WATER MANAGEMENT INITIATIVE (WMI)

Report on the Determination of KAC Water Losses and Recommended Solutions for Improvements; Situational Assessment

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WATER MANAGEMENT INITIATIVE (WMI)

Report on the Determination of KAC Water Losses and Recommended Solutions for Improvements; Situational Assessment

Intervention No. 3.3.7: Support Improving the Conveyance System Efficiency in Jordan Valley

May 2018

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EXECUTIVE SUMMARY

BACKGROUND

The Water Management Initiative (WMI) is a 5-year project to support the Government of Jordan to achieve measurable improvement and greater sustainability of the water sector. WMI is aiming to produce substantial improvement in the water sector in Jordan, supporting the best management of the existing water resources and strengthening preconditions to change. To build good and effective water resources management strategy, it is very important to have a detailed quantitative knowledge of the available resource.

King Abdallah Canal (KAC) is 110 km long concrete lined open canal. It was built in phases from 1961 to 1987 with a total of 37 check gates, and a head discharge capacity of 14.5 m^3s^{-1}. It is the main conveyance system for irrigation water in the Jordan Valley in addition to its role in conveying a portion of drinking water to the capital city of Amman. As such, reliable estimates of quantities and extent of losses from the KAC are important to avoid unnecessary losses, and to recommend areas for refurbishment or enforcement.

The KAC has a Supervisory Control and Data Acquisition (SCADA) system installed to monitor and control canal levels, storages, inflows and outflows. The SCADA system enables centralized operation, but also has issues with several inoperable sensors and significant measurement uncertainties.

The KAC is divided into two main sections: 1) Upper KAC, 65km long, fed by fresh water and used for domestic and irrigation purposes; 2) Lower KAC, 45km long, fed by blended water and used for irrigation. The focus of this Phase 1 draft study is on KAC North. It is recommended that additional measurements in different seasons and irrigation regimes be made to further refine these results and extend them into the lower KAC.

Illegal and unmonitored withdrawals from the KAC is one of the important component of the losses in the canal that may count for high percentage of the administration losses. 24- hour measurements of the water flow in the canal are required to quantify these withdrawals and gives a reference for this quantity.

The quantitative measurement of water losses in KAC is supporting Activity 3.3 Divestment of Irrigation Management to Water User Associations (WUAs) Supported. The consultant for this assignment, performed the following tasks under the supervision of USAID-WMI project.

OVERVIEW AND APPROACH

The primary goal of this first phase of the “Determination of Water Losses in the KAC Conveyance System” project was measure the total losses for each reach of the upper KAC (0-65km), and to determine the relative contribution of evaporation, seepage, and unmetered/illegal use to the total estimated loss. The results presented here are based on observations made in July and October 2017. These results will be updated as more measurements can be obtained from different seasons and water demand scenarios.

Towards this goal nearly 1000 instantaneous discharge measurements were made using the Sontek M9 Acoustic Doppler Current Profiler (ADCP) in July and October 2017, and about 25 days of continuous 5-minute Sontek-IQ ADCP (over 7000 discharge measurements) were collected in October 2017. These observations were analyzed, combined and compared with observations made by the KAC-SCADA system to derive initial estimates of losses for the upper KAC.

The methodology for assessing losses was to measure flow in the canal as accurately as possible at each end of a canal reach, and account for or measure all inflows and outflows into that reach. The difference in flow, less the storage changes, inflows and outflows, and evaporation is the reach loss. A KAC reach is generally defined by operational check gates at either end of the reach that define a continuous canal reservoir. The approach assumes that leaks are relatively constant, and that unmetered/illegal withdrawals change quickly. Instantaneous flow measurement differences provide total loss estimates, and continuous flow measurement differences provide estimates of the partitioning of this loss into consistent loss (seepage) and intermittent loss (unmetered/illegal). Separate estimates of evaporation were modeled using weather and satellite data and are relatively small compared to other losses.

Both instruments, the Sontek M9 and the Sontek IQ, use acoustic Doppler pulses to measure water velocities. The more accurate M9 is mounted on a small boat that is pulled across the canal; as it crosses the canal, it measures water velocities at many different levels, which are integrated to determine the total flow. Six M9 flow measurements were usually made at each location on the canal; outlier measurements were assessed and discarded, and the remaining measurements were averaged. The same M9 was used to make all the measurements, so any bias it may have cancels out when the reach outflow is subtracted from the inflow to find the loss. However, the M9 cannot make continuous flow measurements, so it could miss short-term losses that are characteristic of intermittent unmetered and illegal uses. It was also found that unaccounted canal dynamics could compromise the M9 measurements (for example, if the canal levels and flow changed quickly during the measurement, or if pumps are turned on or off during the reach measurement). It was also found that the flow measurements varied widely based on the positioning technique. The M9 can determine its position through Differential GPS (DGPS) or Bottom Tracking (BT). BT appears to be the preferred technique unless there is a smooth channel bed or a moving bed. Therefore, optimal selection of positioning was done during an extensive post-processing analysis step. The position calculations were done both ways and spurious observations were eliminated from the analysis.

To alleviate these issues, the M9 measurements were supplemented with Sontek IQ measurements. The IQ is specifically designed to measure canal flow and is placed at the bottom of the canal and left there for an extended period – for this project about 24 hours. This was ideal for KAC application because the IQ can be "hidden" below the opaque water and out of notice of illegal users. Three IQ instruments were used, allowing two consecutive reaches to be measured each day. The IQ introduced many technical challenges ranging from developing a waterproof battery pack to developing a suitable and safe deployment and retrieval apparatus. Some of the most challenging issues for the IQ involved trash and sediment in the KAC obscuring the IQ sensors, and independent bias when comparing measurements from different instruments.

The measurement approach for this project evolved as knowledge was gained about the nature and operation of the KAC. The operation of KAC inflows, pump stations, check gates, canal storage, and unmonitored withdrawals are changing constantly causing various waves to occur in the canal. These waves can travel both up and down the canal at a wide range of speeds but are mostly governed by the velocity of the water in the canal. Measuring the canal while it is changing introduces uncertainties; ideally reach measurements would be performed under steady-state conditions. Absent steady-state conditions, the initial approach taken in July 2017 was to measure each reach with the M9 as quickly as possible, so that changes would be minimized. The SCADA water levels were used to track storage changes in each reach while the measurements were done. Manual water level measurements were also selectively performed and found to disagree with the SCADA water level observations. This discrepancy combined with July 2017 reach measurements showing relatively high loss errors, led to a revised measurement approach in October 2017. Rather than making the reach measurements as quickly as possible, a "follow the water" approach with manual stage change measurements was adopted. This approach essentially uses M9 water velocity measurements to calculate how long it takes for the water to flow down the reach. This timing was then imposed on the M9 measurements to measure the same water as it flowed into and out of the reach. A similar delay is calculated and used to analyze the IQ data.

An in-depth post-processing and numerical analysis was performed with the M9, IQ, and SCADA measurements to access loss estimates and attribution. The heart of this analysis is a reach-by-reach water balance assessment, with the loss calculated as a residual of the water balance. Conservation of mass is amongst the most fundamental science principals: for each reach, the water balance dictates that the water output subtracted from the input must equal the change in storage.

MAJOR FINDINGS & CONCLUSIONS

The total water losses for the 65km of the upper KAC are estimated to be 24.4% of the maximum flow, partitioned between 10.7% being constant/seepage, and 13.7% being unmetered/illegal uses. If accounting for evaporation, the total loss would increase by about 1% to 25.4%, with the constant/seepage and unmetered/illegal percentages staying the same.

Some of the largest losses were seen in reach 6, which is a very complex hard-to-measure reach because it contains 4 outlets (Gravity Line 6, PS21, Gravity Line 5, and PS22). After assessing the losses in this reach, it was discovered that substantial part of the losses is legal but unmetered. Accordingly, the measurements were repeated for this reach after stopping all legal abstractions. The newly obtained result was used in the analysis. None-the less, this reach also shows a relatively high unmetered/illegal use (72% of the loss is unmetered/illegal). Reaches 10, 11, and 12 also show relatively high losses – these reaches are in complex terrain that is more likely to absorb seepage from the canal and is a relatively easy area to establish siphons. Reaches 1 and 2 are some of the oldest in the KAC system and have significant damage. Reaches 1 and 2 show high physical losses and reach 1 shows a relatively high unmetered/illegal loss. The lower reaches, near the control center have some of the lowest losses, likely because the terrain is smoother and already saturated, and the canal is better monitored in these areas. Reaches 1-4 show an elevated constant loss likely due to the older age of these canal sections – this could be a good area to target for repair work. Reach 15 shows a high unmetered/illegal loss and may be a good area to increase security of remove illicit pumps.

Some special measurements were made to assess losses in the tunnel and siphons. Despite some evidence of minor leaks seen in the siphons, these structures appear to lose very little water. In fact, some M9 observations showed that the tunnel may be gaining a bit of water (i.e. through underground springs), but that would have to be confirmed with additional measurements.

The utility of having multiple measurements over several seasons is well demonstrated, as it allows outlier data to be identified and eliminated.

MAJOR RECOMMENDATIONS

A summary of the recommendations to reduce KAC loss are below:

- Refurbish lining and fix cracks in older sections showing higher constant losses.
- Refine canal surveillance procedures and security to discourage or eliminate illegal abstractions.
- Require that all inflows and abstractions to be monitored by SCADA. You cannot manage what is not measured.
- Regularly inspect and document canal liner and embankments for sloughs, slumps, bulges, depression, and cracks. Inspections following floods and high flows is especially important. Geolocated photographic evidence is recommended.
- Perform routine cleaning of canal sediments and trash, especially in check gates.
- Systematically remove vegetation from the canal as its roots open cracks and leaks.

- Decrease trash load in the canal, which can obscure SCADA observations, flow estimates, and control.
- Repair and calibrate SCADA system – there are many malfunctioning instruments, and inaccurate flow calibrations.
- Repair leaks in pump stations, repair trash racks, and automate pump stations.

A summary of the recommended next steps to advance this study are below:

- **Lower KAC losses**: Measure and assess losses in the lower KAC.
- **Refine KAC loss estimates**: Refine the KAC loss assessments with measurements from more seasons and irrigation regimes.
- **Longer-term loss partitioning estimates**: Make IQ timeseries measurements over longer periods of time to capture more loss dynamics.
- **Improve IQ measurements:** Make IQ measurements with more M9 calibration points to account for accumulating bias.
- **SCADA calibration:** Make targeted M9 measurements to calibrate the SCADA, which would involve rebuilding rating curves for each gate (multiple M9 measurements at different flow rates). Manual stage measurements and repair of dysfunctional SCADA sensors is also recommended.
- **Long-term loss assessments:** Use calibrated SCADA data to assess long-term loss dynamics in the KAC.
- **Hydrodynamic Loss Modeling:** Use a hydrodynamic model conditioned on M9, IQ, and SCADA data to model KAC losses.

1.0 INTRODUCTION

1.1 WMI PROJECT

The Water Management Initiative (WMI) works on providing the technical support to the water sector to improve efficiency and promote sustainability. It places emphasis on strengthening preconditions to change, such as building service provider autonomy, increasing performance-based accountability, and moving toward commercialization at the service level, all enabled by strong public outreach. WMI is built on the understanding that transformational and sustainable change must originate from broad-based local support in a process owned by all relevant stakeholders. WMI has the following four components and primary activities:

- **Water Supply Systems:** Support development and implementation of a Performance Improvement Plan to improve Yarmouk Water Company´s (YWC) financial performance; support implementation of the IMF Structural Benchmark Action Plan to Reduce Water Sector Losses; and support improvement of Zarqa Water Authority´s (ZWA) Key Performance Indicators (KPIs).
- **Water Conservation and Demand Management**: Support GOJ to strengthen utility demand-side management and support behavior change communication (BCC) in the sector.
- **Water Sector Governance:** Develop and modify utility Assignment Agreements (AA) to improve performance; support divestment of irrigation management to Water User Associations (WUAs); develop and support an independent sector regulator; and support water sector strategic communications, advocacy, gender, and youth.
- **Protection of Water Supply:** Develop a groundwater management framework; strengthen wastewater treatment performance and compliance; and improve water quality management.

WMI works with the water sector in Jordan to overcome various challenges facing the sector including limited water resources and the unpredicted increase in population numbers due to the political situation in neighboring countries, which has placed huge pressure on the already overloaded resource and infrastructure service.

One of the important areas that WMI works on is to support JVA Improving Conveyance System Efficiency in Jordan Valley. As such, reliable estimates of quantities and type of losses from KAC are important to avoid unnecessary losses and to recommend measures to reduce such loses.

1.2 HYDRAULIC SCHEME IN THE JORDAN VALLEY

The hydraulic scheme in the Jordan Valley consists of king Abdallah Canal (KAC) that receives water from Yarmouk River and Wehda Dam and connected directly to network of pressurized pipes that deliver water, by pumping and by gravity, to farm units for agricultural and for domestic uses. In addition to KAC, there are 14 Dams with capacity of 336 MCM spread on the borders of the Jordan Valley to supply water for irrigation, domestic and industrial uses. The schematic below describes the hydraulic scheme in the Jordan Valley.

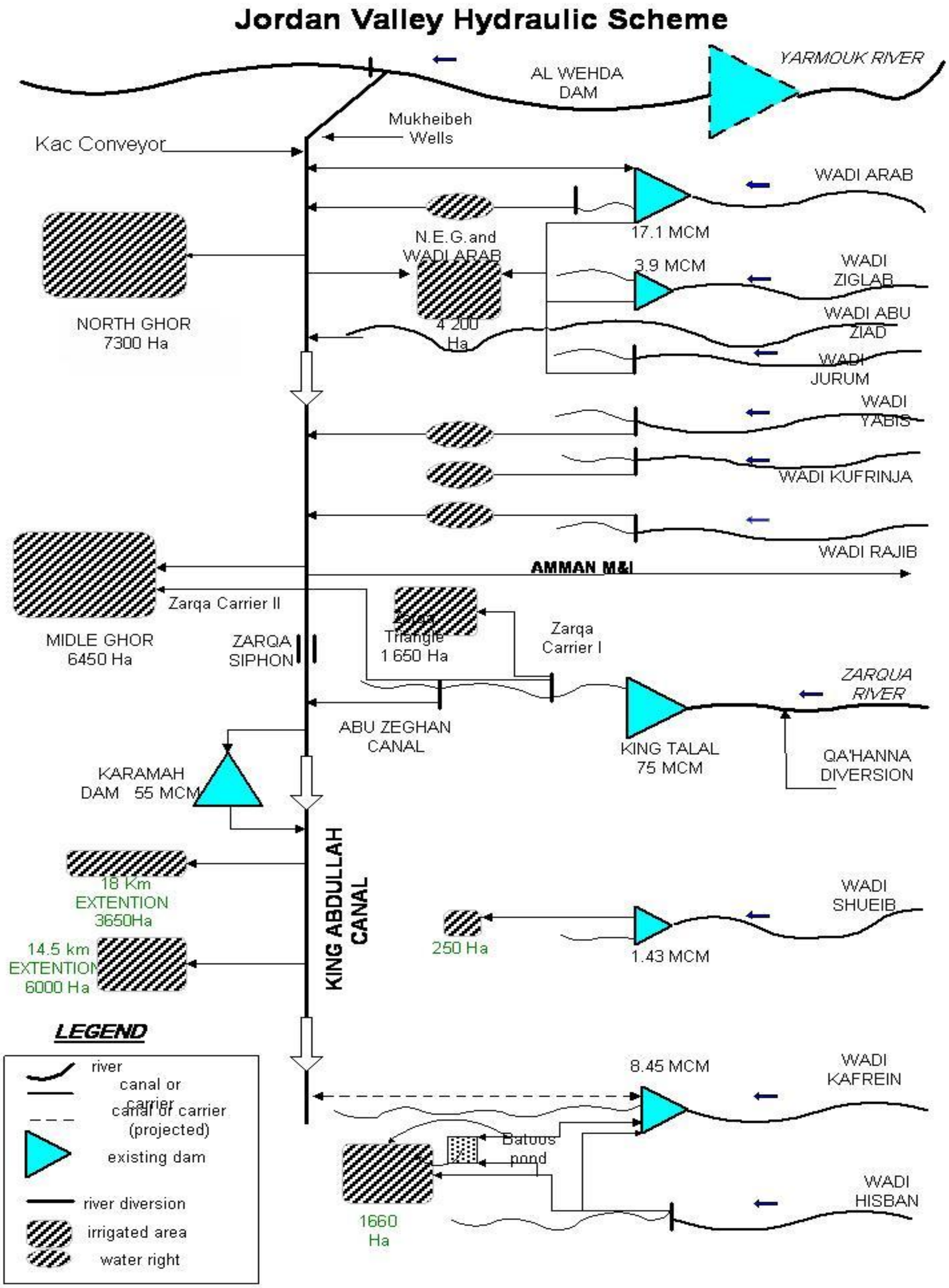


Figure 1: Jordan Valley Hydraulic Scheme

1.2.1 King Abdullah Canal

The King Abdullah Canal is running on the East bank of the Jordan River constitutes the backbone of the Jordan Valley hydraulic scheme. It is 110 km long concrete lined open canal with a head discharge capacity of 14.5 m3/s. It was built in phases from 1961 to 1987. The KAC presents two main sections; KAC North, 65 km long and KAC South, 45 km long. KAC North is fed by, the Yarmouk River including Wehdeh Dam, the Mukheibeh Wells, the KAC conveyor (water supplied from Lake Tiberias under the Peace Treaty since June 1995), and the side wadis whenever water is available, and provided that its quality is acceptable for domestic use. In winter in case of flood, the Yarmouk River water is able to provide for all Northern and Middle valley's water requirements, and KAC South is therefore supplied by KAC North via a 12 m3/s siphon connecting the two sections based on water availability. KAC South provides water to farmers, as well as to the Karama Dam which stores winter water. the King Talal Dam supply KAC South for irrigation. The KAC is controlled by a total of 37 cross regulators (check gates) consisting of radial gates with two weirs on each side.

Automation of the King Abdullah Canal helps to automatically monitor and control 95 km long of King Abdullah Canal (KAC). All the inflows into the canal and the outflows from it are continually measured and observed at the control center in Deir Alla, and the check gates along the 95 km of the canal are remotely adjusted from the center. The telemetry system gathers the following measurements:

- All KAC inflows, either through level sensors associated to thin plate weirs, or through flowmeters
- All KAC outflows (through flowmeters), and status of pumping station
- Upstream and downstream level, gate opening of 27 KAC check gates
- Water salinity in various part of the KAC
- Water levels, volumes and flow release at the main reservoirs
- Flow at main carriers

The measured data is transferred through wireless and GSM systems to JVA Control Center where it is displayed by a SCADA software. From the Deir Alla Center, the operator can assess the global status of the King Abdullah Canal. In addition, the operator can remotely control the KAC tunnel entrance gate (Yarmouk River), and the 27 measured cross-check gates.

Dynamic Regulation relies on the program of outflow (provided by the WMIS) and on the measured KAC water levels and inflows. Based on this data, target volumes and flows are computed in each canal reach. The results are updated every 15 minutes through a PID.

