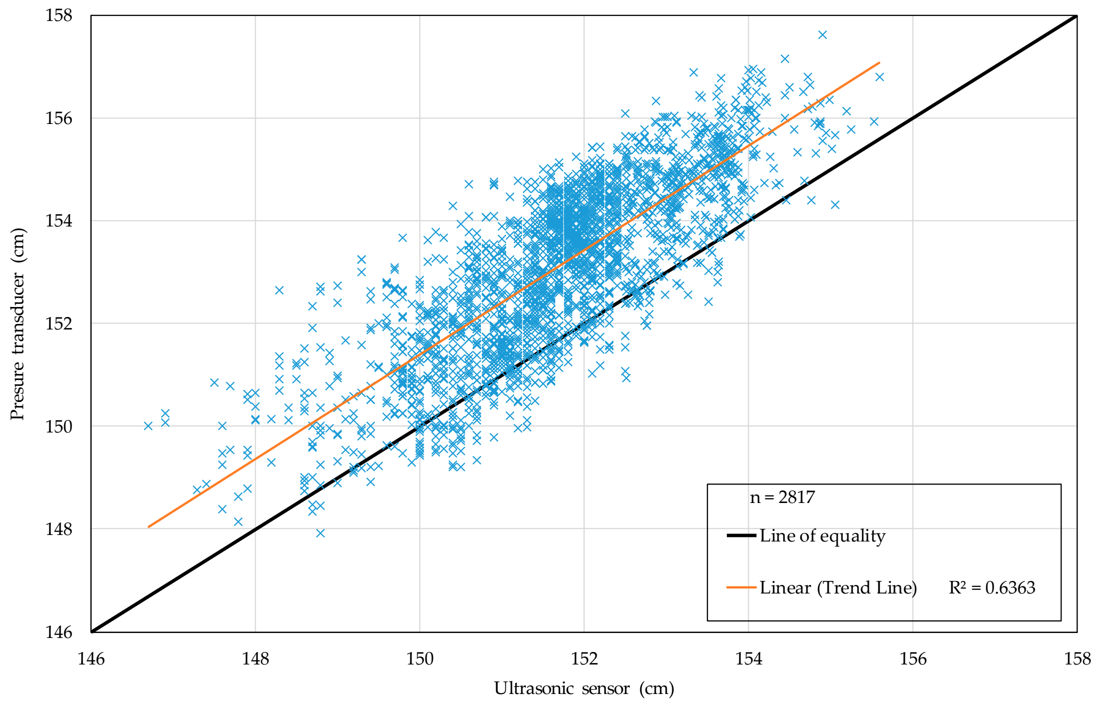
Table 3. Normality tests applied to differences between depth-of-flow measured by ultrasonic sensor and pressure transducer (June 2019).

Normality Test	N	α	t-stat	t-crit	p-value	Decision Rule	
						t-stat > t-crit	p-value < α
Kolmogorov–Smirnov	2817	0.05	0.5139	0.0256		Reject Ho	
Anderson–Darling	2817	0.05	6.3903	0.7518	0.0000	Reject Ho	Reject Ho
Jacque–Bera	2817	0.05	22.9684	5.9915	0.0000	Reject Ho	Reject Ho
Cramer–von Mises	2817	0.05	4.5720	0.2200		Reject Ho	