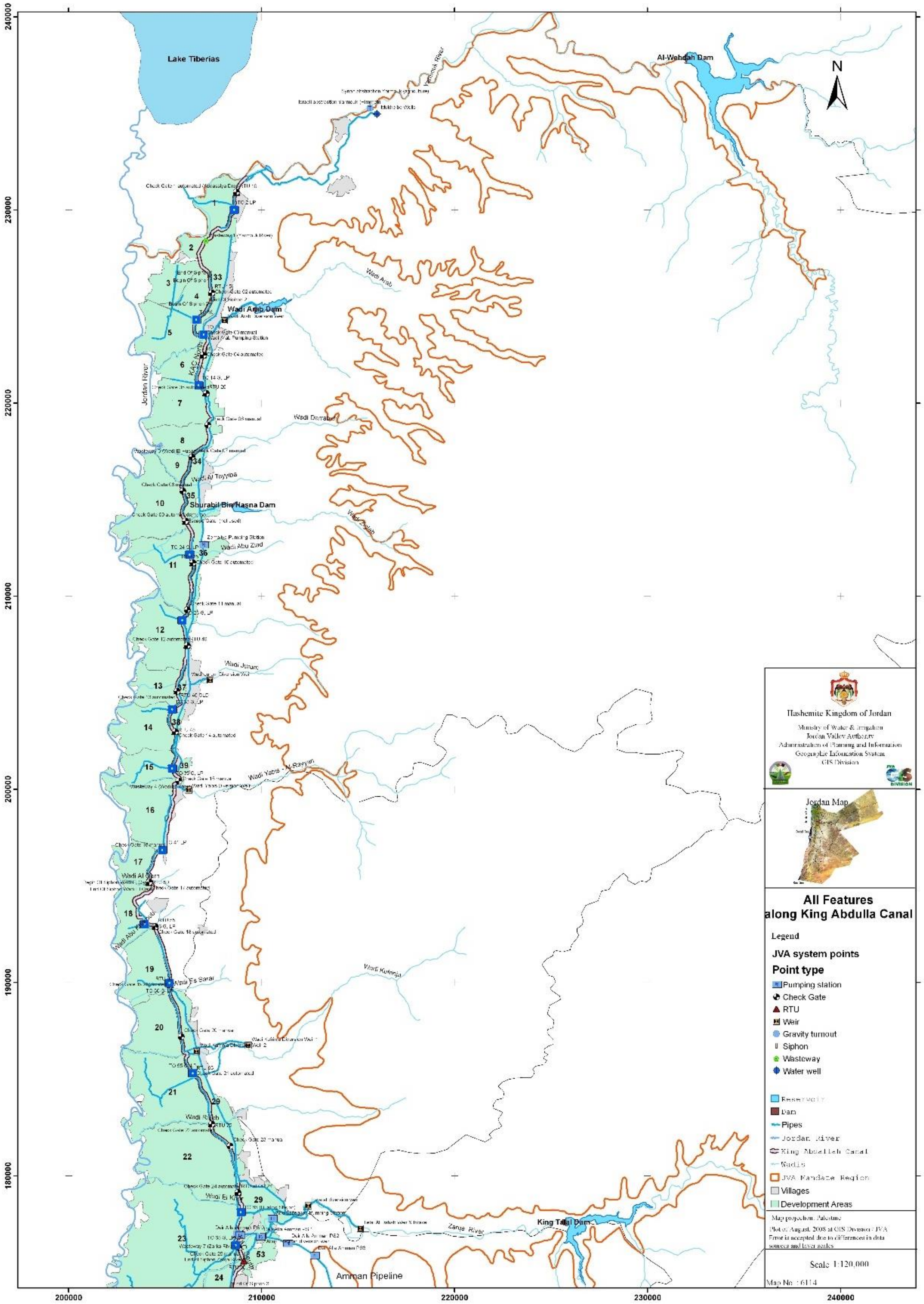


Figure 2: Map of the King Abdullah Canal (KAC)

1.3 BACKGROUND ABOUT THE OPEN CANALS (LINED) WORLDWIDE AND THEIR EXPECTED PHYSICAL LOSSES WITH AGE

Estimation, measurement and reduction of losses from open canals has been of concern to irrigators for decades. Lancaster (1952) identifies that a large portion of the water diverted into irrigation channels is lost in transit through (a) leakage, (b) waste, (c) evaporation, (d) transpiration, and (e) seepage, Lancaster (1952) defines leakage as the water lost through poorly maintained gates and structures. Waste represents the amount which is lost through automatic wasteways or merely discharged into wasteways, perhaps during flood events. The rate of evaporation from irrigation canals has been measured in several instances with the floating-type pan, and in nearly all cases the quantity is negligible, hence this source of loss can be ignored. Transpiration losses from vegetation growing inside or near the canal are also small. However, Lancaster (1952) reports that on average 30 percent of all water diverted for irrigation in an unlined canal is lost by seepage, and 15 percent for a lined canal.

Lancaster (1952) identifies the following methods to measure the seepage from canals:

- **Inflow-outflow method:** involves the measuring of the flow into a certain section, and the flow out of the section, the difference being the seepage after correction for any flow through turnouts in the reach. This method requires either very long reaches or very accurate discharge measurements.

- **Ponding method:** requires the construction of dikes in the canal to segregate a particular section. The section is then filled with water, usually by pumping, and the measure of the drop-in water surface for a certain period combined with the physical dimensions of the area ponded, will permit computation of the rate of seepage.

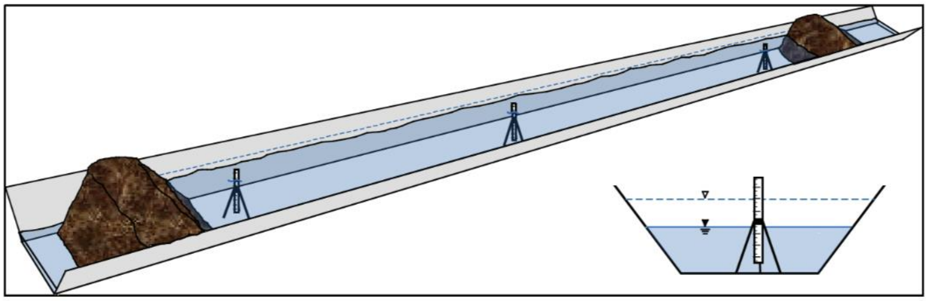


Figure 3: Ponding Test (Leigh and Fipps, 2017)

- **Constant and variable head permeameters or seepage meters:** consists of a pipe placed in the bottom or sides of a canal. The head of water is maintained in the pipe equivalent to the depth in the canal. The constant head is maintained with a tank inverted on top of the pipe. Models of water flow and interaction with groundwater under the canal can be used to estimate seepage loss.

Determining canal seepage is usually a difficult undertaking. Fluctuations in canal levels as well as groundwater levels can lead to variations throughout a year and within an irrigation season. Additionally, the amount lost to seepage often falls within the discharge measurement errors of traditional methods.

The ponding method was long considered the only viable option for reliable seepage estimates. Permeameters require installation prior to canal construction, and the inflow-outflow method requires highly accurate discharge measurements generally considered impossible with manual flow meters. However, with the relatively recent development of acoustic doppler current profilers, discharge measurements are now accurate enough for seepage estimates using the inflow-outflow method (Mohsen and Mohammed, 2016). Virtually all previous studies require that the storage in the canal was not changing (steady-state); if water level changes were detected during the measurements, then the measurements were discarded.

It may also be possible to estimate seepage loss directly using an ADCP to map the 3-dimensional flow field of the canal. This would involve moving the ADCP along the canal as well as side-to-side to identify and measure water flowing into cracks in the canal liner. This method has been successfully implemented to measure springs in the bottom of rivers.

Saha (2015) summarizes canal seepage losses from many previous studies which vary dramatically depending on the underlying soil characteristics, canal geometry, and liner. In this study, seepage was expressed as a conveyance efficiency. Unlined canals have had measured conveyance efficiencies as low as 32% (68% of water is lost). Lining a canal can reduce water loss by as little as 10% and as much as 22.5%. A study of the Kim branch canal, Gujrat found seepage losses can be reduced to nearly 87.68%,99.3% and 99.7% by using brick lining, P.C.C lining, P.C.C with L.D.P.E. film lining respectively (Kavita A. Koradiya, R.B.Khasiya ,2014).

Kinzli et al., (2011) reports that the average water conveyance efficiency in the United States in 78%. In the lower Rio Grande Valley, canal seepage accounts for 30-36% of the total water diverted, with negligible evaporation. Their study used the inflow-outflow method with an ADCP over ~3km reaches, finding seepage losses ranging from 0.64% to 1.93% per kilometer, with no statistically significant seasonal variation.

The literature shows that estimating and measuring canal losses, especially seepage is a very time consuming, expensive, and challenging task. This task has become easier with the relatively recent development of the ADCP, however there are no studies that show how losses change with canal age. One of the most comprehensive canal seepage studies was done by Molina, (2008) who evaluated seepage in 11 irrigation canals in the Logan and Blacksmith Fork Irrigation Systems of Cache Valley, Utah. The measurements were performed from June to October 2008, using the inflow-outflow ADCP method to measure seepage. Spatial variation was observed along each canal in which a descending trend of the mean seepage loss was found in the downstream direction. Additionally, spatial variation was found between canals, the reaches

located in the east part of Logan city presented higher seepage losses than reaches on the west

side of the city. Canals on steeper slopes and in areas of lower groundwater levels showed more seepage. Temporal variations were identified by a monthly comparison of seepage losses

within reaches which indicated higher seepage losses during late July and August.

1.4 OBJECTIVES AND SOW

WMI is aiming to produce substantial improvement in the water sector in Jordan, supporting the best management of the existing water resources and strengthening preconditions to change. To build good and effective water resources management strategy, it is very important to have a detailed quantitative knowledge of the available resource.

King Abdallah Canal, 110 km long concrete lined open canal, is divided into two main sections: 1) KAC North, 65km long, fed by fresh water and used for domestic and irrigation purposes; 2) KAC South, 45km long, fed by blended water and used for irrigation. The KAC has a Supervisory Control and Data Acquisition (SCADA) system installed to monitor and control canal levels, storages, inflows and outflows. The SCADA system enables centralized operation, but also has issues with several inoperable sensors and significant measurement uncertainties

The primary goal of this first phase of the "Determination of Water Losses in the KAC Conveyance system" is to physically measure the losses in KAC-North, 65 km long, using SonTeck M9 ADCP (Acoustic Doppler Current Profiler) instrument during summer high use/evaporation season.

Illegal and unmonitored withdrawals from the KAC is one of the important component of the losses in the canal that may count for high percentage of the administration losses. To capture day/night dynamics of evaporation and illegal use, a SonTek IQ$^+$ ADCP that can be hidden at the bottom of the canal, was used to make measurements on specific reaches over a 24-hour period to quantify these withdrawals and gives a reference for this quantity.

It is recommended that additional measurements in different seasons and irrigation regimes be made to further refine these results and extend them into the lower KAC.

Figure 4: Unmonitored Extractions from the KAC, July 2017

Figure 5: Damage to KAC Lining

Figure 6: Trucks Extracting Water from KAC

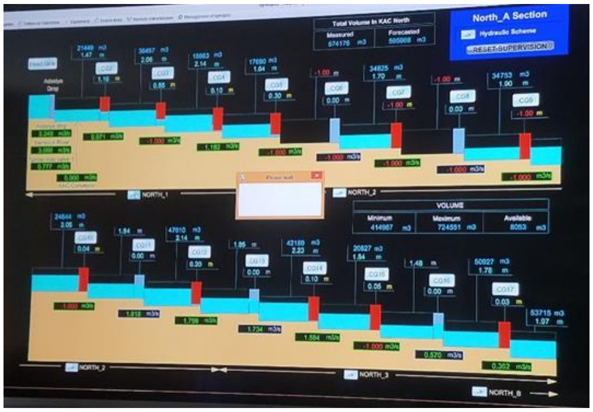


Figure 7: The KAC-SCADA Control Center

The quantitative measurement of water losses in KAC is supporting Activity 3.3 Divestment of Irrigation Management to Water User Associations (WUAs) Supported. The consultant for this assignment, performed the following tasks under the supervision of USAID-WMI project.

1. Identify and help procure required ADCP equipment.
    a. One SonTek M9 ADCP
    b. Two SonTek IQ+ ADCPs
2. Identify KAC reaches and locations to be measured.

3. Perform SonTek M9 measurements at selected reach locations.
4. Perform SonTek IQ+ measurements at selected reaches where unmetered/illegal withdrawals are expected.
5. Retrieve relevant SCADA data for the reaches and times measured by the ADCPs.
6. Perform a desk analysis to determine losses and attribute them to evaporation, seepage, or unmetered/illegal for each reach.
7. Identify the canal reaches with the largest issues and determine overall canal losses.
8. Reporting results and suggesting recommendation measures to overcome/reduce losses.

2.0 WATER BALANCE IN JV

2.1 WATER LOSSES IN THE UPPER KAC BASED ON JVA WATER BALANCE

JVA on yearly bases produce their report on the amount of water produced from all the resources and the amount of water used for the different uses. For the purpose of this report, the consultant extracted the data related to the calculation of the administrative losses occurred in the northern part of KAC (the first 65 km) for the period 2010 to 2016.

The table below shows a summary of the losses results, Annex (A), shows more detailed data about the water balance of the northern part of KAC.

Year	Total Delivered to KAC (MCM)	Total Released from KAC (MCM)	Losses in KAC (MCM)	% losses in KAC
2010	109.65	95.29	14.36	13.10%
2011	100.27	82.84	17.43	17.38%
2012	119.47	98.67	20.8	17.41%
2013	148.05	122.89	25.16	16.99%
2014	131.4	108.64	22.76	17.32%
2015	143.94	115.75	28.19	19.58%
2016	158.51	124.59	33.92	21.40%

As shown in the table, the annual conveyance losses in the upper KAC have are increased by 20 MCM between 2010 to 2016. Part of these losses could be unavoidable, but a substantial part is manageable to be avoided in case it is analyzed precisely.

Figure (8) illustrates the losses calculated by the WMI team for each part of the network to emphasize the part with high potential losses that we need to concentrate on with further analysis. It worth to mention here that the calculation of the losses in the distribution system was based on the water quantities delivered at the pumping stations and gravity turnouts based on water orders by the farm units within the distribution network. Due to the malfunction of most of the water meters at the farm gates, it was not possible to calculate the losses in the distribution system precisely.

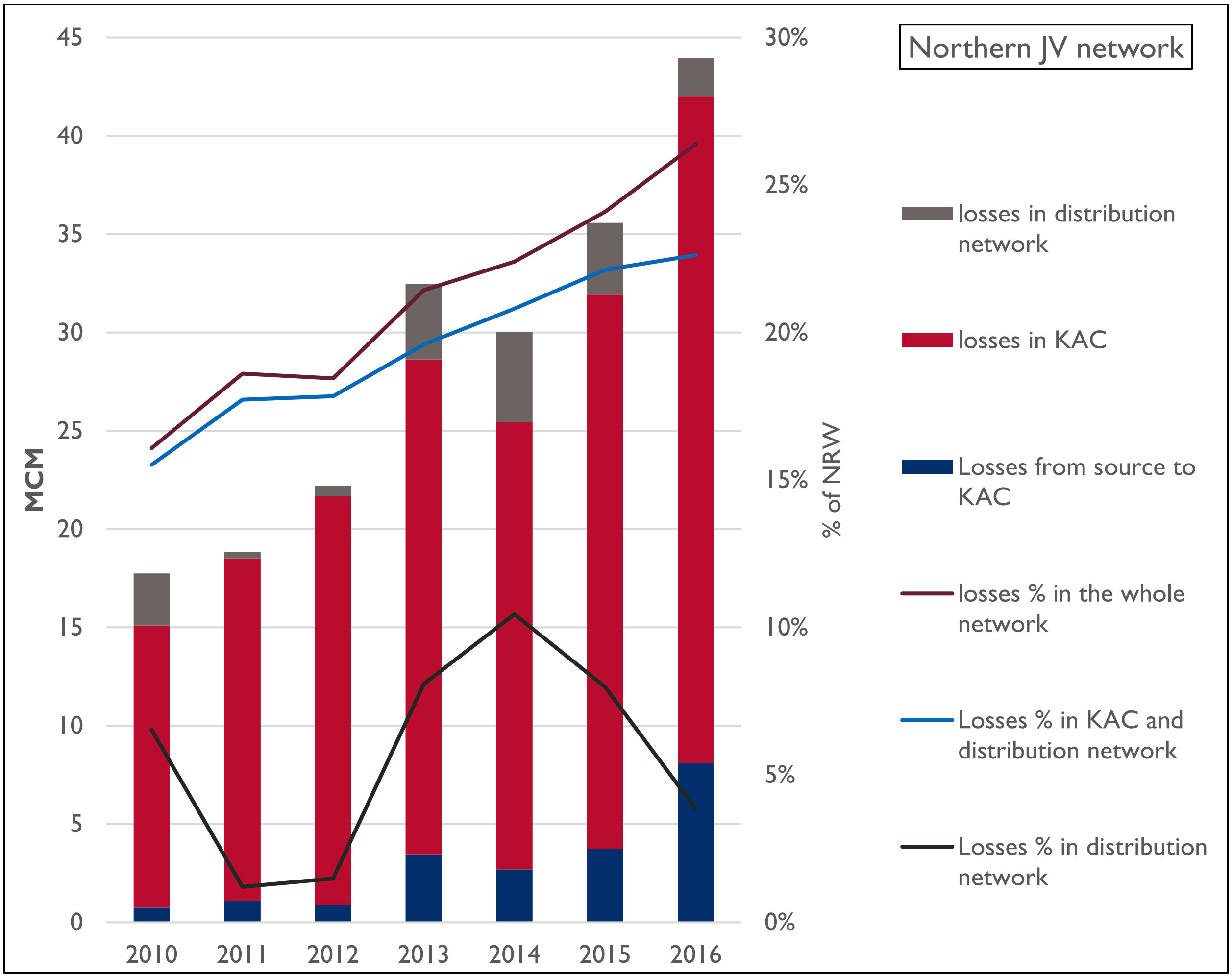


Figure 8: Losses in the Different Part of the Northern JV Network

3.0 METHODOLOGY

3.1 INSTRUMENTS USED

The instruments used in this study are both advanced Acoustic Doppler Current Profilers (ADCP) adapted for different objectives. The SonTek M9 is a boat-based down looking profiler that can make rapid and highly accurate current measurements in both canals and streams. The SonTek IQ is an ADCP that sits at the bottom of the canal and takes long-term measurements of flow. The IQ is designed only for use in engineered structures who geometry is known and has the advantage of being hidden under the water and is therefore able to make long-term measurements of current timeseries.

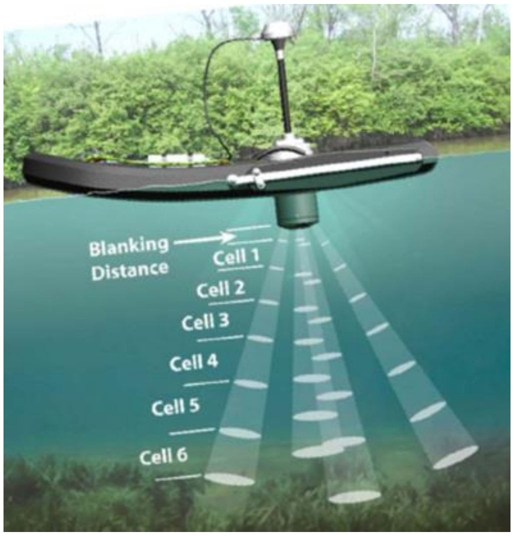


Figure 9: Multiple Beam Acoustic Doppler

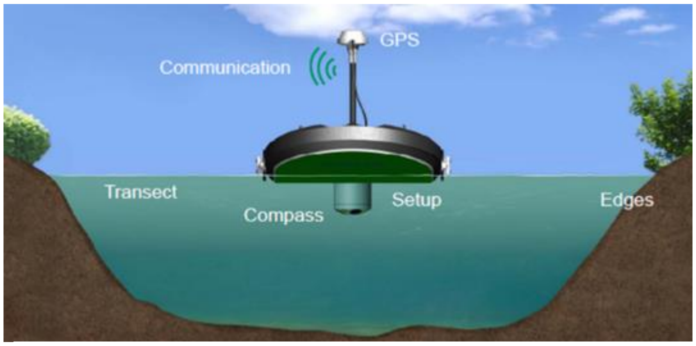


Figure 10: SonTek M9 ADCP and Hydroboard

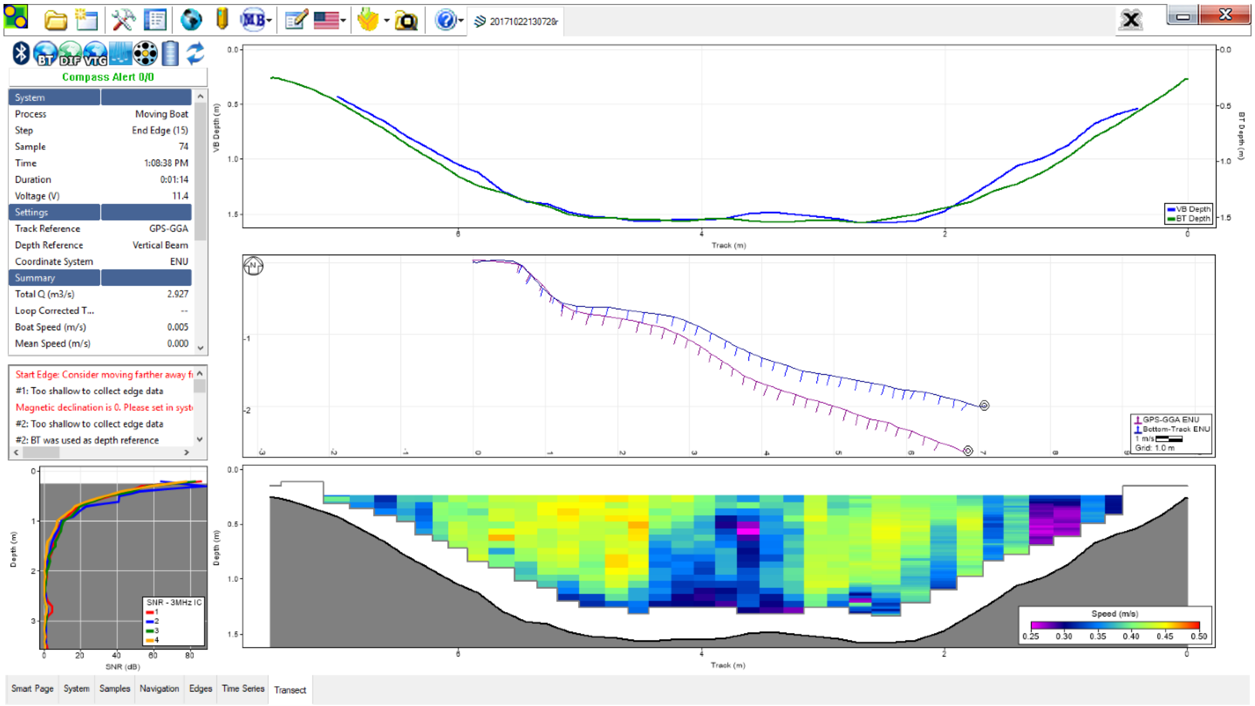
3.1.1 Sontek M9

The SonTek RiverSurveyor system is a robust and highly accurate Acoustic Doppler Current Profiler (ADCP) system specifically designed to measure river discharge, 3-Dimensional water currents, depths, and bathymetry from a moving or stationary vessel. The RiverSurveyor system combines proven state-of-the-art acoustic Doppler velocity profiler instrumentation with a Windows-based software package that can be used on a Personal Computer (PC) or Mobile device. The high degree of accuracy and ease of use allows you to measure confidently without having to change measurement settings for a specific channel condition.

The SonTek M9 ADCP is a nine-beam system with two sets of four profiling beams (each set having its own frequency) and one vertical beam. The M9 has a velocity profiling range of up to 40 m and a discharge measurement range of 80 m (when referencing GPS and the vertical beam). Multiple acoustic frequencies fused with precise bandwidth control make for the

Figure 11: SonTek M9 instrument deployed on the KAC, July 2017

most robust and continuous shallow-to-deep measurements. A deterministic microcontroller automatically apportions the appropriate acoustics and pulse schemes as it crosses the channel. This allows the user to focus on the measurement technique, and not on the instrument setup. The end result of the automatic adjustments is the best measurement settings possible at all times, no matter the depth and velocity of the river. As you go from shallow to deep water, the cell size automatically adjusts to optimize performance and resolution. This feature further enhances continuous measurement of dynamic channel conditions. A low-frequency, fast-sampling vertical beam extends the maximum depth range of the system and provides superior channel definition for discharge measurements and bathymetric surveys. The vertical beam also provides confidence of depth measurements during extreme conditions such as high-sediment flows and floods. All calculations are performed inside the ADCP and all data is stored in the unit. This gives you the increased flexibility to collect data, disconnect from the system, and then reconnect to the system during data collection without stopping the data collection process and without the fear of losing data. It avoids any possibility of data loss if communication is lost or becomes intermittent. SmartPulseHD is an intelligent algorithm that looks at water depth, velocity, and turbulence, and then adapts the acoustic pulse scheme to those conditions. It uses multi-band acoustics, pulse-coherent, broadband, and incoherent techniques to provide the highest resolution velocity data possible [summarized from SonTek M9 manual, 2017].



Compass Alert 0/0

System	
Process	Moving Boat
Step	End Edge (15)
Sample	74
Time	1:08:38 PM
Duration	0:01:14
Voltage (V)	11.4
Settings	
Track Reference	GPS-GGA
Depth Reference	Vertical Beam
Coordinate System	ENU
Summary	
Total Q (m3/s)	2.927
Loop Corrected T...	--
Boat Speed (m/s)	0.005
Mean Speed (m/s)	0.000

Start Edge: Consider moving farther away fi
#1: Too shallow to collect edge data
Magnetic declination is 0. Please set in syst
#2: Too shallow to collect edge data
#2: BT was used as depth reference

Figure 12: SonTek RiverSurveyer Software Data Display Page

This data is from the waterfall near the beginning of the KAC on 21 October 2017. The top graph is 2 different estimates of channel depth. The middle plot is two different estimates of boat position. The lower plot is a map of velocity. Note that the velocities are not estimated close to the channel bed, but flow calculations are still performed.

3.1.2 Sontek IQ

The IQ is an acoustic Doppler current meter designed for water velocity, level, and flow measurements in the field. The SonTek-IQ product line provides the technological advantages of complex/expensive current profilers, but in a simple, inexpensive, and easy to use package. Son-Tek-IQ performs horizontally and vertically integrated velocity measurement (using along axis and skew beams) to measure the maximum possible extent of the water column. It has excellent performance for low and high flows with an accuracy of 1% of measured velocity. Water level is measured by vertical beam and pressure sensor, and the unit has a built-in temperature sensor.

Figure 13: Preparing the SonTek IQ for Deployment in its Custom-Designed Frame, October 2017

Figure 14: Deploying the SonTek IQ in the KAC, October 2017

The IQ combines horizontally and vertically integrated velocity data with precise stage measurements to determine real-time flow data. A variety of real-time flow calculations are supported, including natural

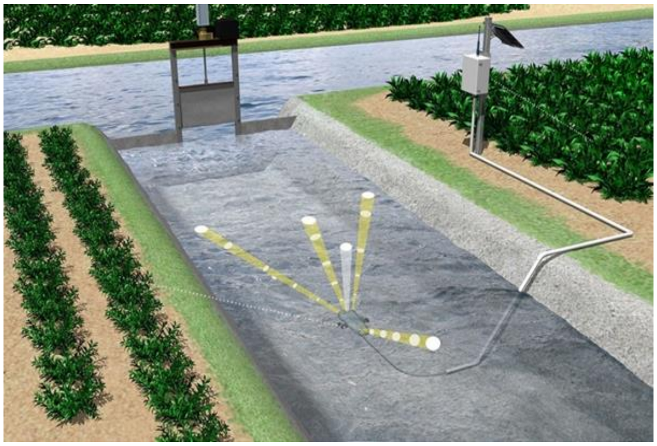
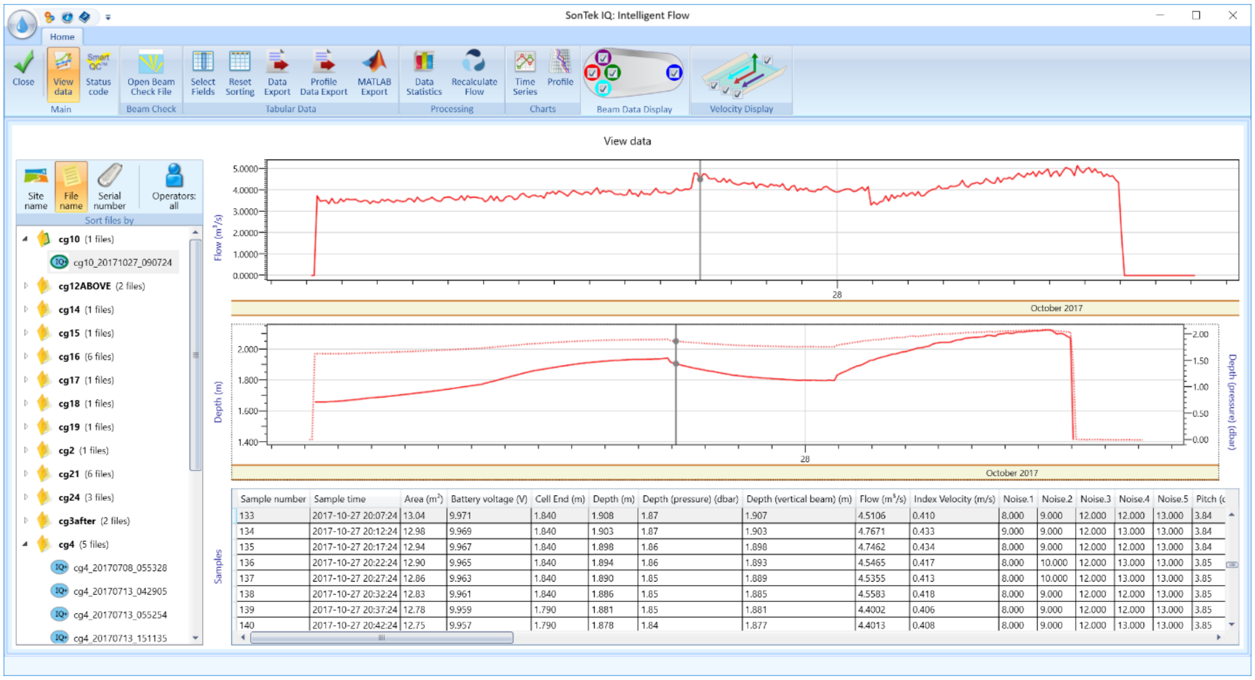


Figure 15: Sontek-IQ Canal Placement and Acoustic Beams

Figure 16: Two Variations of the SonTek IQ

streams, regular and irregular channels, pipes and closed conditions. [summarized from the SonTek-IQ manual, 2017].



Sample number	Sample time	Area (m²)	Battery voltage (V)	Cell End (m)	Depth (m)	Depth (pressure) (dbar)	Depth (vertical beam) (m)	Flow (m³/s)	Index Velocity (m/s)	Noise.1	Noise.2	Noise.3	Noise.4	Noise.5	Pitch (c
133	2017-10-27 20:07:24	13.04	9.971	1.840	1.908	1.87	1.907	4.5106	0.410	8.000	9.000	12.000	12.000	13.000	3.84
134	2017-10-27 20:12:24	12.98	9.969	1.840	1.903	1.87	1.903	4.7671	0.433	9.000	9.000	12.000	13.000	13.000	3.84
135	2017-10-27 20:17:24	12.94	9.967	1.840	1.898	1.86	1.898	4.7462	0.434	8.000	9.000	12.000	12.000	13.000	3.84
136	2017-10-27 20:22:24	12.90	9.965	1.840	1.894	1.86	1.893	4.5465	0.417	8.000	10.000	12.000	13.000	13.000	3.85
137	2017-10-27 20:27:24	12.86	9.963	1.840	1.890	1.85	1.889	4.5355	0.413	8.000	10.000	12.000	13.000	13.000	3.85
138	2017-10-27 20:32:24	12.83	9.961	1.840	1.886	1.85	1.885	4.5583	0.418	8.000	9.000	12.000	12.000	13.000	3.85
139	2017-10-27 20:37:24	12.78	9.959	1.790	1.881	1.85	1.881	4.4002	0.406	8.000	9.000	12.000	12.000	13.000	3.85
140	2017-10-27 20:42:24	12.75	9.957	1.790	1.878	1.84	1.877	4.4013	0.408	8.000	9.000	12.000	13.000	13.000	3.85

Figure 17: SonTek-IQ Data Analysis Software

This data is from KAC check gate 10 on 27-28 October 2017. The top window shows flow data, while the lower window shows depth data.

3.2 ADAPTATION OF INSTRUMENTS TO LOCAL CONDITIONS

The KAC presents many challenges for the use of the SonTek M9 and IQ, requiring sometimes significant adaptation to local conditions. These will be briefly described below.

M9 deployment and stability control: Important considerations for M9 deployment are (a) to get the boat safely from the shore to the water, (b) precise control of the boat while in the water – it needs to be consistently pointed upstream and moved slowly (half the speed of the water velocity) from one side of the canal to the other, (c) safe removal of the boat from the water. We accomplished this by using two sets of rope, tied in the middle to the front and the back of the boat. The rope allows an operator on either side of the canal to precisely control the speed and direction of the boat. This requires two operators, one on each side of the canal. The operator on the far side of the canal (most often the east side of the canal), must cross the canal on a bridge or gate crossing. These crossings are usually close to the measurement site, but in a few cases a drive or long walk was required. The rope is passed to the other side of the canal by tying a weight to the rope and throwing it across. The canal is rather wide, and the rope is easily tangled in fencing or vegetation, so this can be one of the most challenging aspects of deployment. Once each operator has an end of the rope, the M9 can be lifted by the ropes and transported from the side of the canal into the water. Care must be taken to not scrape the instrument on the ground or cement during deployment. Although this method does not require operator contact with the water, proper safety gear is required, including boots, gloves, and approved flotation devices. This procedure requires 3 operators: 2 to work the M9 ropes, and a third to operate the computer and take notes. Detailed notes were taken on each measurement to aid in the subsequent analysis.

M9 radio heat issues: During the July 2017 field measurements, the M9 instrument would periodically lose wireless connection with the field computer. Through extensive and frustrating investigation, it was discovered that the M9 radio dongle used in the field computer was sensitive to excessive heat. If the dongle was kept cool, the radio worked well. But when the radio was hot it would fail. Conditions in the Jordan Valley in July are extremely hot, so we adopted a methodology of working in the earliest part of the day when it was cooler, and we operated the computer from inside the car to take advantage of the air conditioning. We contacted SonTek about this issue and were able to replace the radio dongle for the October field trip, and that resolved this issue.

M9 Field Computer: This project required a field computer that could go for long periods in the field without recharging, and in harsh heat, dust, and other rough conditions. A old miniature "netbook" computer with a few extra batteries worked well. However, it is recommended that a "Toughbook" be used in the future due to its sun viewable screen and rugged design.

M9 power: The M9 requires 16 "AA" batteries and can deplete the batteries with one day of use. An effective way to reduce power needs is to remove the battery packs when transporting the instrument from one site to another. However, this also resets the GPS lock, and the wireless connection to the computer must be reestablished. In October 2017 rechargeable batteries were used to reduce the number of batteries that were wasted.

M9 compass calibration: The M9 has an internal electronic compass for use in determining its orientation with respect to flow. It is an important part of the measurement and must both be properly calibrated and not have local interference. The calibration procedure is described well in the manual; however, we did experience many "compass alerts" from the M9 software that needed to be address before measurement. We found that M9 measurements near bridges, powerlines or reinforced concrete (large metal objects) often produced these compass alerts. We were able to mitigate these alerts by either recalibrating the compass, moving the measurement site away from the metal structure, or both.

M9 DGPS & BT: The M9 has several different ways to determine its location along the transect. The most common are using the Differential Global Positioning System (DGPS), and Bottom Tracking (BT). We found that the DGPS option was consistently providing a bias in the discharge between measurements that started on the right or left bank. The BT option does not show this issue, and was found to perform more consistently than the DGPS option, except for areas that have a very smooth or moving bed. The choice of using the BT or DGPS option can be made in a post-processing mode, so all the data was reprocessed and the best option for the conditions was chosen. Additionally, measurement outliers identified by SonTek's RiverSurveyer software were eliminated from the discharge averages.

IQ deployment & frame: The SonTek IQ instrument was identified for use in this project because it can be deployed for long periods under the water. To measure illegal withdrawals which were hypothesized to occur mostly at night, the instrument needs to be hidden. Since the canal water is muddy, it serves to effectively hide the instrument. The SonTek IQ instrument is designed to be attached to the bottom center of the canal, ideally when it is dry. Unfortunately, the KAC is never drained, so we needed to develop a way to deploy the instrument that was possible when the canal was full of water. In July 2017 we tried attaching the instrument to a steel plate and dropping it into the water on a string. The current was too fast, and the instrument and plate were uncontrollable, and it was impossible to determine its position in the water. One of the JVA technicians volunteered to place and retrieve the instrument in the bottom of the canal manually, attached to a brick. This method worked, but it was deemed too labor intensive and potentially dangerous to perform on a routine basis. In October 2017 we developed a metal frame that held the IQ instrument above the sediment and was made with metal loops that allowed rope to be passed through for easy deployment. This designed proved to be highly effective and was used successfully with all 3 IQ instruments throughout the October 2017 deployment. Fortunately, the IQ instruments were hidden well enough that none were stolen or lost.

IQ Retrieval: Once the metal IQ frame is deployed in the center of the canal, the ropes are removed to reduce drag. This presents a problem in retrieving the instrument so that it can be moved to the next measurement location. Therefore, we developed a retrieval method based on using thin nylon string tied to the frame and left to drag in the water. The nylon string was then attached to a clear fishing line and secured to a twig or fence post on the bank. To retrieve the instrument, the fishing line is found and pulled until the nylon string emerges. The nylon string has enough strength to drag the IQ frame back to the shore for safe removal.

IQ trash: The KAC has an abundance of trash that presented a significant challenge for the IQ deployment. The most challenging trash was plastic bags that could collect on the retrieval string and turn into small parachutes, effectively moving and even turning over the IQ frame. In several cases the forces were strong enough to break the retrieval line. In these cases, a hook was developed to retrieve the frame and instrument. The retrieval line was also moved well downstream so that any trash would be pulled to the side of the stream where there are less currents. Weights were also added to the string to keep it near the canal bottom where it is less likely to catch trash.

IQ sediment: For several reaches the sediments in the KAC are quite significant. These sediments can (a) cover or partially cover the IQ transducers which results in measurement failure, (b) get stuck in the IQ pressure measurement port, causing issues with the IQ depth measurement, and (c) larger debris can cause deployment issues with the IQ frame – rocks or other debris can cause the frame to be tilted which compromises the measurements (in one case we pulled up long boards that had become tangled in the IQ frame). These issues are particularly difficult to solve, and for the most part we just had to redo the measurements when these issues arose. When only one of the IQ transducers was covered with sediment or trash, or when the pressure transducer was clogged, some elaborate post-processing was done to rescue the data.

IQ power: Another challenge for deploying the IQ instrument was to provide 12V power underwater. To address this we modified a small waterproof pelican box by routing the IQ power cord through a small hole drilled in the box, and silicon sealing the cord in place. An 8-cell AA battery pack was placed inside to provide power to the IQ. The battery pack lasted on average for about 2 days. There were numerous issues with these boxes leaking through the silicone seal or the box closure, compromising the batteries. Dust had to be removed from box seal and the silicone seal had to be of high quality. For future deployments it is recommended that a larger battery be used for greater endurance.

3.3 APPROACH

3.3.1 Data Collection

The primary goal of this first phase of the "*Determination of Water Losses in the KAC Conveyance System*" project was to measure the total losses for each reach of the upper canal (0-65km), and to determine the relative contribution of evaporation, seepage, and unmetered/illegal use to the total estimated loss. The results presented here are based on observations made in July and October 2017. These results will be updated as more measurements can be obtained from different seasons and water demand scenarios.

Figure 18: A KAC Reach is Typically Defined as an Uninterrupted Canal Section between Two Check Gates

Figure 19: The SonTek M9 Operating on the KAC in July 2017

Towards this goal nearly 1000 instantaneous discharge measurements were made using the SonTek M9 Acoustic Doppler Current Profiler (ADCP) in July and October 2017, and about 25 days of continuous 5-minute SonTek-IQ ADCP (over 7000 discharge measurements) were collected in October 2017. These observations were analyzed, combined and compared with observations made by the KAC-SCADA system to derive initial estimates of losses for the upper KAC.

The methodology for assessing losses was to measure flow in the canal as accurately as possible at each end of a canal reach, and account for or measure all inflows and outflows into that reach. The difference in flow, less the storage changes, inflows and outflows, and evaporation is the reach loss. A KAC reach is generally defined by operational check gates at either end of the reach that define a continuous canal reservoir. The approach assumes that seepage is relatively constant, and that unmetered/illegal withdrawals change quickly. Instantaneous flow measurement differences provide total loss estimates, and continuous flow measurement differences provide estimates of the partitioning of this loss into consistent loss (seepage) and intermittent loss (unmetered/illegal). Separate estimates of evaporation were modeled using weather and satellite data and are relatively small compared to other losses.