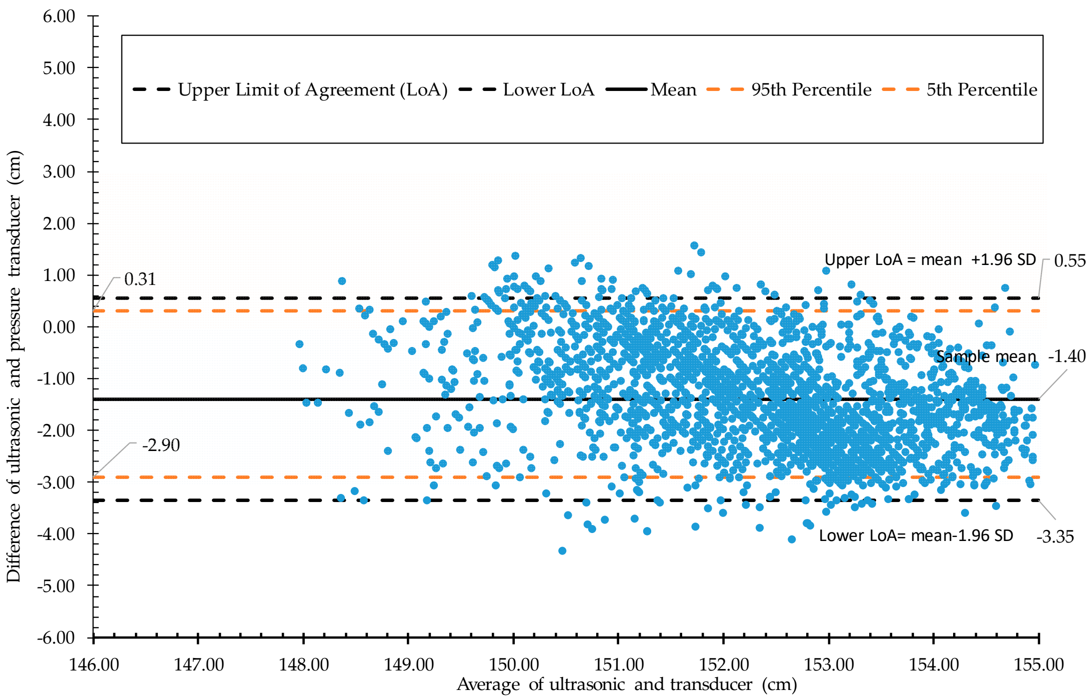
Null Hypothesis Ho = Depth-of-flow is normally distributed; Alternative Hypothesis Ha = Depth-of-flow is not normally distributed.

Figure 3a presents the depth-of-flow measured using the two sensors with a line of equality. The correlation coefficient is weak between the data ($r^2 = 0.63$). Correlation simply measures the strength of a relation between two variables, not the agreement between them. We have perfect agreement only if the points in Figure 3a lie along the line of equality, but we will have perfect correlation if the points lie along any straight line.

Figure 3b is a difference plot of the d-b-m. The mean of the d-b-m was −1.40 cm and the standard deviation (SD) was 1.00 cm. If the d-b-m values were normally distributed, we would expect 95% of the d-b-m values to lie between the extreme values or the upper and lower LoAs. These LoAs were calculated as (mean + 1.96SD) and (mean − 1.96SD). We calculate the upper and lower LoAs as 0.55 cm and −3.35 cm, respectively. About 96% of the d-b-m values lie within the LoAs in Figure 3b. With the caveat that the d-b-m values are non-normally distributed, the difference plot can lead us to conclude that the measurements agree sufficiently. On the other hand, how small or large the limits of agreement should be to conclude that the measurements agree sufficiently is a contractual, not a statistical, decision. This decision should be made in advance of the analysis and clearly defined in the DaaS at the definition stage.



(**a**)



(**b**)

Figure 3. (**a**) Depth-of-flow measured with two different sensors; (**b**) Difference plot for depth-of-flow data.

We have noted in Table 3 that the d-b-m did not pass common normality tests. In general, this will not have a great impact on the limits of agreement but suggests that we should preferably use the non-parametric approach of difference plots [34,35]. In Section 2.5.2 we explained that there are two ways to describe data while using the non-parametric approach: (i) We calculate the proportion of d-b-m values within the reference values (±1, 2, and 3 cm). These reference values are similar to the

LoAs used in the parametric approach of the difference plot. The region within the reference values ±3 cm is shaded in Figure 3b. (ii) The 5th and 95th percentiles of the ranked d-b-m values define the reference values, i.e., 5% of the data are removed from each end. The reference values thus calculated (0.31 cm and −2.90 cm) are also superimposed in Figure 3b as a dotted line (brown), and we calculate the proportion of d-b-m values within these reference values.