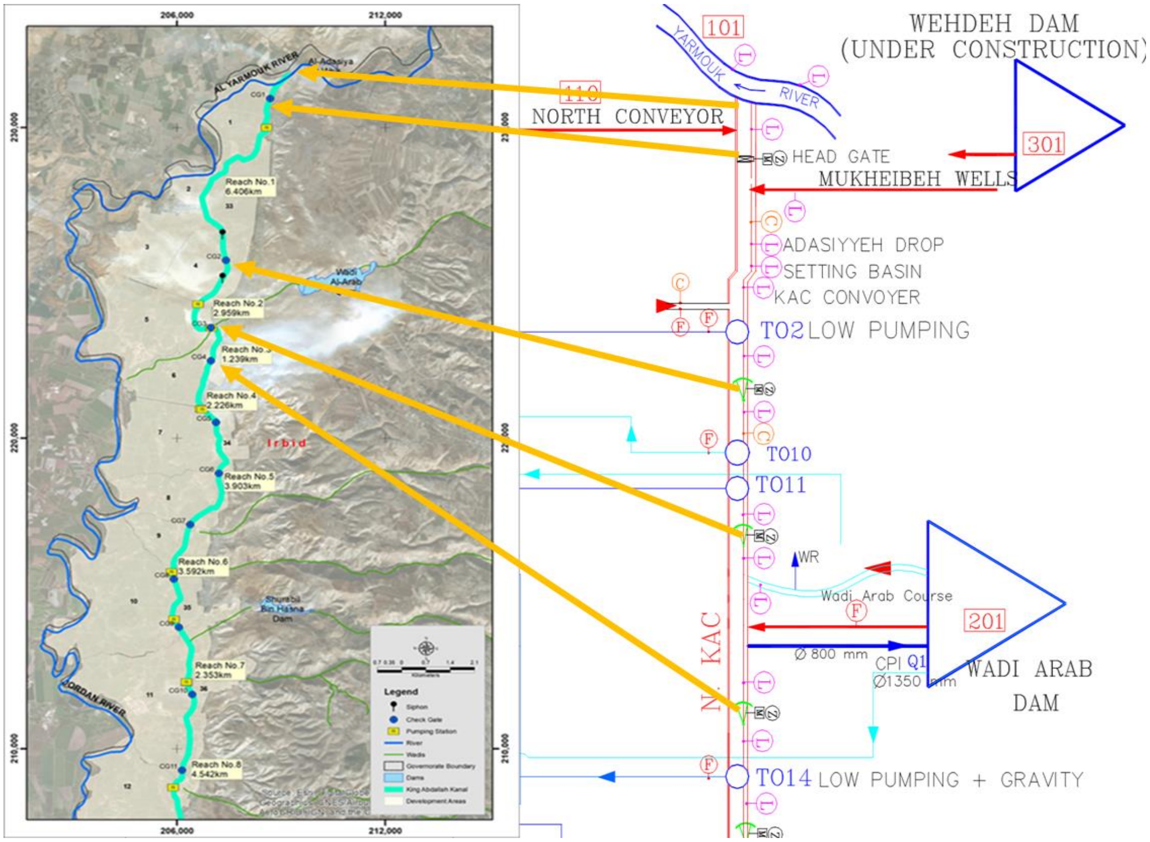


Figure 20: Identification of KAC Reaches and Measurement Locations

Figure 21: SonTek IQ Frame for Deployment in KAC, October 2017

Both instruments, the SonTek M9 and the SonTek IQ use acoustic Doppler pulses to measure water velocities. The more accurate M9 is mounted on a small boat that is pulled across the canal; as it crosses the canal, it measures water velocities at many different levels, which are integrated to determine the total flow. Six M9 flow measurements were usually made at each location on the canal; outlier measurements were assessed and discarded, and the remaining measurements were averaged. The same M9 was used to make all the measurements, so any bias it may have cancels out when the reach outflow is subtracted from the inflow to find the loss. However, the M9 cannot make continuous flow measurements, so it could miss short-term losses. It was also found that unaccounted canal dynamics could compromise the M9 measurements (i.e., if the canal levels and flow changed quickly during the measurement, or if pumps are turned on or off during the reach measurement). It was also found that the flow measurements varied widely based on the positioning technique. The M9 can determine its position through Differential GPS (DGPS) or Bottom Tracking (BT). BT appears to be the preferred technique unless there is a smooth channel bed or a moving bed. Therefore, optimal selection of positioning was done during an extensive post-processing analysis step. The position calculations were done both ways and spurious observations were eliminated from the analysis.

The IQ is specifically designed to measure canal flow and is placed at the bottom of the canal and left there for an extended period – for this project about 24 hours. This was ideal for KAC application because the IQ can be "hidden" below the opaque water and out of notice of illegal users. Three IQ instruments were used, allowing two consecutive reaches to be measured each day. The IQ introduced many technical challenges ranging from developing a waterproof battery pack to developing a suitable and safe deployment and retrieval apparatus. Some of the most challenging issues for the IQ involved trash and sediment in the KAC obscuring the IQ sensors, and independent bias when comparing measurements from different instruments.

Figure 22: Manual Stage Measurement, October 2017

The measurement approach for this project evolved as knowledge was gained about the nature and operation of the KAC. The operation of KAC inflows, pump stations, check gates, canal storage, and unmonitored withdrawals are changing constantly causing various waves to occur in the canal. These waves can travel both up and down the canal at a wide range of speeds but are mostly governed by the velocity of the water in the canal. Measuring the canal while it is changing introduces uncertainties; ideally reach measurements would be performed under steady -state conditions. Previous studies restricted inflow-outflow lost estimation methods to steady-state conditions. Absent steady-state conditions, the initial approach taken in July 2017 was to measure each reach with the M9 as quickly as possible, so that changes would be minimized. The SCADA water levels were used to track storage changes in each reach while the measurements were done. Manual water level measurements were also selectively performed and found to disagree with the SCADA water level observations. This discrepancy combined with July 2017 reach measurements showing relatively high loss errors, led to a revised measurement approach in October 2017. Rather than making the reach measurements as quickly as possible, a "follow the water" approach with manual stage change measurements was adopted. This approach essentially uses M9 water velocity measurements to calculate how long it takes for the water to flow down the reach. This timing was then imposed on the M9 measurements in an attempt to measure the same water as it flowed into and out of the reach. A similar delay is calculated and used to analyze the IQ data.

3.3.2 Data Analysis

An in-depth post-processing and numerical analysis was performed with the M9, IQ, and SCADA measurements to access loss estimates and attribution. The heart of this analysis is a reach-by-reach water balance assessment largely based on M9 measurements, with the loss calculated as a residual of the water balance. Conservation of mass is amongst the most fundamental science principals: for each reach, the water balance dictates that the water output subtracted from the input must equal the change in storage. Using this concept, the following equation guides the analysis (in units of discharge rate m^3/s):

$$L_r + U_r = \Delta Q_r + I_r - O_r - \Delta S_r/t - E_r$$

ΔQ_r: Change is discharge across the reach

I_r&**O_r**: Inflow or outflow from the reach

ΔS_r: Storage change in the reach during the measurements

E_r: Evaporation

L_r: Leaks or seepage

U_r: Unmetered/ Illegal uses

The change is discharge across the reach (**ΔQ_r**) is measured using the M9 or IQ at the beginning and end of the reach, usually near the check gates. Inflow (**I_r**) or outflow (**O_r**) from the reach is usually measured with M9 observations before and after the abstraction. Alternatively, measurements were made when these abstractions were zero (at night or late afternoon). Storage change in the reach during the measurements (**ΔS_r**) were initially made (in July 2017) using the SCADA level observations. However, these were found to be suspect, so manual level measurements were made in October 2017. Note that storage changes were modeled in the reach as a wedge, where the storage change was assumed zero at the beginning of the reach, and the measured level was used at the end of the reach. The level change was multiplied by the reach length and width and divided by the elapsed time of measurement to determine the storage change rate. Evaporation (**E_r**) was determined using potential evaporation estimates provided by the NASA Global Land Data Assimilation System (GLDAS). GLDAS uses advanced land-atmosphere models, surface meteorology, numerical weather forecasts, and weather satellite data to make accurate estimates of surface water conditions across the globe at high resolution. Leaks or seepage (**L_r**) and unmetered/illegal uses (**U_r**) were estimated as a residual of the reach water balance, and then separated using a time-series frequency analysis of the IQ reach differences. Essentially unmetered/illegal uses are assumed to be "flashy" or temporary, such as a pump turning on and off, a siphon being placed temporarily, or a water truck filling. This allows the longer-term losses to be separated from the short-term losses.

Since leaks or seepage are likely relatively constant, this process allows separation of the different kinds of losses.

The “follow the water” measurement approach adopted in October 2017, simply used the ADCP measured KAC velocity combined with the length of the reach to determine how long to wait to make the downstream measurement. Essentially the goal was to measure a “parcel of water” at the beginning of a reach, then wait to measure the same “parcel of water” as it passes through the end of a reach. We considered using a float in the canal to determine this wait period but thought it likely that the float may get hung up in the various obstacles (pipes, bushes, ropes, etc.) in the canal.

Calculating the reach flow delay, say for the combined reach 15, 16, and 17 (between check gate 21 and the control center) is simply the length (9394m) divided by the flow velocity (0.24m/s), resulting in 661 minutes or nearly 11 hours. This delay was confirmed by detailed analysis of the IQ timeseries for these reaches. A lagged timeseries correlation analysis reveals a peak at a delay of about 660 minutes (see Figure). This analysis is done by calculating the timeseries correlation of the IQ timeseries at the beginning and end of the reach, then progressively “sliding” the upper IQ timeseries by 5 minutes at a time and recalculating the correlation. The lag time of highest correlation indicates the timing where the variations in the timeseries are most similar to each other. Similar analyses were done for all available canal reaches, and the velocity-determined delay was prominent in all cases.

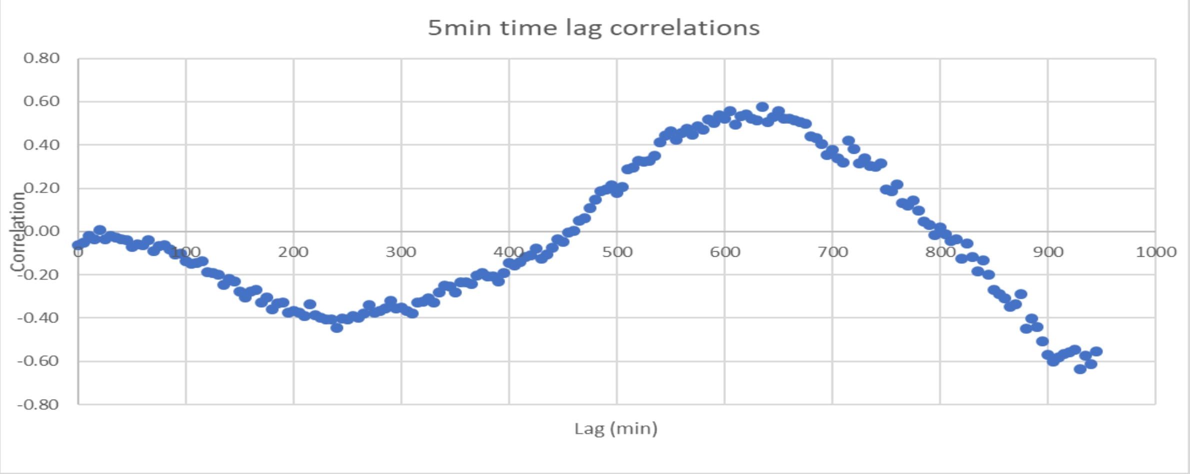


Figure 23: Time Lag Correlations for Reaches 15, 16, and 17, October 31, 2017

This second-time lag correlation analysis figure (Figure 24) is from KAC reaches 3 and 4, with a total length of 3465 meters and a velocity of 0.55 m/s for a delay of 106 minutes. There is a relatively high correlation at 106 minutes, but the correlations are high from 0 to 140 minutes delay. So, what is going on here? It turns out that there are many complex waves traveling at different speeds up and down the canal that are triggered by changes in inflow, outflow, gate positions, etc. that cause correlated fluctuations in the flow. In a their paper “Surge Wave Propagation in a Common Tailrace Channel for Two Large Pumped-Storage Plants”, Terrier et al show that a canal wave has a velocity that is significantly larger than the flow velocity, and dependent on the wave height. Based on our measurements we estimate this wave velocity for these reaches to be 3.78 m/s, resulting in a reach delay of 15 minutes. It can be seen that this corresponds closely with one of the highest delay correlations for these reaches, and further proves the highly dynamic and complex flow and waves in the KAC.

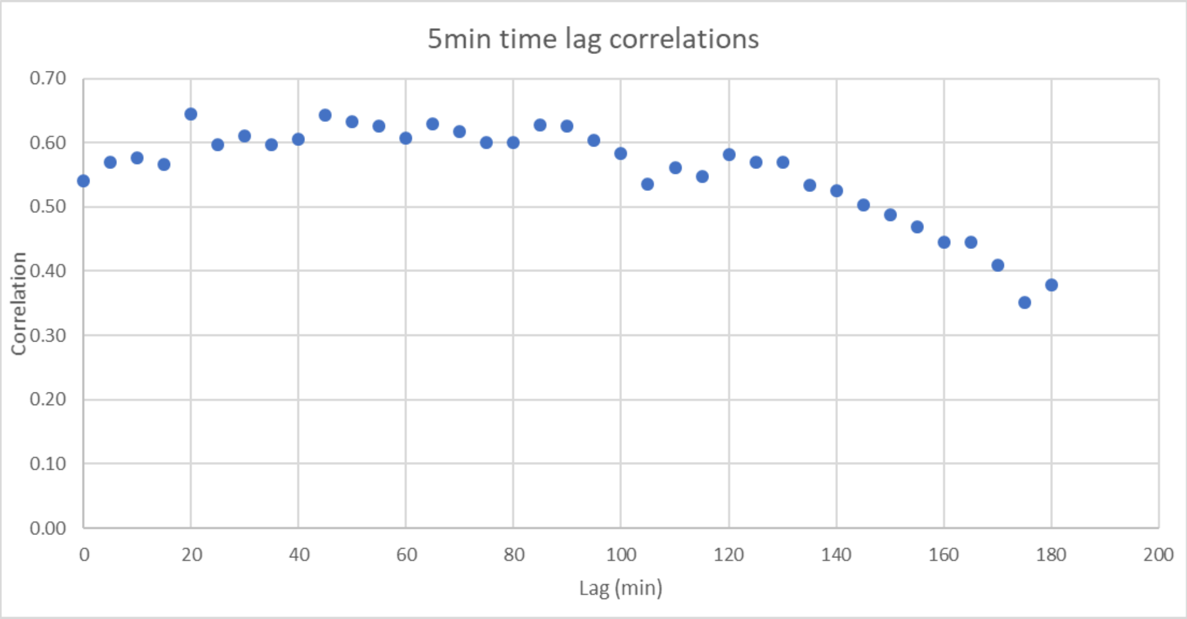


Figure 24: Time Lag Correlations for Reaches 3 and 4 (3465 Meters Long), 26 October 2017

3.3.3 Separation of between Constant and Dynamic Loss

One of the assumptions going into this project was that much of the unmetered/illegal use was during the night. Therefore, we endeavored to make continuous night-time loss measurements by "hiding" the IQ instruments at the bottom of the canal and at each end of the reach. We hoped that the detailed overnight 5-minute IQ measurements would allow us to separate the more constant losses (seepage) from the more intermittent losses (unmetered/illegal), or to see the diurnal patterns of losses. The analyses of the IQ timeseries is complicated by the flow delay (previously shown), and of course any abstractions. The discharge timeseries at each end of the reach were time-lagged to account for the flow delay, then subtracted to determine the reach inflow-outflow. Pumping as estimated by the SCADA was subtracted from the loss estimates, as was reach storage change and evaporation. When several reaches were analyzed together delays in storage or pumping were also imposed as determined by water velocities. The resulting timeseries of 5-minute losses for reaches 3 and 4 (between KAC check gates 3 and 5) are shown in the Figure (blue dots). It took a lot of analysis of these figures for many reaches to figure out how to interpret these loss timeseries. The blue dots represent losses over 5-minute intervals. It can be seen that there is a lot of variability in these 5min losses, but also a slowly changing pattern (estimated by the orange dotted line). The orange dotted line is a moving two-hour average less the standard deviation. A two-hour average was used as that appears to be about the drift time of the bias between the two instruments. The difference between the blue and orange dot pairs essentially captures the short-term variability which would result from temporary canal losses, such as those from illegal pumping.

These analyses brought forward a fundamental issue in the IQ timeseries loss estimates, which is that the different IQ instruments placed at either end of the reach have independent bias. Recall the since the same M9 instrument is used to measure all KAC reaches, its bias is cancelled out in the subtraction of flow across the reach. In the case of the IQ, any independent bias in different instruments results in additive bias when subtracted across the reach. The IQ bias can come from the instrument itself but can also result from a slight tilt in the instrument installation, changes in sedimentation, or the orientation of the instrument within the canal. These factors are impossible to control for, so we must find a different way to deal with these biases. From experience, these kinds of instrument bias differences tend to vary slowly in time, so we modeled the bias (the orange dotted line) and subtracted it from the loss timeseries, providing a means to estimate the variable part of the loss (the difference between the orange and blue dots). The variable part of the loss (the average difference between the orange and blue dots) is attributed to unmetered/illegal use. The constant loss (mostly seepage) is determined by subtracting the variable unmetered/illegal use from the total loss. Similar analyses were done for all reaches that were measured with the IQ in October 2017.

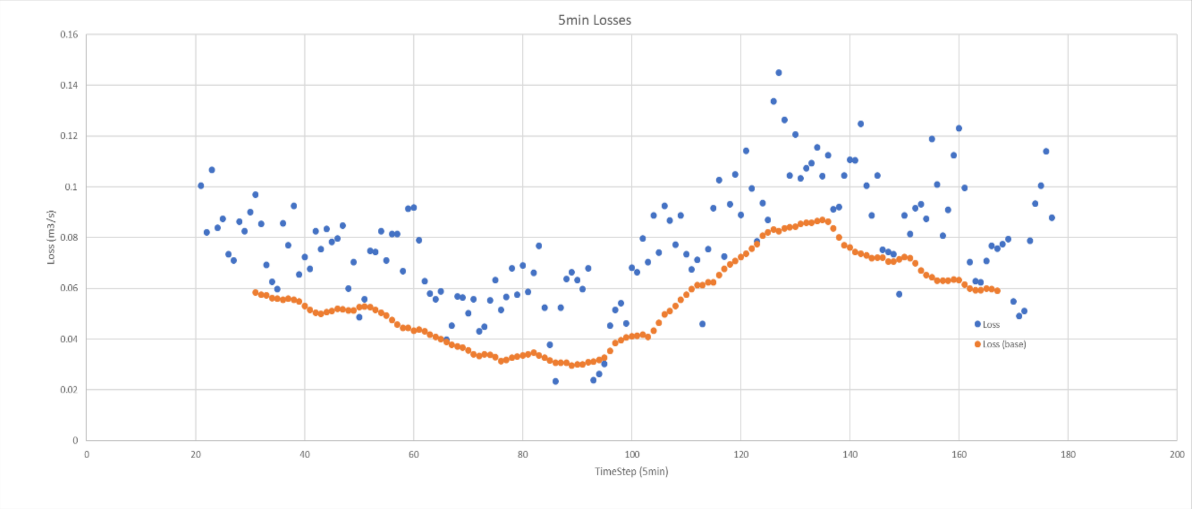


Figure 25: Timeseries of Losses from KAC Reaches 3 and 4, 26 October 2017

It is interesting to note that there does not seem to always be a diurnal pattern to the variable part of the loss, showing that the unmetered/illegal use was not always at night. In fact, we observed first hand many unmetered/illegal uses during the day, ranging from temporary siphons, pumps, livestock water, and water truck extractions. The IQs were generally placed in the afternoon, and removed in the morning, so the middle of the timeseries is around midnight. Reaches 1 and 17 appear to have more unmetered loss during the day than night. Reaches 2 and 7 appear to have more unmetered/illegal loss in the early morning and reaches 13 and 14 have more unmetered/illegal loss in the evening. Reaches 9, 15, and 16 have highly variable unmetered/illegal losses throughout the day and night, while reaches 3, 4, 5, 8, 10, 11, and 12 appear to have more consistent losses throughout the day.

To improve these estimates, it is recommended to make (a) longer-term measurements of each reach, (b) use M9 reach flow differences to provide independent calibration points for the IQ pairs, (c) make IQ measurements during different seasons, and (d) make IQ measurements at times when canal pumping can be curtailed to minimize reliance on SCADA pumping estimates.

3.3.4 Estimation of Evaporation

Evaporation was determined using potential evaporation estimates provided by the NASA Global Land Data Assimilation System (GLDAS). GLDAS uses advanced land-atmosphere models, surface meteorology, numerical weather forecasts, and weather satellite data to make accurate estimates of surface water conditions across the globe at high resolution. 3hr, ¼ degree potential evaporation data was extracted for the KAC region interpolated to 5-minute timeseries. Evaporation rate (m/s) was averaged for the time period required to make the M9 measurements across the reach, then multiplied by the area of the reach. Using this data, it is estimated that the canal loses about 11 mm of water daily during July (about 6738 m^3 or 1.2% of the flow volume), and 6.4 mm of water daily (about 3720 m^3 or 0.7 % of the flow volume) during October. In other words, evaporation is a minor component of the total losses.

3.3.5 Difficulties Overcame

The most significant issue with this overall analysis is the lack of steady-state conditions at any time in the KAC. An analysis of the SCADA data for the month of July was done to determine if the canal ever approaches steady state, with the hope that there may be a time during the day or perhaps the weekend that the canal experiences less fluctuations. It turns out that because the canal itself is used to store water at night, and the inflows are constantly changing, it is always changing and never approaches a steady state. The non-steady (transient) state nature of the KAC flows makes the analysis and interpretation of the inflow-outflow measurements much more challenging, and potentially adds uncertainties.

Two approaches to deal with the non-steady state conditions were explored:

1) **Fast inflow-outflow method:** if the canal reach stage does not change during the time it takes to make the inflow-outflow measurements, then the reach can be defined as steady-state. Further, even if the stage is changing, it may not change a lot over a short time period, and the storage change can be incorporated into the water balance calculations. So making the measurements quickly will result in a more likely chance that the reach is near steady-state. If the stage does change, then the measurements can be repeated until no change is detected. This is the approach we took in July 2017, and we also included any storage changes that were observed by the SCADA. Unfortunately, the SCADA storage changes were not as reliable as we had hoped, so manual stage measurements were made in October 2017.

2) **Following the water method:** After a lot of careful analysis and consideration, we decided to try a "following the water" approach for the October 2017 measurements. Essentially, for this method we measure the changes to a "parcel of water" as it travels down the reach. To do this we must know how fast the water is traveling, then time the inflow-outflow measurements to measure the same water at the beginning and end of the reach, as well as any storage, evaporation and pumping changes it experiences. Additionally, for the October 2017 measurements we manually measured the stage changes because of uncertainties in the SCADA stage measurements.

Figure 26: A KAC SCADA Stage Sensor Contaminated with Debris

Both methods have merit in addressing the non-steady state conditions in the KAC, but it is not clear that either method is entirely valid. A systematic comparison between the methods would be warranted but was not performed as part of this study. In non-steady state conditions, short-term waves, oscillations, or trends in the discharge at either end of a reach could be unintentionally interpreted as a loss or cancel out actual losses. Many of these issues are addressed by averaging 6 discharge measurements at each end of the reach.

Another issue with this approach is that we are only able to measure losses during the time we are making the M9 measurements. It is well recognized that while the seepage loss is likely more consistent, the unmetered/illegal losses are likely much more dynamic. So, without a longer timeseries of inflow-outflow reach measurements, we likely miss some important loss dynamics. To address these issues, we performed 5-minute inflow-outflow measurements over 24-hour periods using the IQ. This only partially addresses the issues because there are likely additional loss dynamics at the weekly, seasonal, and yearly scale. To measure these dynamics, we could deploy the IQ sensors for a longer period, but only a few reaches could be studied in this manner and a more complex deployment strategy would be required. Alternatively, we could attempt to use the SCADA measurements to do the loss calculations. JVA already does this exercise on a routine basis, but we would improve it by calibrating the SCADA measurements using the M9. There is some risk in this approach, because there are some SCADA issues that cannot be addressed through calibration such as trash in the check cates that modify flow, missing stage data, missing pumping data, and contaminated sensors, see Figure 26.

4.0 RESULTS

4.1 M9 AND IQ RESULTS FOR EACH REACH

Below we present M9 and IQ results for each upper KAC reach. The table for each reach is a summary of the M9 data collected for each reach in July and October 2017, as well as the calculations of inflows, outflows, evaporation, storage change, and loss. The M9 discharge measurements are averages of 4-8 individual M9 measurements at each site, quality controlled and composited using the SonTek RiverFlow software. Several different methods were used for M9 positioning (Bottom Tracking and GPS), and several methods were used for stage/storage calculations (SCADA and manual), resulting in several different estimates of loss. Depending on the quality of the measurements and analysis, some of the data were eliminated from the final analysis. The IQ data is presented as timeseries loss plots, with 5-minute timesteps. The blue dots are the actual flow differences, and the orange dots are a 2-hour running average less the standard deviation of the loss measurements. Often the IQ 5-minute loss data covers several reaches, so it is repeated for the relevant reaches.

The below acronym is used in the following analysis for the reaches

Q: Canal discharge

I: Inflow to canal

O: Outflow or pumping from canal

dS: Change in reach storage

E: Evaporation

GPS: M9 positions via GPS

BT: M9 positions via bottom tracking

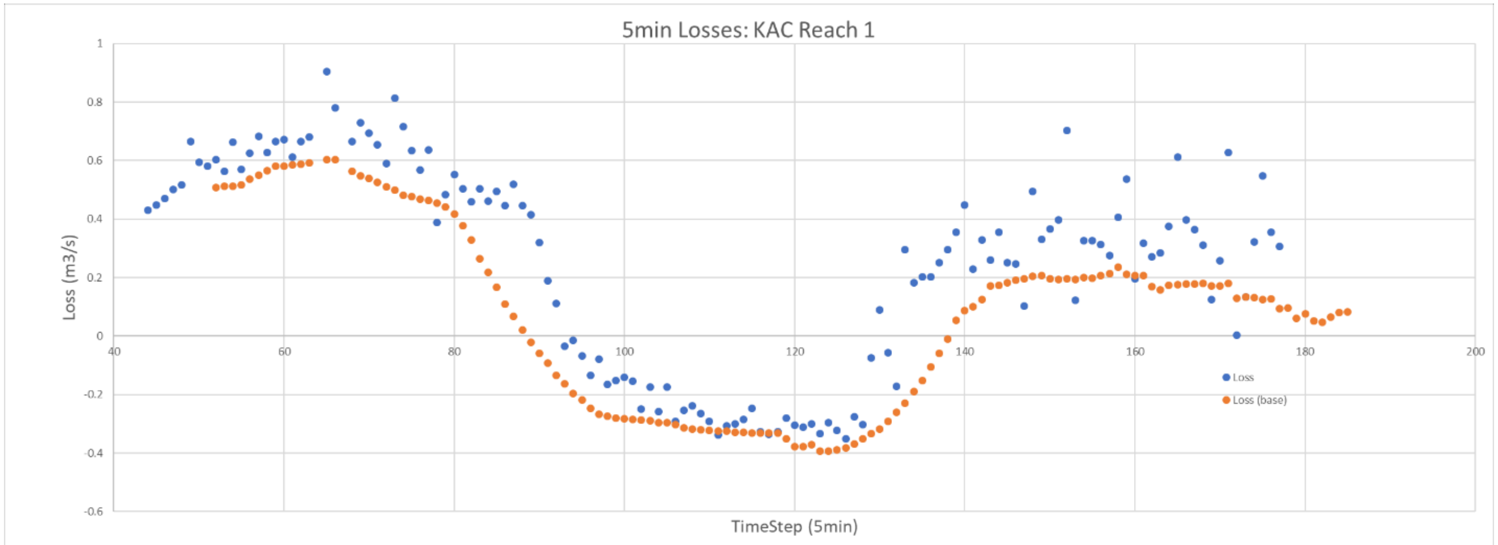
Manual: Manual stage measurement

SCADA: SCADA stage measurement

L: Loss (seepage and unmetered extractions)

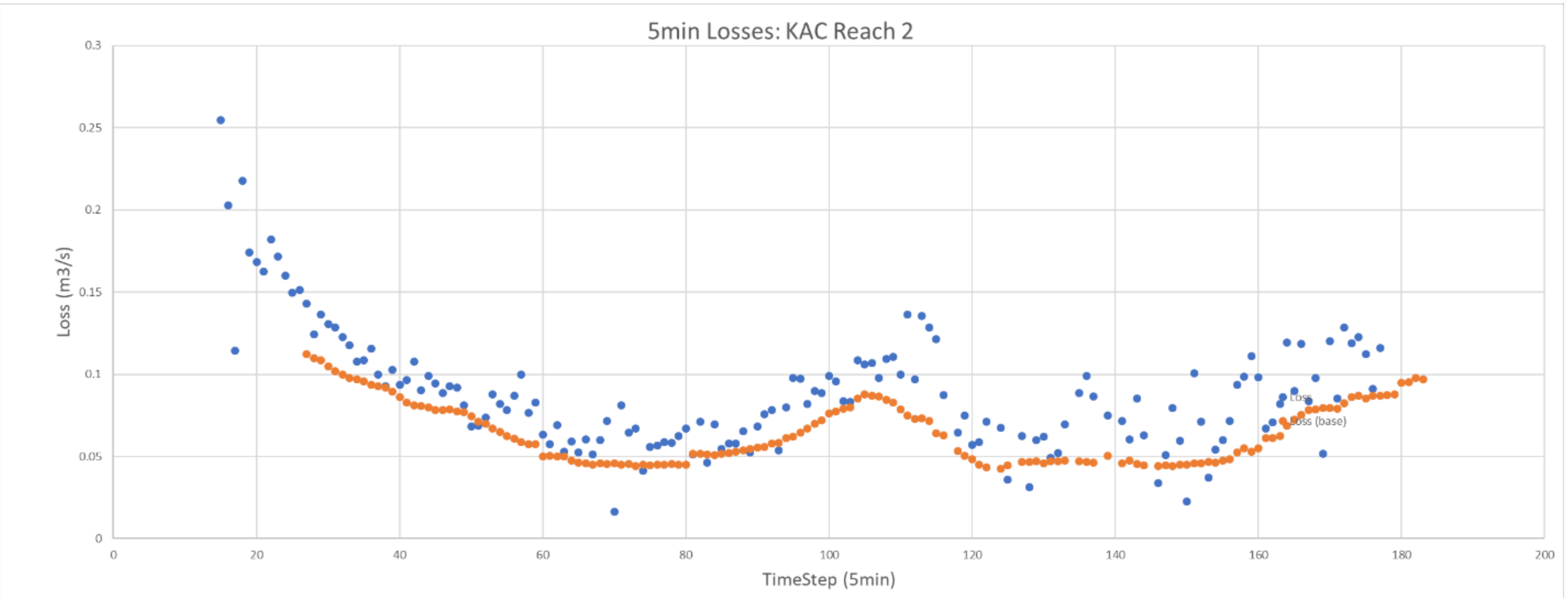
KAC Reach I

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
0-2	0 - 8.6	6.406	7.73	Waterfall	3-Jul-2017	6:05	6:14	3.631	3.684											
				Waterfall	3-Jul-2017	8:53	8:57	3.685	3.782											
				Waterfall Average				3.658	3.733											
				PS2-down	3-Jul-2017	7:25	7:39	6.209	6.413											
				Taberia IN-up	3-Jul-2017	8:35	8:40	3.883	3.906											
				Taberia IN-down	3-Jul-2017	8:03	8:15	6.513	6.707	2.630	2.801									
				CG2	3-Jul-2017	9:35	9:54	6.377	6.411						0.273	0.0045		0.179		0.391
				Waterfall	7-Jul-2017	5:42	5:48	3.638	3.593											
				TaberialN-up	7-Jul-2017	6:37	6:44	3.678	3.663											
				PS2-down	7-Jul-2017	7:03	7:12	6.332	6.439	2.654	2.776									
				CG2	7-Jul-2017	7:34	7:42	5.890	5.964						-0.172	0.0008		0.229		0.232
				Falls	23-Oct-2017	4:45	4:45	3.417	3.417											
				Tiberia	23-Oct-2017	5:00	5:00			1.910	1.910									
				PS2	23-Oct-2017	5:15	5:15													
				CG2-up	23-Oct-2017	8:34	8:43	5.116	5.191					0.092	0.086	-0.0001	0.303	0.297	0.228	0.262



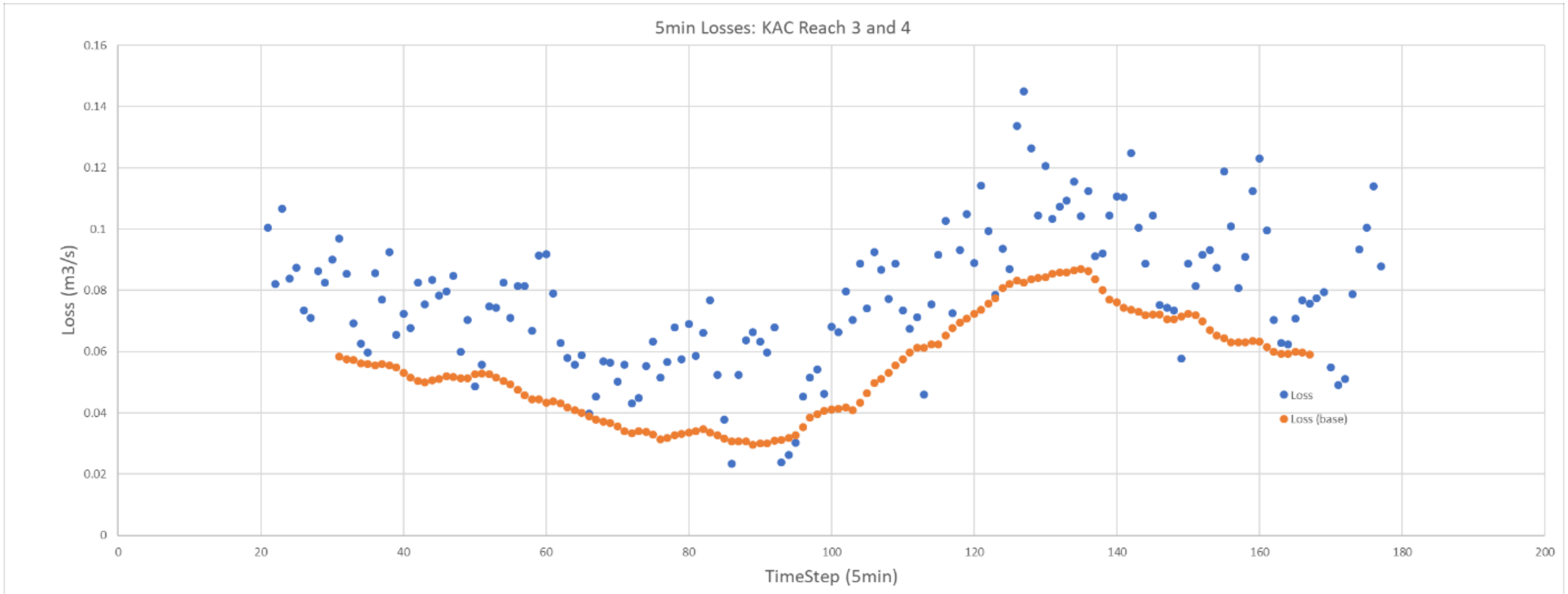
KAC Reach 2

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
2-3	8.6 - 11.6	2.959	7.84	CG2	3-Jul-2017	9:35	9:54	6.377	6.411											
				PS10-up	3-Jul-2017	10:11	10:24	6.287	6.330											
				PS10-down	3-Jul-2017	10:37	10:41	5.984	5.987			0.303	0.343							
				PS11&CG3-up	3-Jul-2017	11:22	11:31	6.176	6.120						0.000	0.0030		-0.105		-0.055
				CG2	7-Jul-2017	7:34	7:42	5.890	5.964											
				PS10-up	7-Jul-2017	8:01	8:10	5.893	5.927											
				PS10-down	7-Jul-2017	8:30	8:38	5.639	5.648			0.254	0.279							
				CG3&PS11-up	7-Jul-2017	8:56	9:01	5.727	5.827						0.000	0.0010		-0.016		-0.143
				CG2-up	23-Oct-2017	8:34	8:43	5.116	5.191											
				PS10-up	23-Oct-2017	9:12	9:20	5.037	5.138											
				PS10-down	23-Oct-2017	9:28	9:35	4.828	4.856			0.209	0.282							
				CG3-up	23-Oct-2017	10:36	10:46	4.740	4.788					-0.015	-0.050	0.0006	0.138	0.116	0.092	0.070



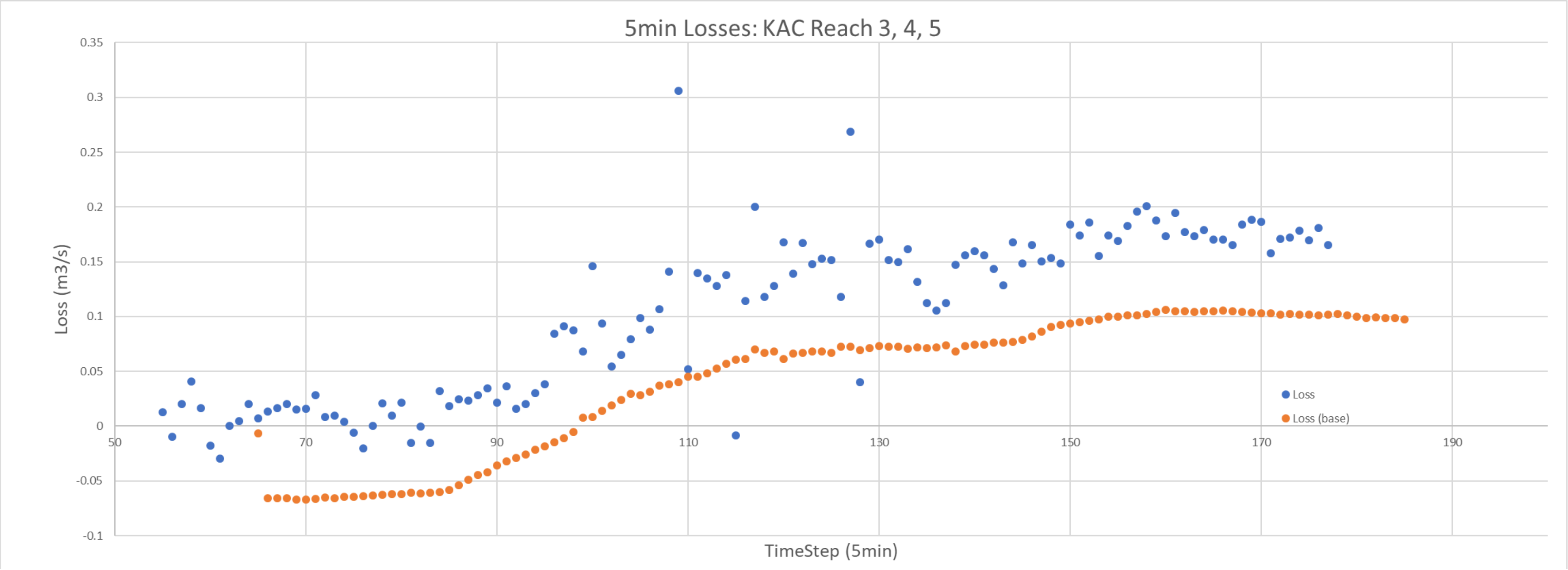
KAC Reach 3

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
3-4	11.6 - 12.8	1.239	8.4	PS11&CG3-down	3-Jul-2017	19:20	19:29	5.194	5.217											
				CG4	4-Jul-2017	5:26	5:33	5.112	5.129						-0.011	0.0018		0.069		0.075
				CG3&PS11-down	7-Jul-2017	9:29	9:41	5.613	5.688											
				CG4	7-Jul-2017	9:52	9:56	5.607	5.723						0.000	0.0010		0.005		-0.036
				CG3-down	23-Oct-2017	10:03	10:12	4.388	4.523											
				CG4-up	23-Oct-2017	11:21	11:32	4.408	4.495						-0.023	-0.0313	-0.044	-0.052	0.004	-0.004