When we use various reference values (±1, 2, and 3 cm), a grading criterion can be defined for the sensors we used for measurements, similar to that suggested for blood pressure devices by [47]. Table 4 shows the conditions which the sensor data must meet to receive a grade of A, B, or C. The grading again is a decision made for the DaaS contract in advance of the analysis. The proportions of d-b-m values within reference values of ±1, 2, and 3 cm were, respectively, 33.5%, 69.9%, and 96.3%, so based on the selected reference value we get the scores and grades for our sensor as shown in Table 4.

Table 4. Grading of ultrasonic sensors based on differences between depth-of-flow measurements by ultrasonic sensor and those by pressure transducers.

Grade	Proportion (in Percent) of d-b-m * within the Reference Values		
	±1 cm	**±2 cm**	**±3 cm**
A	60	85	95
B	50	75	90
C	40	65	85
D	fails to achieve C		
Observed proportion and corresponding grade achieved			
	33.5	*69.9*	*96.3*
	D	*B*	*A*

* Difference between the measurements.

Table 5 shows the statistical errors calculated for depth-of-flow data from the ultrasonic rangefinders (as the x variable) and pressure transducers (as the y variable). The results show good agreement between the two data sets with MAPE and sMAPE errors of less than 1%.

Table 5. Statistical errors to assess data accuracy from the Lower Bari Doab Canal.

Number of Readings	n		2817
Mean Absolute Difference	MAD	%	1.477
Mean Standard Error	MSE	%	2.961
Root-Mean-Squared Error	RMSE	%	1.721
Mean Absolute Percentage Error	MAPE	%	0.97
Symmetric Mean Absolute Percent Error	sMAPE (Armstrong)	%	0.96
	sMAPE (Flores)	%	0.48

3.4. External Parameters

It is apparent from Table 6 that the change observed in bed elevation was relatively modest over the months. Therefore, it would be a poor use of resources to insist within a DaaS contract that the bed elevation be measured very frequently, e.g., every six months. This would make such a contract unnecessarily expensive. On the other hand, the rating curve coefficient did change substantially.

Table 6. Critical external parameters for two irrigation canals.

Canal Name	Date of Record	Av Bed Elev. (m)	Rating Eq Coeff. ($m^{4/3}s^{-1}$)	Elapsed Months	% Change Av Bed Elev.	% Change Coeff. C
Baku Shah	18 Mar 2014	163.44	0.255		Baseline	
	4 Nov 2014	163.44	0.178	7.71	0.00%	−30.18%
	1 Feb 2015	163.60	0.178	10.67	0.10%	−30.18%
	11 Jun 2015	163.60	0.202	15.00	0.10%	−21.09%
	7 Dec 2015	163.60	0.109	20.97	0.10%	−57.45%
Bhagsen	18 Mar 2014	157.16	0.643		Baseline	
	3 Nov 2014	157.16	0.511	7.67	0.00%	−20.52%
	14 Mar 2015	157.21	0.511	12.04	0.03%	−20.52%
	11 Jun 2015	157.21	0.603	15.00	0.03%	−6.21%
	7 Dec 2015	157.21	0.562	20.97	0.03%	−12.57%

Figure 4 presents the change in the rating curve coefficient for all 17 tertiary canals of the Hakra Branch Canal system from the baseline value. The change can be quite substantial and was up to +50% (based on sediment transport and moving bed load); from Equation (1) this implies a +50% change in the estimated discharge. Strictly speaking, from Equation (2) the rating curve is a function of the physical properties of a canal and should therefore not change substantially. The rating curve coefficient is the Achilles' heel of a telemetry system that relies on measuring the range to the water surface and then estimating the discharge using a rating curve of the form of Equation (3). In revisiting telemetry in the IBIS, a practical solution to this problem would be to construct dedicated measuring structures (typically flumes or broad crested weirs) whereby the rating equation can be derived semi-empirically and will not need frequent verification and validation.