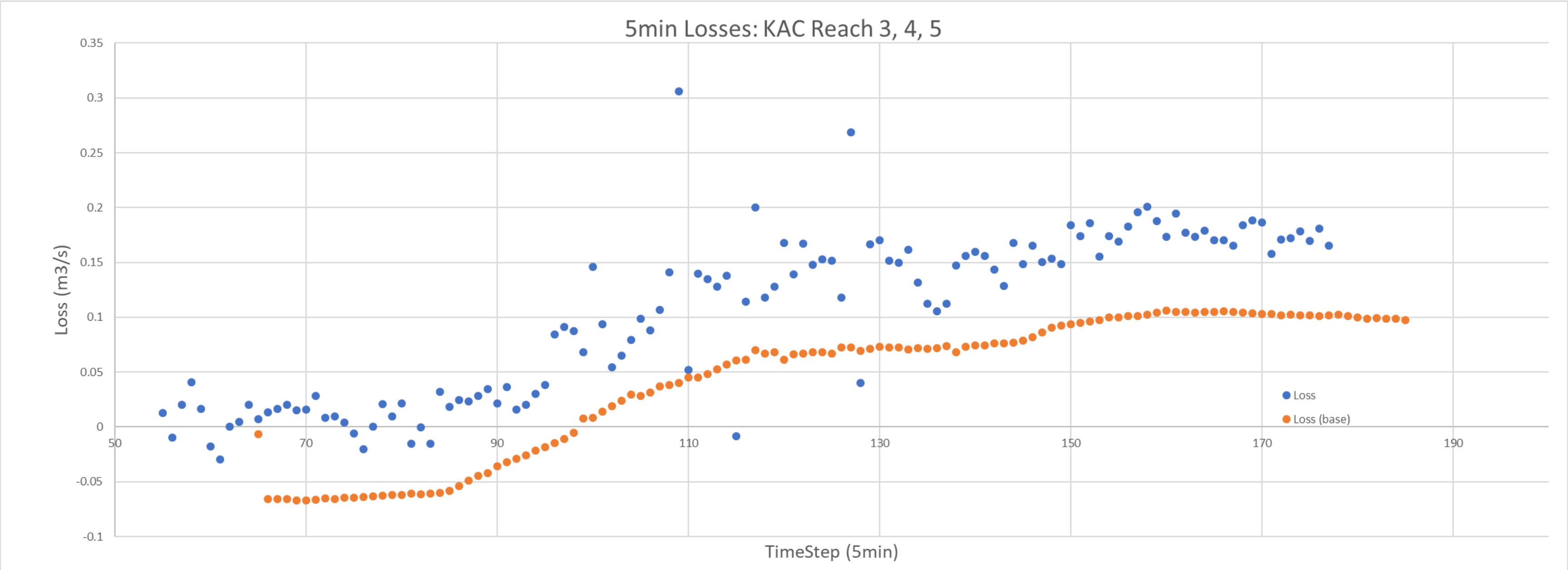
KAC Reach 4

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
4-5	12.8 - 15.0	2.226	8.5	CG4	4-Jul-2017	5:26	5:33	5.112	5.129											
				CG5	4-Jul-2017	5:53	6:01	4.949	5.145						0.000	0.0000		0.163		-0.016
				CG4	8-Jul-2017	5:34	5:39	5.684	5.863											
				CG5	8-Jul-2017	6:25	6:32	5.705	5.844						-0.027	0.0001		-0.048		-0.008
				CG4-up	23-Oct-2017	11:21	11:32	4.408	4.495											
				CG5-up	23-Oct-2017	12:23	12:31	3.507	3.588					0.000	-0.024	0.0013	0.168	0.144	0.087	0.150



KAC Reach 5

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
5-7	15.0 - 18.9	3.903	8.5	CG5	4-Jul-2017	5:53	6:01	4.949	5.145											
				CG6	4-Jul-2017	6:20	6:29	4.977	4.800											
				CG7	4-Jul-2017	6:45	6:52	4.985	5.100						-0.047	0.0003		-0.083		-0.002
				CG5	8-Jul-2017	6:25	6:32	5.705	5.844											
				CG6	8-Jul-2017	6:49	6:56	5.605	5.676											
				CG7	8-Jul-2017	7:09	7:21	5.439	5.446						0.049	0.0005		0.315		0.447
				CG5-up	23-Oct-2017	12:23	12:31	3.507	3.588											
				CG7-up	23-Oct-2017	14:17	14:24	3.557	3.595					0.034	0.121	0.0040	-0.020	0.067	-0.058	0.033



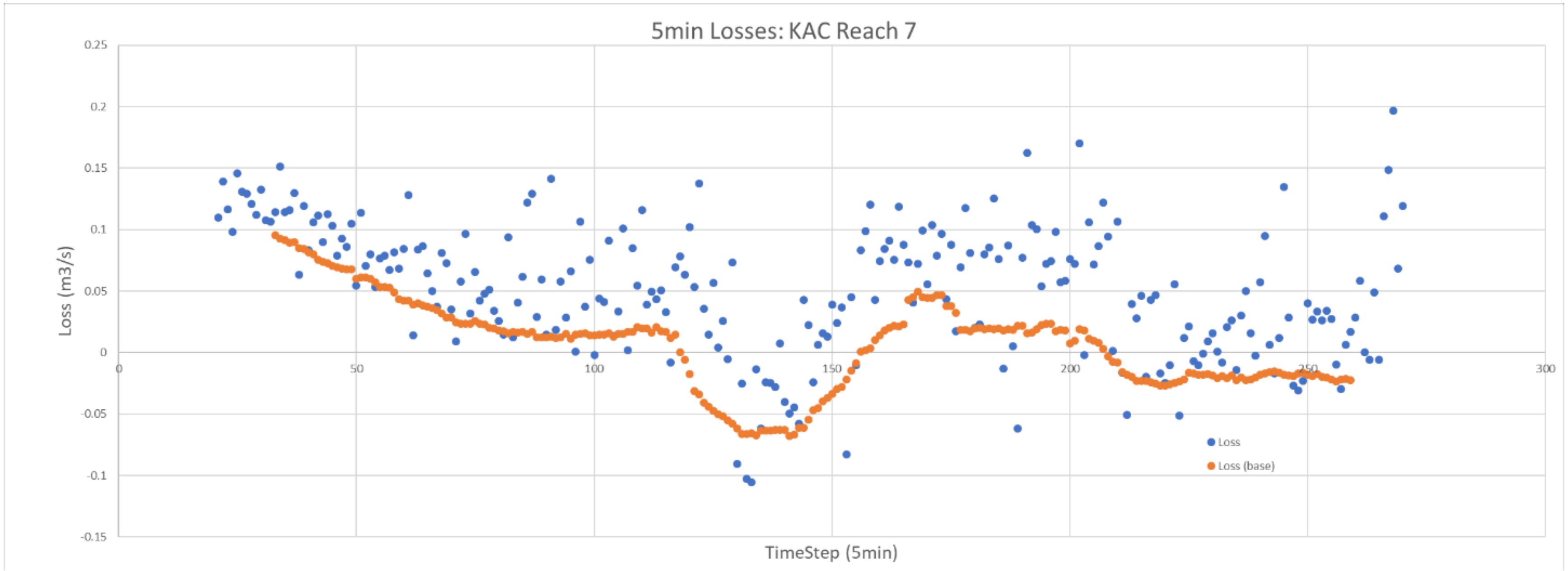
KAC Reach 6

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
7-9	19.9 - 22.5	3.592	8.5	CG7	4-Jul-2017	6:45	6:52	4.985	5.100											
				PS20(Prince)-up	4-Jul-2017	7:09	7:21	5.151	5.413											
				PS20(Prince)-dowr	4-Jul-2017	7:34	7:56	4.789	4.560			0.362	0.362							
				CG8	4-Jul-2017	8:04	8:14	4.320	4.620											
				CG9&PS22-up	4-Jul-2017	8:42	8:47	4.417	4.468						0.125	0.0011		0.330		0.394
				CG7	8-Jul-2017	7:09	7:21	5.439	5.446											
				PS20(Prince)-up	8-Jul-2017	7:46	7:56	5.548	5.472											
				PS20(Prince)-dowr	8-Jul-2017	8:00	8:10	5.263	5.309			0.285	0.163							
				CG8&PS21-up	8-Jul-2017	8:39	8:50	5.208	5.174											
				CG8&PS21-down	8-Jul-2017	8:57	9:05	4.554	4.706			0.654	0.468							
				PS22-up	8-Jul-2017	9:28	9:34	4.806	4.827											
				PS22-down	8-Jul-2017	9:45	9:50	4.520	4.625			0.286	0.202		0.912	0.0015		0.605		0.899
				CG7 up	14-Jan-2018	11:30	11:40	0.000	2.453											
				CG9 up	14-Jan-2018	13:35	13:45	0.000	2.400					0.044					0.097	

No IQ measurements were done on Reach 6 due to the complex pumping regime on this reach. The loss partitioning between constant/seepage and unmetered/illegal was estimated for this reach using adjacent reach estimates.

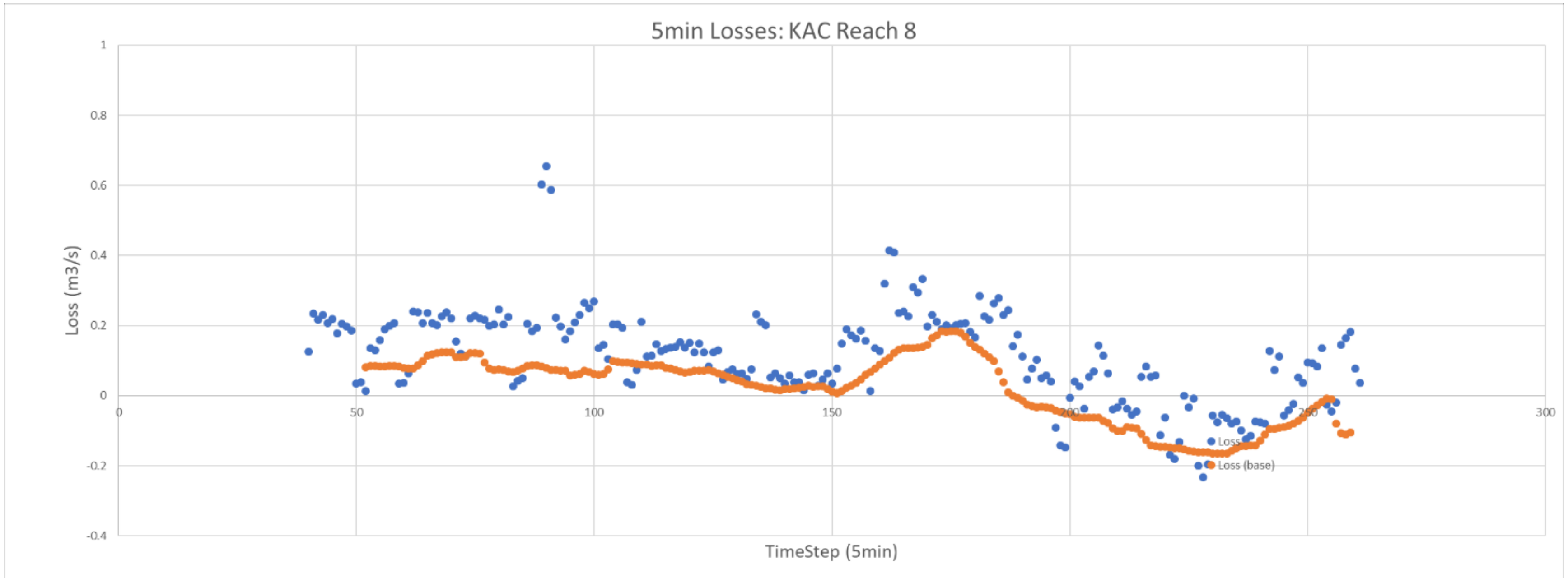
KAC Reach 7

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
9-10	22.5 - 24.9	2.353	8.5	CG9-down	5-Jul-2017	6:02	6:11	4.600	5.726											
				PS24-up	5-Jul-2017	6:30	6:42	4.784	5.020											
				CG10	5-Jul-2017	6:52	6:57	4.073	4.267			0.711	0.753		0.030	0.0002		-0.154		0.736
				PS22-down	8-Jul-2017	9:45	9:50	4.520	4.625											
				PS24-up	8-Jul-2017	10:03	10:11	4.775	4.815											
				PS24-down	8-Jul-2017	10:14	10:21	3.971	4.269			0.804	0.546							
				CG10	8-Jul-2017	10:31	10:35	3.948	4.220						0.261	0.0021		0.027		0.118
				CG9-up	24-Oct-2017	12:04	12:13	3.437	3.454											
				PS24-up	24-Oct-2017	12:27	12:35	3.373	3.413											
				PS24-down	24-Oct-2017	12:44	12:52	3.096	3.166			0.277	0.247							
				CG10-up	24-Oct-2017	13:24	13:32	3.263	3.315					0.141	-0.064	0.0027	0.035	-0.169	0.030	-0.174



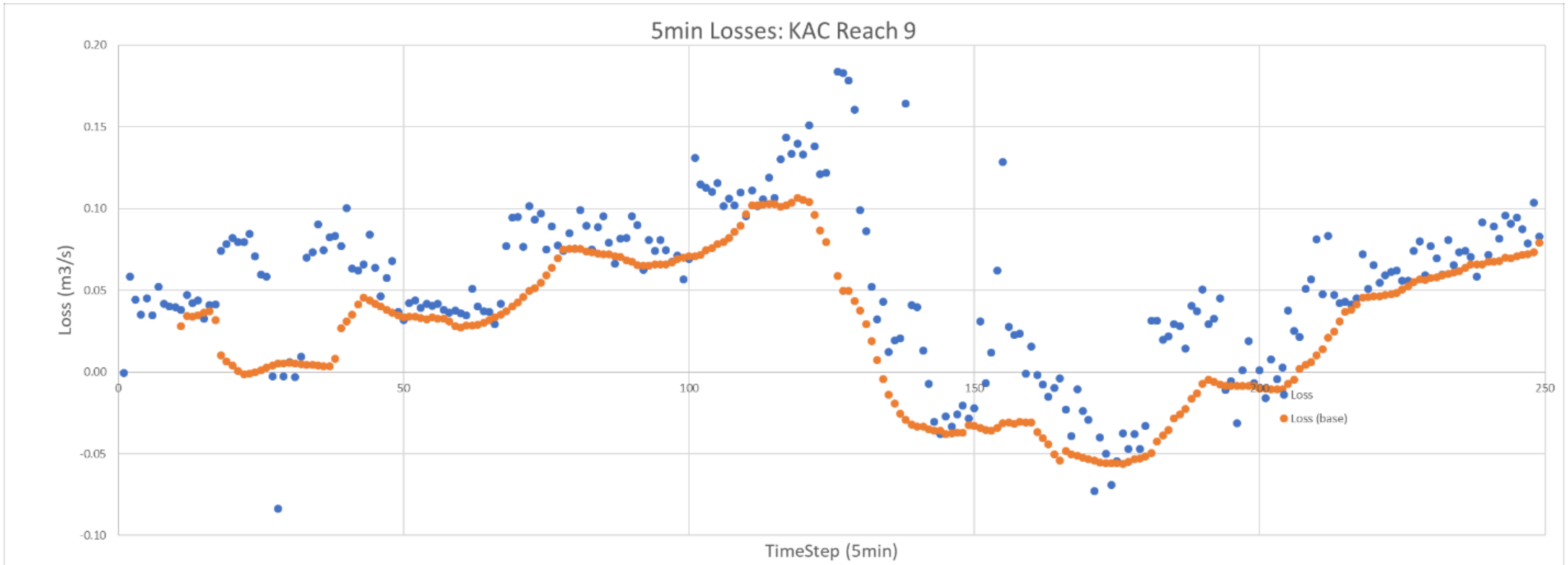
KAC Reach 8

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
10-12	24.9 - 29.4	4.542	8.5	CG10	5-Jul-2017	6:52	6:57	4.073	4.267											
				PS28-up	5-Jul-2017	7:16	7:21	4.311	4.510											
				PS28-down	5-Jul-2017	7:35	7:45	3.601	3.966			0.710	0.544							
				CG12	5-Jul-2017	8:01	8:07	3.755	3.883						0.214	0.0013		-0.179		0.053
				CG10	8-Jul-2017	10:31	10:35	3.948	4.220											
				PS28-up	8-Jul-2017	10:50	10:58	4.297	4.397											
				PS28-down	8-Jul-2017	11:06	11:12	3.654	3.648			0.643	0.749							
				CG12	8-Jul-2017	11:32	11:41	3.568	3.671						-0.719	0.0057		-0.988		-0.925
				CG10-up	24-Oct-2017	13:24	13:32	3.263	3.315											
				PS28-up	24-Oct-2017	14:41	14:50	3.319	3.356											
				PS28-down	24-Oct-2017	15:00	15:09	3.106	3.173			0.213	0.183							
				CG12-up	24-Oct-2017	15:20	15:28	3.056	3.088					0.145	-0.116	0.0071	0.132	-0.129	0.182	-0.079



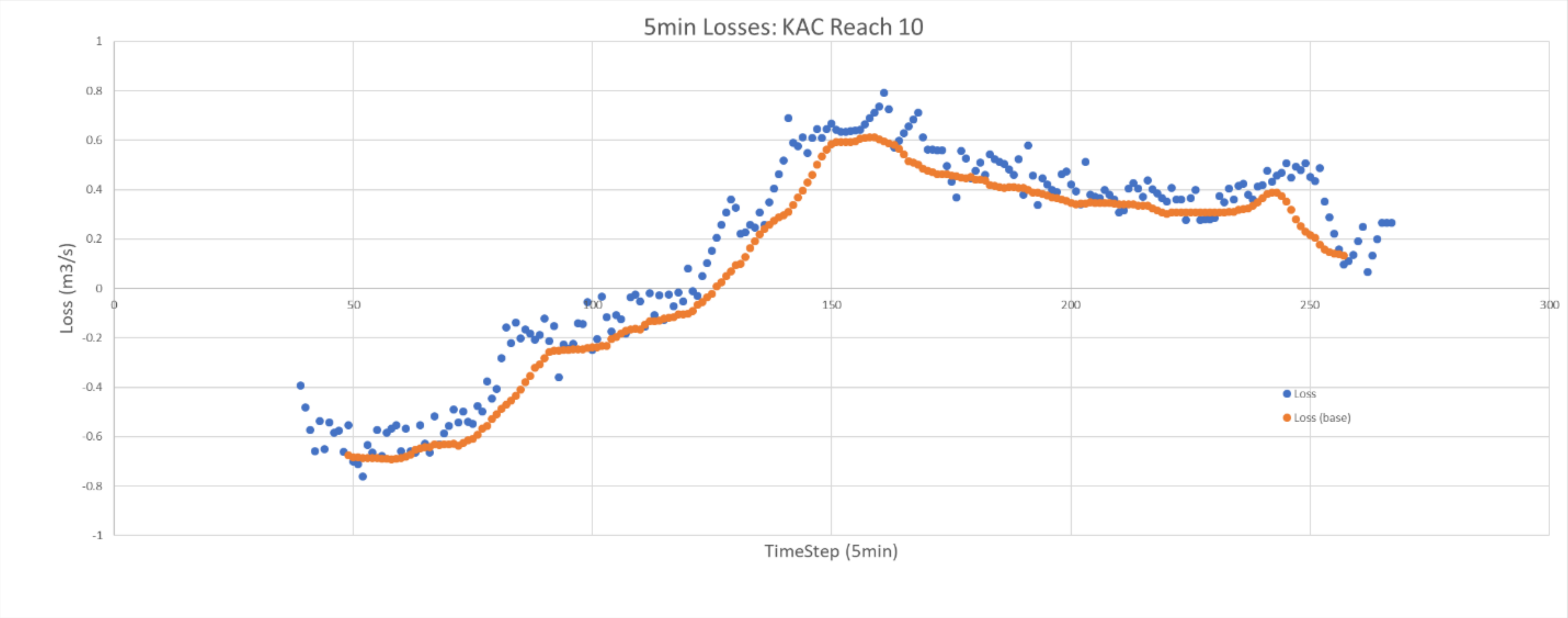
KAC Reach 9

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}		m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
12-14	29.4 - 34.4	4.98	9	CG12	5-Jul-2017	8:01	8:07	3.755	3.883											
				PS33-up	5-Jul-2017	8:28	8:37	3.894	3.999											
				PS33-down	5-Jul-2017	8:47	8:51	3.351	3.376			0.543	0.623							
				CG14	5-Jul-2017	9:15	9:21	3.458	3.678						0.305	0.0025		0.056		-0.116
				CG12	8-Jul-2017	11:32	11:41	3.568	3.671											
				PS33-up	8-Jul-2017	11:54	11:58	3.574	3.644											
				PS33-down	8-Jul-2017	12:03	12:07	3.098	3.147			0.476	0.497							
				CG14	8-Jul-2017	12:19	12:24	3.109	3.199						-0.144	0.0077		-0.168		-0.176
				CG12-up	24-Nov-2017	13:30	14:09	1.714	1.766											
				CG14-up	24-Nov-2017	14:33	14:40	1.584	1.677					0.237	0.107	0.0071	0.050	-0.080	0.009	-0.121



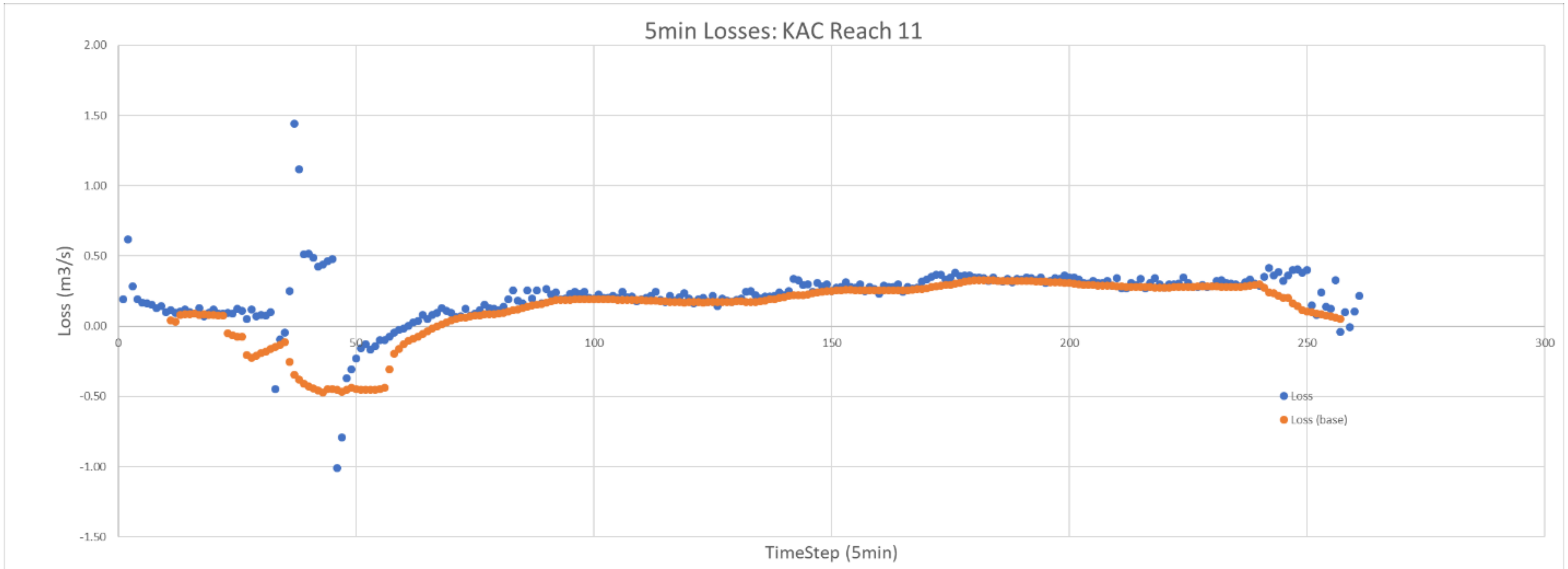
KAC Reach 10

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
14-15	34.4 - 37.3	2.887	8.3	CG14	5-Jul-2017	9:15	9:21	3.458	3.678											
				PS36-up	5-Jul-2017	9:43	9:50	3.368	3.504											
				PS36-down	5-Jul-2017	10:15	10:25	2.581	2.504			0.787	1.000							
				CG15	5-Jul-2017	12:56	13:04	2.800	2.780						0.096	0.0039		-0.037		-0.010
				CG14	8-Jul-2017	12:19	12:24	3.109	3.199											
				PS36-up	8-Jul-2017	12:37	12:42	3.084	3.111											
				PS36-down	8-Jul-2017	12:44	12:48	2.742	2.742			0.342	0.369							
				CG15	8-Jul-2017	13:14	13:18	2.682	2.788						0.000	0.0051		0.080		0.037
				CG14-up	25-Oct-2017	8:24	8:31	2.261	2.269											
				PS36-up	25-Oct-2017	8:47	8:54	2.456	2.473											
				PS36-down	25-Oct-2017	9:00	9:06	2.079	2.119			0.377	0.354							
				CG15-up	25-Oct-2017	9:54	10:00	1.817	1.920					0.188	0.158	0.0003	0.254	0.225	0.182	0.153



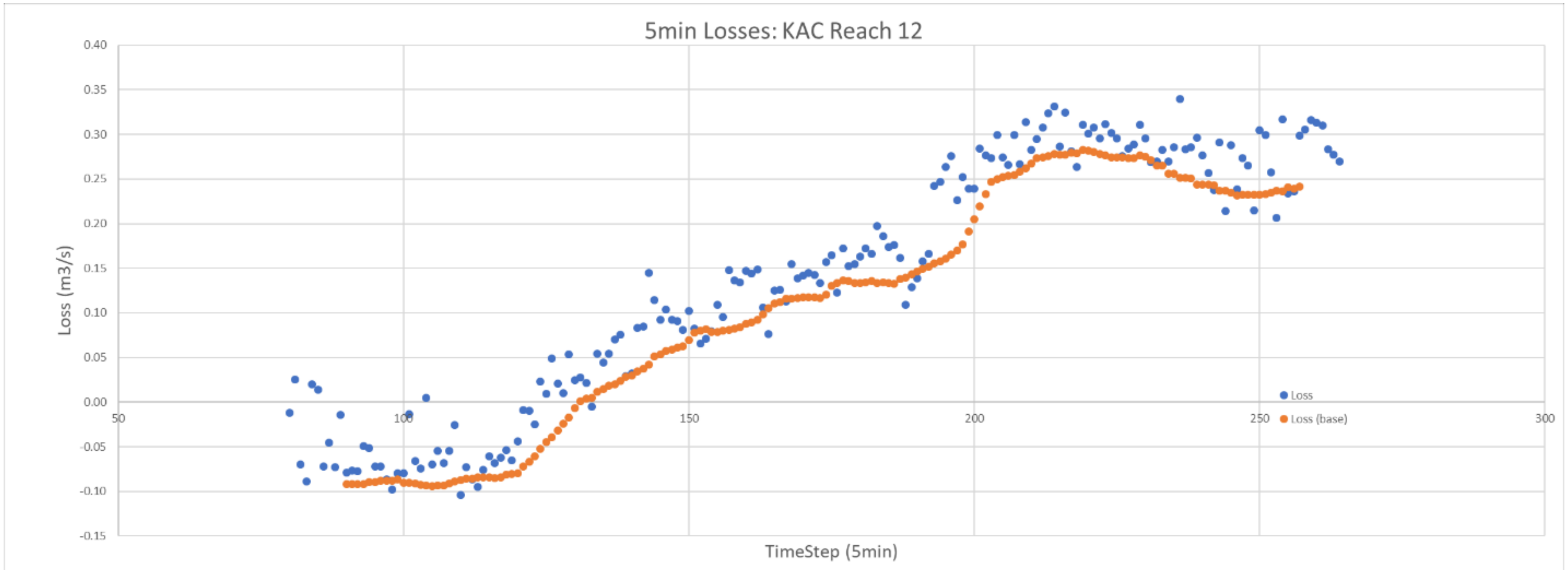
KAC Reach 11

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
15-17	37.3 - 43.2	5.931	7.92	CG15	5-Jul-2017	12:56	13:04	2.800	2.780											
				PS41-up	5-Jul-2017	13:24	13:29	2.877	2.931											
				CG16	5-Jul-2017	13:41	13:46	2.691	2.739											
				CG17	5-Jul-2017	14:11	14:26	2.628	2.679						0.130	0.0124		0.290		0.219
				CG15-up	9-Jul-2017	5:34	5:41	3.826	3.991											
				CG16	9-Jul-2017	6:14	6:23	3.650	3.711											
				CG17&Siphon-up	9-Jul-2017	6:38	6:42	3.608	3.505						-0.131	0.0002		0.087		0.355
				CG15-up	43033	0.413	0.42	1.817	1.92											
				CG17-up	43033	0.608	0.61	2.056	2.09					0.428	0.432	0.0053	0.184	0.188	0.253	0.257



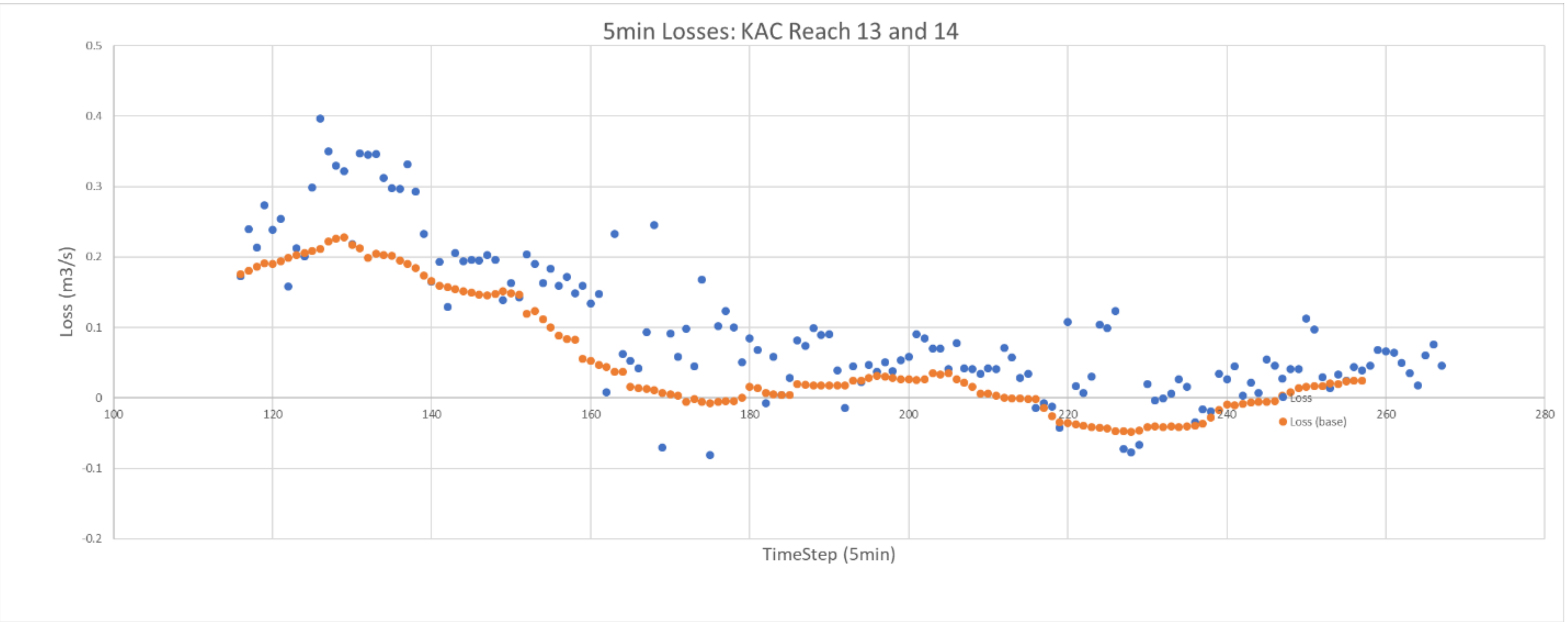
KAC Reach 12

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
17-18	43.2 - 47.0	3.725	7.76	CG17&Siphon-up	6-Jul-2017	5:36	5:43	3.176	3.220											
				CG18	6-Jul-2017	6:36	6:43	2.937	2.976						-0.252	0.0001		-0.013		-0.008
				CG17&Siphon-up	9-Jul-2017	6:38	6:42	3.608	3.505											
				CG18	9-Jul-2017	7:24	7:30	3.346	3.340						0.000	0.0007		0.261		0.164
				CG17-up	26-Oct-2017	7:57	8:04	3.578	3.614											
				PS46-up	26-Oct-2017	8:49	8:59	3.334	3.327											
				PS46-down	26-Oct-2017	9:01	9:09	3.120	3.140			0.214	0.187							
				CG18-up	26-Oct-2017	9:45	9:53	2.957	3.002					-0.174	-0.048	0.0004	0.233	0.358	0.251	0.376



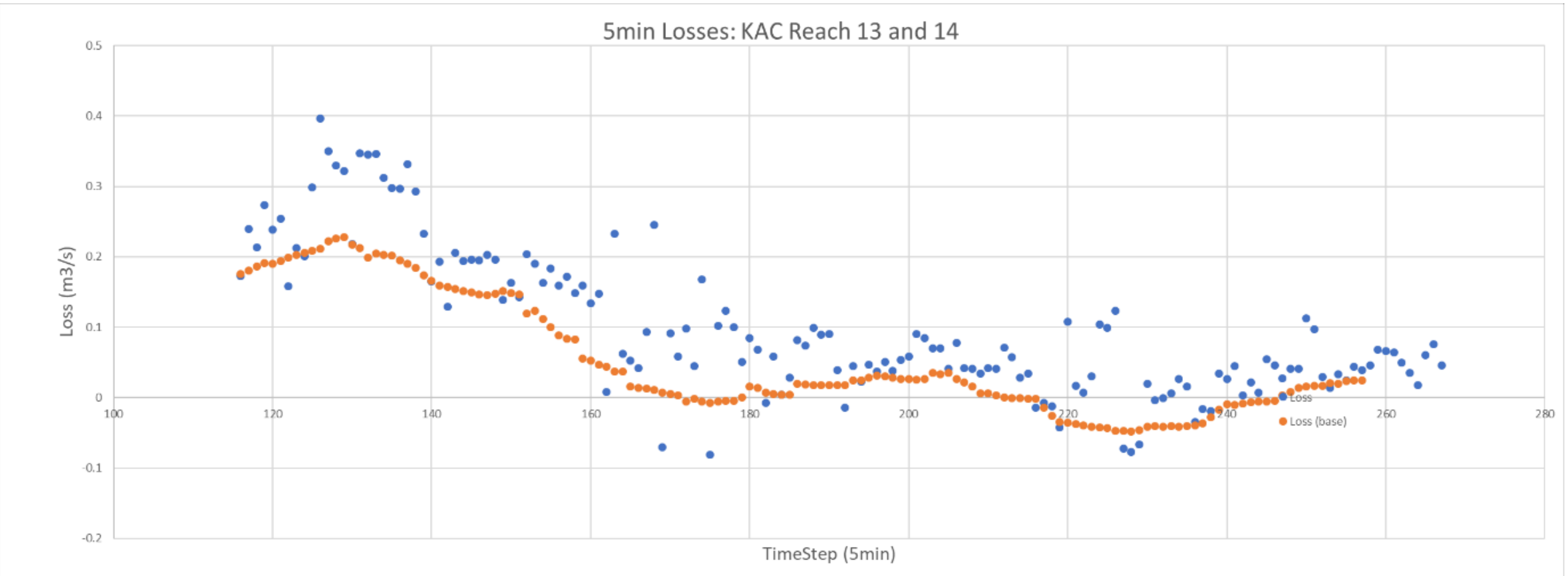
KAC Reach 13

CG	KAC (km)	Length (km)	Width (m)	Location	Date	Time Start	Time End	Q_{GPS} m^3s^{-1}	Q_{BT} m^3s^{-1}	I_{GPS} m^3s^{-1}	I_{BT} m^3s^{-1}	O_{GPS} m^3s^{-1}	O_{BT} m^3s^{-1}	dS_{MANUAL} m^3s^{-1}	dS_{SCADA} m^3s^{-1}	E (m^3s^{-1}) m^3s^{-1}	$L_{GPS+dSmanual}$ m^3s^{-1}	$L_{GPS+dSscada}$ m^3s^{-1}	$L_{BT+dSmanual}$ m^3s^{-1}	$L_{BT+dSscada}$ m^3s^{-1}
18-19	47.0 - 50.1	3.12	9.19	CG18	6-Jul-2017	6:36	6:43	2.937	2.976											
				CG19	6-Jul-2017	7:11	7:16	2.779	2.822						-0.179	0.0005		-0.022		-0.026
				CG18	9-Jul-2017	7:24	7:30	3.346	3.340											
				CG19	9-Jul-2017	7:55	8:00	3.338	3.457						0.000	0.0009		0.007		-0.118
				CG18-up	2-Nov-2017	8:25	8:35	2.695	2.695											
				CG19-up	2-Nov-2017	9:10	9:20	2.591	2.591					0.000	0.000	0.0008	0.103	0.103	0.103	0.103



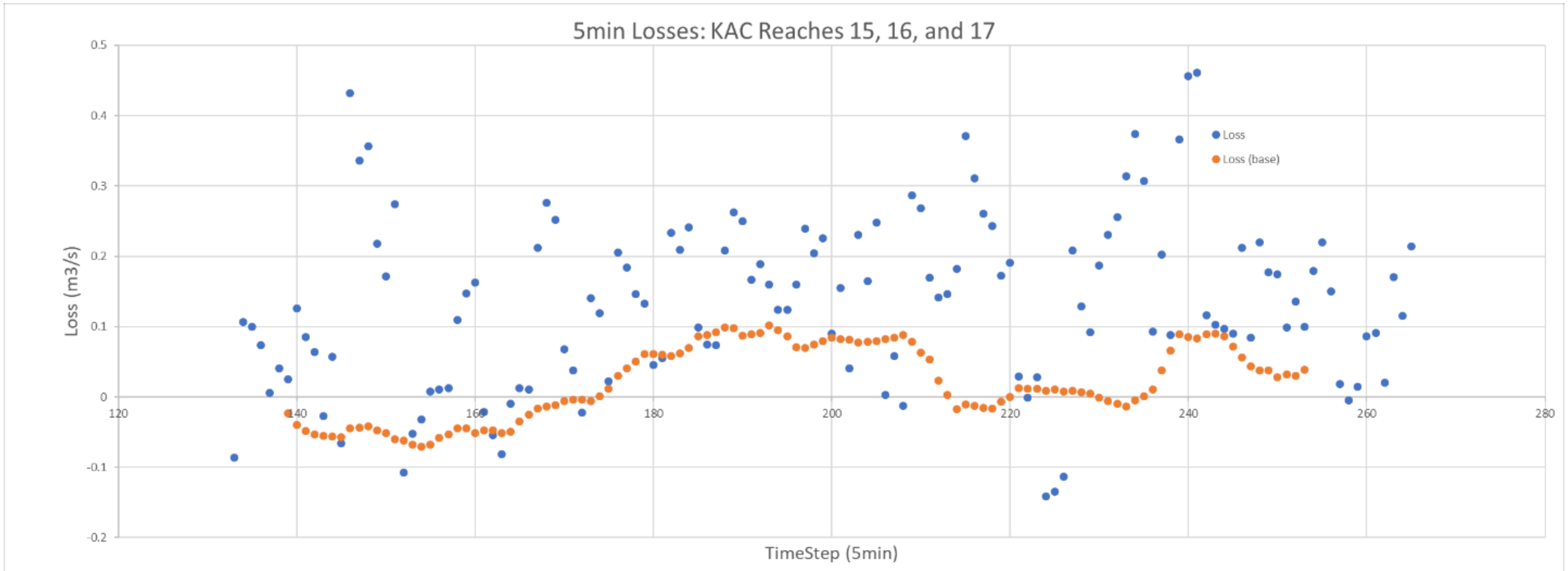
KAC Reach 14

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
19-21	50.1 - 55.1	5.006	8.88	CG19	6-Jul-2017	7:11	7:16	2.779	2.822											
				CG20	6-Jul-2017	7:32	7:37	2.471	2.673											
				CG21	6-Jul-2017	7:56	8:04	2.503	2.728						-0.210	0.0013		0.065		-0.117
				CG19	9-Jul-2017	7:55	8:00	3.338	3.457											
				CG21	9-Jul-2017	8:35	8:43	3.261	3.292						-0.156	0.0021		-0.082		0.006
				CG19-up	2-Nov-2017	9:36	9:43	2.591	2.685											
				CG21-up	2-Nov-2017	10:04	10:11	2.598	2.660					0.119	0.000	0.0028	0.109	-0.010	0.141	0.022



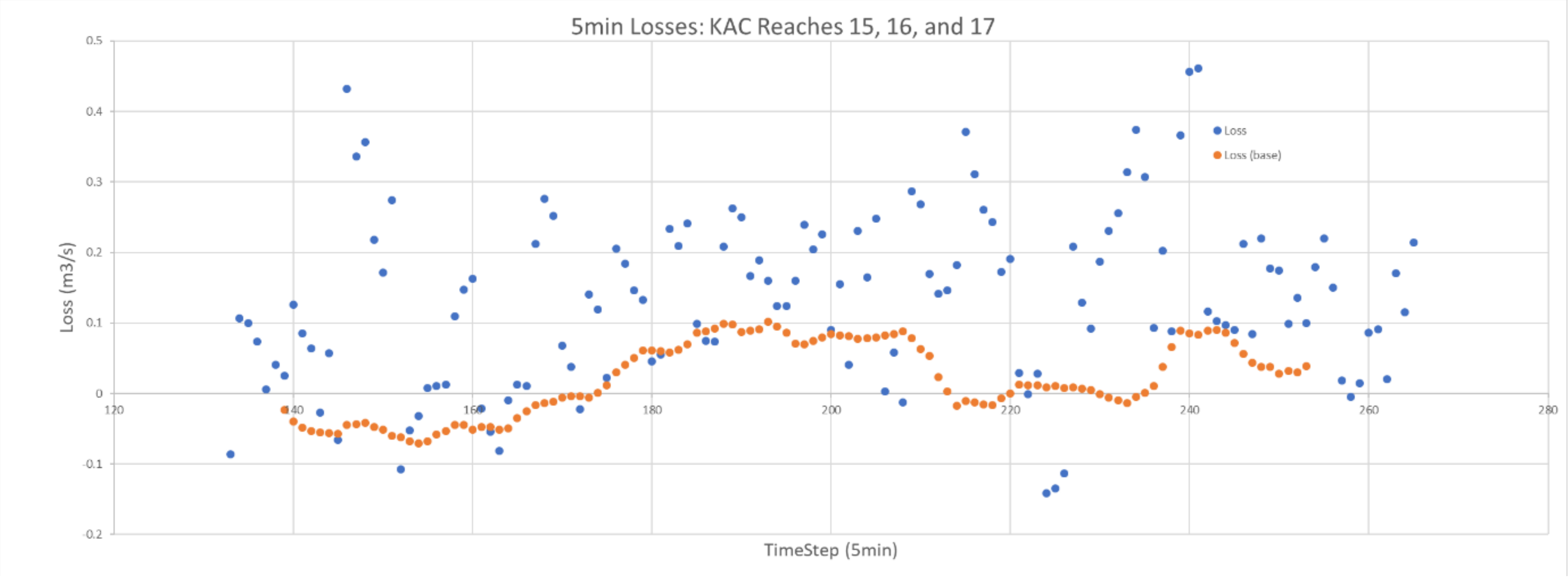
KAC Reach 15

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
21-22	55.1 - 58.0	2.871	9.29	CG21	6-Jul-2017	7:56	8:04	2.503	2.728											
				CG22	6-Jul-2017	8:18	8:27	2.614	2.595						0.000	0.0011		-0.112		0.132
				CG21	9-Jul-2017	8:35	8:43	3.261	3.292											
				CG22	9-Jul-2017	9:00	9:09	3.113	3.028						-0.063	0.0015		0.083		0.199
				CG19-up	2-Nov-2017	9:36	9:43	2.591	2.685											
				CG21-up	2-Nov-2017	10:04	10:11	2.598	2.660					0.119	0.000	0.0028	0.109	-0.010	0.141	0.022