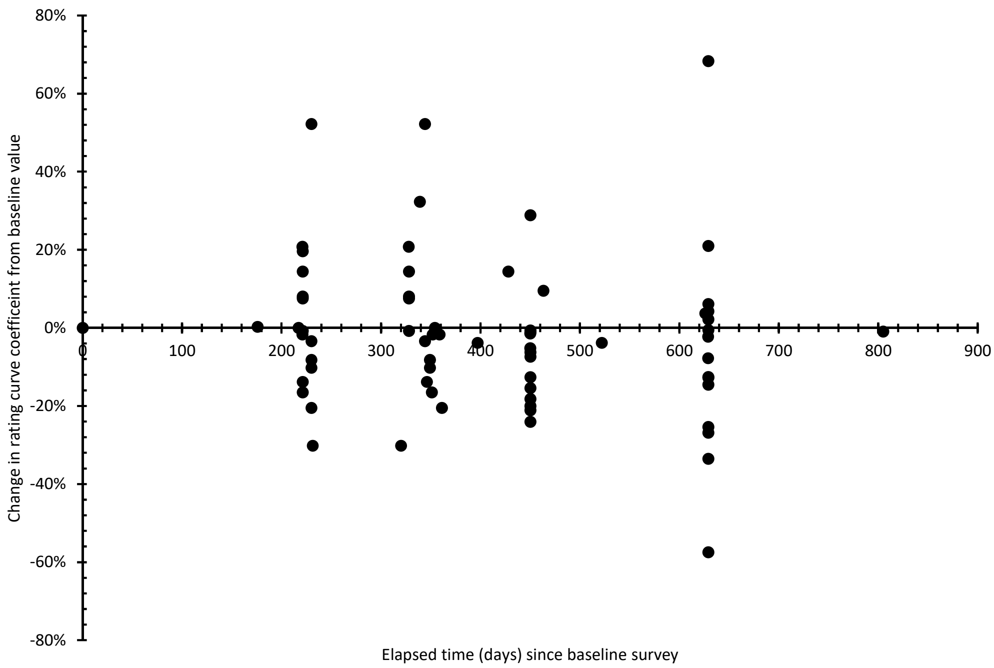


Figure 4. Change in rating curve coefficient from baseline.

Another alternative may be through direct measurement of the velocity and then only using the depth to estimate the area of flow and application of the continuity equation to estimate the discharge. Velocity can be measured directly using an acoustic Doppler current profiler (ADCP) or particle image velocimetry (PIV); however, this requires more research in the context of the IBIS shallow canals with heavy sediment loads and intermittent flows. In the absence of using technology, i.e., measurement structures or techniques such as PIV and ADCP, the only option is to stipulate in a DaaS contract that key external parameters need to be measured periodically, e.g., bi-annually, although this period is rather arbitrary.

4. Conclusions

This paper presents the experience of a pilot study of instrumenting canals in the IBIS, and the experience suggests that data as a service (DaaS) contract could be a better model rather than the more conventional approach of procuring hardware for investment in a telemetry system. A key feature of such a DaaS contract will be to ensure data quality. This work offers insight into a data quality process. A six-step data quality process was proposed in this research: definition, assessment, analysis, control, implementation, and improvement. The authors performed an assessment of data quality covering attributes such as the integrity, timeliness, and accuracy of the acquired data. The authors developed a new statistical indicator for data timeliness and also applied various statistical indicators to assess data integrity and accuracy. The results of instrumentation suggest that statistical limits (upper or lower bounds) can be set for these indicators in DaaS, beyond which punitive measures may be applied.

The assessment results show that the ultrasonic sensors installed at four canals performed reasonably well. The data integrity during the reporting period was in the range of 92.1 to 99.8 percent, showing very little data loss. The lower bound of latency per day in this research was 6.21 h. The average latency per day was 8.37 h to 17.10 h during the reporting period. This is higher than the lower bound, but considering the poor Internet connectivity at these remote locations, it is deemed acceptable. The latency can be improved by changing the transmission frequency but with the caveat of consuming more power. The data accuracy was assessed by comparing data collected independently by two sensors. The statistical analysis shows that the data were not distributed normally. The analysis of difference plots showed that a non-parametric approach to compare methods is particularly useful in this case when the difference between the methods does not have a normal distribution. The statistical errors, e.g., the mean absolute percentage error (MAPE) and its symmetric forms, can be good indicators to compare data from two sensors. In our analysis, we found statistical errors of less than one percent.

In a DaaS contract, the results from the assessment step and compliance with the statistical limits would then be analyzed by a data quality assurance (third party) organization. This will constitute the third step of the data quality process. The quality assurance organization can also analyze the root causes for inferior data quality (if that is the case). The analysis will help in identifying the weak links in the data acquisition, processing, and communication processes. The next steps of the data quality process will deal with improvement based on the analysis and, finally, implementation and quality control.

The authors suggest an iterative approach for a DaaS contract based on this pilot study. In the first iteration, the data contractor provides only one variable, i.e., depth-of-flow, because it involves a lower number of external parameters. In a second iteration, the data could be processed with external parameters to obtain further information, e.g., discharge, volume, proportions, etc. This would avoid the pitfall of a contractor being blamed for errors in the rating curve coefficient, which may be outside his/her control and may lead to endless disputes which, in turn, may yet again jeopardize the development investment.

In a flow measurement system that relies on measuring depth-of-flow and then using a rating curve to estimate discharge (assuming uniform flow), this rating curve is the weakest link in the system. A concerted effort needs to be made in the IBIS to replace this practice by constructing dedicated measuring structures (flumes or broad crested weirs) and/or to explore new technologies that might allow direct measurement of velocity and avoid using rating curves altogether.

With the renewed interest of the Government of Pakistan in investing in a telemetry system in the IBIS, it is important to learn lessons from the earlier investment made in 2004, particularly with respect to the data quality. This research exploits developments in technology—particularly in information and communication technology—and demonstrates the automation of flow at a few canals at key locations of the IBIS. The results from this research can inform future investment in a telemetry system.

Author Contributions: Conceptualization, M.T.B. and A.A.A.; methodology, M.T.B.; software, M.A.A.S.; formal analysis, M.T.B.; writing—original draft preparation, M.T.B. and A.A.A.; writing—review and editing, M.T.B. and A.A.A.; supervision, A.A.A.; project administration, A.A.A. and M.T.B.; funding acquisition, A.A.A.

Funding: IWMI is in receipt of financial support from the Department for International Development, U.K., Grant #202775-111, and The United States Agency for International Development, Grant # 72039118I000003, which were used in part to support this study and/or prepare this manuscript.

Acknowledgments: We would like to thank the reviewers for their helpful comments and for improving the manuscript. The authors wish to acknowledge the contribution of Mr. Muhammad Awais, intern at IWMI Pakistan, in troubleshooting the hardware and Muhammad Hamza for preparing GIS map. The study design, data collection, analysis, and interpretation of the results are exclusively those of the authors and do not necessarily represent the views or opinion of the International Water Management Institute (IWMI) or the CGIAR Research Program on Water, Land and Ecosystems.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

Notation

Δ	data processing delay
B	width of canal
C	rating curve coefficient
H	depth-of-flow
i	index, 0,1,2, ...
$\mathcal{L}$	latency
N_S	sample size aggregated at the data logging period
n_r	roughness coefficient
n	number of non-missing data points
Q	discharge, determined empirically
S	bed slope of canal
T_D	data logging period
T_S	data sampling period
T_T	data transmission period
x_i	actual data
y_i	estimated or forecasted data
$\|\|$	absolute values.

Appendix A

Table A1. Main instruments of the Indus Telemetry.

Sr #	Component Description	Manufacturer	Model #
1	Data Logger	Campbell Scientific	CR 800
2	Range Finder	APG	IRU-6429
3	Modem	Sierra Wireless	LS 300
4	Rechargeable Battery 12 V	Any Manufacturer	12V
5	Solar Panel 10 W	Campbell Scientific	SP-10
6	Charging Regulator 12 V	Campbell Scientific	CH-200
7	Pressure Transducer	Eijkelkamp Soil & Water	CTD-Diver
8	Omni Cellular Antenna 800 MHZ	Campbell Scientific	1 db
9	Allied Cables, Mountings, Surge Suppressors	Campbell Scientific	

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