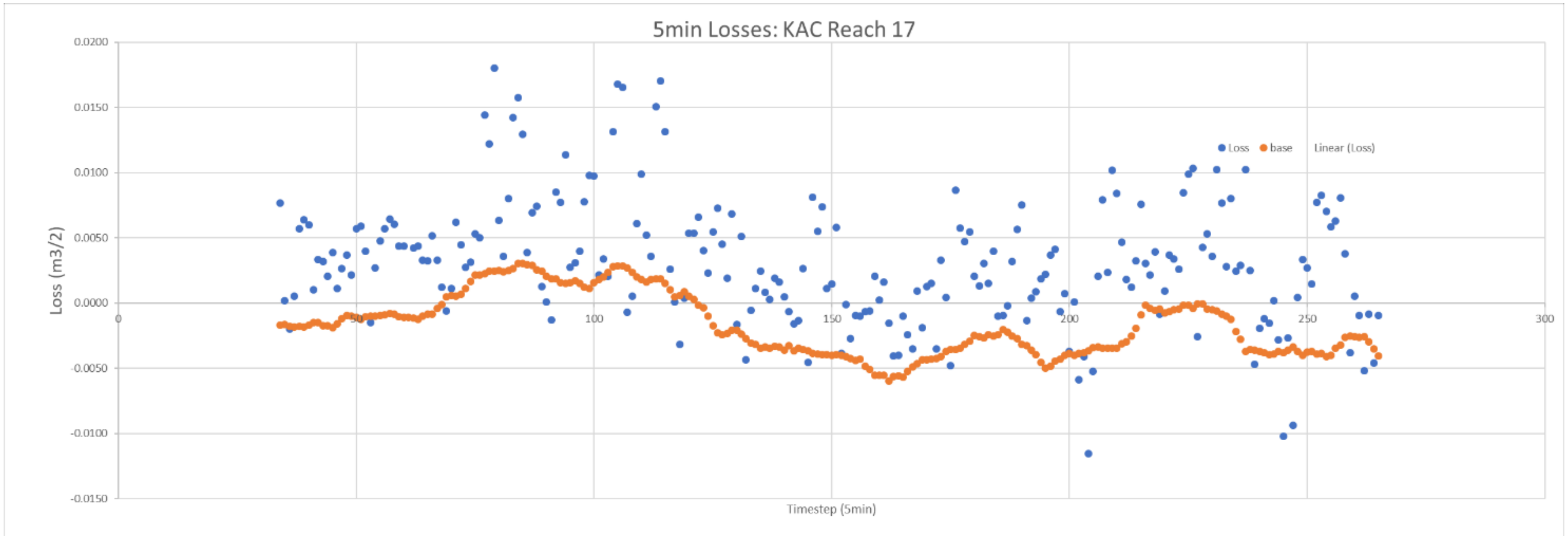
KAC Reach 16

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
22-24	58.0 - 62.1	4.1	8.24	CG22	6-Jul-2017	8:18	8:27	2.614	2.595											
				CG23	6-Jul-2017	8:40	8:45	2.581	2.610											
				CG24	6-Jul-2017	9:01	9:08	2.465	2.599						-0.056	0.0018		0.091		-0.062
				CG22	9-Jul-2017	9:00	9:09	3.113	3.028											
				CG24	9-Jul-2017	9:32	9:38	2.821	2.869						-0.243	0.0028		0.046		-0.087
				CG22-up	30-Oct-2017	12:32	12:40	2.457	2.555											
				CG24-up	30-Oct-2017	15:26	15:34	2.346	2.463					-0.141	0.000	0.0049	-0.034	0.106	-0.053	0.087



KAC Reach 17

	KAC	Length	Width			Time	Time	Q_{GPS}	Q_{BT}	I_{GPS}	I_{BT}	O_{GPS}	O_{BT}	dS_{MANUAL}	dS_{SCADA}	E (m^3s^{-1})	$L_{GPS+dSmanual}$	$L_{GPS+dSscada}$	$L_{BT+dSmanual}$	$L_{BT+dSscada}$
CG	(km)	(km)	(m)	Location	Date	Start	End	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}	m^3s^{-1}
24-25	62.1 - 65.2	2.423	8.53	CG24	6-Jul-2017	9:01	9:08	2.465	2.599											
				AmmanPS-up	6-Jul-2017	9:28	9:33	2.455	2.481						-0.108	0.0014		-0.099		0.009
				CG24	9-Jul-2017	9:32	9:38	2.821	2.869											
				AmmanOut-up	9-Jul-2017	9:54	10:03	2.821	2.884						0.000	0.0021		-0.002		-0.017
				CG24-up	30-Oct-2017	11:59	12:07	2.452	2.459											
				CG25-AmmanPS	30-Oct-2017	13:20	13:27	2.269	2.292					0.000	-0.021	0.0026	0.180	0.160	0.164	0.144



4.2 SUMMARY OF SCADA POINTS WITH ERRORS/ISSUES

The goal of this study is to determine canal water losses and their attribution to seepage, evaporation or unmetered/illegal extraction. As part of this study, we used and evaluated some of the KAC SCADA observations, but a true evaluation of SCADA issues and errors would require additional and more focused study. For example, we specifically avoided many the pump stations in our measurements, so the quality of the SCADA measurements for these cannot be assessed. There are also many SCADA sensors that are not operational, and a number of inflows and pump station flows that are estimated: these are also not assessed here.

Some of the KAC SCADA measurements we evaluated are listed below:

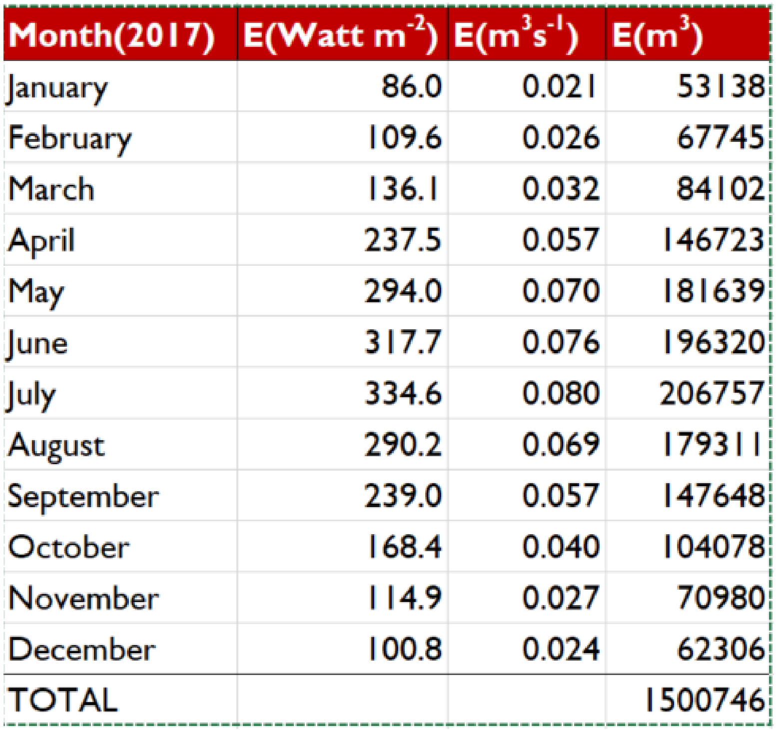
- PS24: SCADA reports significantly low
- PS28: SCADA reports are slightly low
- PS36: SCADA appears to be accurate
- CG2-up: SCADA stage changes are accurate
- CG3-up: SCADA stage changes are too high
- CG4-up: SCADA stage changes are slightly too high
- CG5-up: SCADA stage changes are too high
- CG7-up: SCADA stage changes are significantly too high
- CG10-up: SCADA stage changes are opposite of those measured manually
- CG12-up: SCADA stage changes are opposite of those measured manually
- CG14-up: SCADA stage changes are too low
- CG15-up: SCADA stage changes are slightly too low
- CG17-up: SCADA stage changes are accurate
- CG18-up: SCADA stage changes are too low
- CG19-up: SCADA stage changes are accurate, but unchanging during measurement
- CG21-up: SCADA stage changes are reasonable, but unchanging during measurement
- CG22-up: SCADA stage changes are accurate
- CG24-up: SCADA stage changes are too low or insensitive
- CG25-up: SCADA stage changes are reasonable, but unchanging during measurement

Overall, we found the SCADA observations to be of inadequate quality to be used to assess losses. The inflow and pumping measurements had large errors or were missing entirely, and the stage observations were only accurate in a few locations. It is strongly recommended that the SCADA sensors be repaired, replaced, and/or calibrated. We did not assess SCADA discharge estimates at check gates, but because of issues with SCADA stage measurements, the discharge estimates would likely also be unreliable.

4.3 MONTHLY SUMMARY OF EVAPORATION LOSSES FOR 2017

Evaporation was determined using potential evaporation estimates provided by the NASA Global Land Data Assimilation System (GLDAS). GLDAS uses advanced land-atmosphere models, surface meteorology, numerical weather forecasts, and weather satellite data to make accurate estimates of surface water conditions across the globe at high resolution. 3hr, ¼ degree potential evaporation data was extracted for the KAC region interpolated to 5-minute timeseries. Evaporation rate (m/s) was averaged for the time period required to make the M9 measurements across the reach, then multiplied by the area of the reach. Using this data it is estimated that the canal loses about 11 mm of water daily during July (about 1.2% of the flow volume), and 6.4 mm cm of water daily (about 0.7 % of the flow volume) during October. In other words, evaporation is a minor component of the total losses.

Table 1: Monthly Summary of KAC Evaporation Losses



Month(2017)	E(Watt m^{-2})	E(m^{3}s^{-1})	E(m^3)
January	86.0	0.021	53138
February	109.6	0.026	67745
March	136.1	0.032	84102
April	237.5	0.057	146723
May	294.0	0.070	181639
June	317.7	0.076	196320
July	334.6	0.080	206757
August	290.2	0.069	179311
September	239.0	0.057	147648
October	168.4	0.040	104078
November	114.9	0.027	70980
December	100.8	0.024	62306
TOTAL			1500746

5.0 CONCLUSION

The tables and figures below are a summary of all the analyses based on the M9 and IQ data that was collected on the upper KAC in July and October 2017. In July, 2 complete sets of measurements were made on each KAC reach, and these are represented by July-A and July-B. The October measurements are in the 3rd column, and the "Best Average" was assessed by excluding the greyed outliner data from the average. The greyed data was excluded from the analysis due to issues with the SCADA storage changes, large canal dynamics, and other measurement issues. For each set of measurements, values of Loss (m^3s^{-1}), total flow Q (m^3s^{-1}), Loss (%), and Loss ($m^3s^{-1}km^{-1}$) are shown. The partitioning of losses between constant/seepage and unmetered/illegal is in the second table in units of m^3s^{-1}, $\%km^{-1}$, %, $m^3s^{-1}km^{-1}$ and % unmetered/illegal of the total loss. These loss numbers do not include evaporation, which was relatively small and was accounted for using the procedures outlined above. The July data used SCADA level data for storage changes and is generally considered less reliable than the October data where manual measurements of level data were used as well as SCADA observations. July data was collected as fast as possible to minimize the impact of canal level changes, while the October data was collected based on the water velocity time delay or the "follow the water" technique. A future study is planned to evaluate the relative merits of these two approaches. Finally, there were significant issues measuring flow into the tunnel due to very complex flow conditions (swirling water).

The total water losses for the 65km of the upper KAC are estimated to be 24.4% of the maximum flow, partitioned between 10.7% being constant/seepage, and 13.7% being unmetered/illegal uses. If accounting for evaporation, the total loss would increase by about 1% to 25.4%, with the constant and unmetered/illegal percentages staying the same.

Some of the largest losses were seen in reach 6, which is a very complex hard-to-measure reach because it contains 4 outlets (Gravity Line 6, PS21, Gravity Line 5, and PS22). After assessing the losses in this reach, it was discovered that substantial part of the losses is legal but unmetered. Accordingly, the measurements were repeated for this reach after stopping all legal abstractions. The newly obtained result was used in the analysis. None-the less, this reach also shows a relatively high unmetered/illegal use (72% of the loss is unmetered/illegal). Reaches 10, 11, and 12 also show relatively high losses – these reaches are in complex terrain that is more likely to absorb seepage from the canal and is a relatively easy area to establish siphons. Reaches 1 and 2 are some of the oldest in the KAC system and have significant damage. Reaches 1 and 2 show high physical losses and reach 1 shows a relatively high unmetered/illegal loss. The lower reaches, near the control center have some of the lowest losses, likely because the terrain is smoother and already saturated, and the canal is better monitored in these areas. Reaches 1-4 show an elevated constant loss likely due to the older age of these canal sections – this could be a good area to target for repair work. Reach 15 shows a high unmetered/illegal loss and may be a good area to increase security of remove illicit pumps.

Some special measurements were made to assess losses in the tunnel and siphons. Despite some evidence of minor leaks seen in the siphons, these structures appear to lose very little water. In fact, some M9 observations showed that the tunnel may be gaining a bit of water (i.e. through underground springs), but that would have to be confirmed with additional measurements. The utility of having multiple measurements over several seasons is well demonstrated, as it allows outlier data to be identified and eliminated.

Table 2: Summary of Upper KAC Losses by Reach

				July-A				July-B				October				Best Average			
Reach	**CG**	**KAC**	**Length**	**L**	**Q**	**L**	**L**	**L**	**Q**	**L**	**L**	**L**	**Q**	**L**	**L**	**L**	**Q**	**L**	**L**
		km	km	m^3s^{-1}	m^3s^{-1}	%	$m^3s^{-1}km^{-1}$	m^3s^{-1}	m^3s^{-1}	%	$m^3s^{-1}km^{-1}$	m^3s^{-1}	m^3s^{-1}	%	$m^3s^{-1}km^{-1}$	m^3s^{-1}	m^3s^{-1}	%	$m^3s^{-1}km^{-1}$
0	Tunnel			-0.09	3.69	-2.5%	-0.012	0.02	3.77	0.5%	0.002	---	---	---	---	0.02	3.77	0.5%	0.002
1	Falls-2	0 - 8.6	6.406	0.29	6.61	4.3%	0.045	0.23	6.39	6.4%	0.036	0.23	5.33	4.3%	0.036	0.25	6.11	5.0%	0.039
2	2-3	8.6 - 11.6	2.959	-0.05	6.41	-0.9%	-0.019	-0.09	5.89	-1.6%	-0.031	0.09	5.19	1.8%	0.031	0.09	5.19	1.8%	0.031
3	3-4	11.6 - 12.8	1.239	0.07	5.21	1.4%	0.058	0.00	5.61	0.1%	0.004	0.00	4.52	0.1%	0.004	0.03	5.11	0.5%	0.022
4	4-5	12.8 - 15.0	2.226	0.07	5.12	1.4%	0.033	-0.01	5.86	-0.1%	-0.004	0.09	4.50	1.9%	0.039	0.05	5.16	1.1%	0.023
5	5-7	15.0 - 18.9	3.903	0.00	5.15	0.0%	-0.001	0.38	5.77	6.6%	0.098	0.03	3.59	0.9%	0.008	0.03	3.59	0.9%	0.008
6	7-9	19.9 - 22.5	3.592	0.33	4.99	6.6%	0.092	0.60	5.44	13.3%	0.168	0.10	2.45	4.0%	0.027	0.10	2.45	4.0%	0.027
7	9-10	22.5 - 24.9	2.353	0.29	5.16	5.6%	0.124	0.07	4.57	1.6%	0.031	0.03	3.45	0.9%	0.013	0.05	4.01	1.2%	0.022
8	10-12	24.9 - 29.4	4.542	0.05	4.27	1.2%	0.012	-0.92	4.22	-21.9%	-0.204	0.18	3.32	5.5%	0.040	0.12	3.79	3.4%	0.026
9	12-14	29.4 - 34.4	4.980	0.06	3.76	1.5%	0.011	-0.17	3.62	-4.8%	-0.035	0.05	1.71	2.9%	0.010	0.05	2.73	2.2%	0.011
10	14-15	34.4 - 37.3	2.887	0.14	3.05	4.7%	0.050	0.06	3.15	1.9%	0.020	0.18	2.27	8.0%	0.063	0.13	2.82	4.9%	0.044
11	15-17	37.3 - 43.2	5.931	0.25	2.79	9.1%	0.043	0.22	3.91	5.7%	0.037	0.22	1.87	11.8%	0.037	0.23	2.86	8.9%	0.039
12	17-18	43.2 - 47.0	3.725	-0.01	3.22	-0.2%	-0.002	0.16	3.51	4.7%	0.044	0.25	3.61	6.9%	0.067	0.14	3.45	3.8%	0.036
13	18-19	47.0 - 50.1	3.120	-0.02	2.96	-0.8%	-0.008	0.01	3.35	0.2%	0.002	0.10	2.70	3.8%	0.033	0.03	3.00	1.1%	0.009
14	19-21	50.1 - 55.1	5.006	0.06	2.78	2.3%	0.013	0.01	3.46	0.2%	0.001	0.14	2.69	5.3%	0.028	0.07	2.97	2.6%	0.014
15	21-22	55.1 - 58.0	2.871	0.01	2.62	0.4%	0.003	0.14	3.28	4.3%	0.049	0.15	2.57	5.8%	0.052	0.10	2.82	3.5%	0.035
16	22-24	58.0 - 62.1	4.100	0.01	2.60	0.6%	0.004	0.05	3.11	1.5%	0.011	0.03	2.51	1.1%	0.006	0.03	2.74	1.0%	0.007
17	24-25	62.1 - 65.2	2.423	0.01	2.60	0.3%	0.004	0.00	2.82	-0.1%	-0.001	0.16	2.46	6.7%	0.068	0.00	2.63	0.1%	0.001
Sum				**1.48**		**35.1%**	**0.025**	**0.76**		**18.3%**	**0.013**	**2.04**		**71.6%**	**0.033**	**1.52**		**2.6%**	**0.022**

L: Total Losses

Q: Canal discharge

Table 3: Summary of Upper KAC Losses Partitioning by Reach

Reach	**CG**	**C**	**C**	**C**	**C**	**U**	**U**	**U**	**U**	**U/L**
		m^3s^{-1}	% km^{-1}	%	$m^3s^{-1}km^{-1}$	m^3s^{-1}	% km^{-1}	%	$m^3s^{-1}km^{-1}$	%
0	Tunnel-Falls	---	---	---	---	---	---	---	---	---
1	Falls-2	0.092	0.24%	1.51%	0.015	0.156	0.40%	2.55%	0.026	63%
2	2-3	0.073	0.48%	1.41%	0.014	0.019	0.12%	0.37%	0.004	21%
3	3-4	0.014	0.23%	0.28%	0.003	0.013	0.20%	0.25%	0.002	47%
4	4-5	0.027	0.23%	0.52%	0.005	0.024	0.21%	0.46%	0.005	47%
5	5-7	0.011	0.08%	0.32%	0.003	0.022	0.16%	0.61%	0.006	66%
6	7-9	0.03	0.34%	1.22%	0.012	0.070	0.79%	2.85%	0.029	72%
7	9-10	0.011	0.12%	0.27%	0.003	0.040	0.42%	1.00%	0.010	78%
8	10-12	0.031	0.18%	0.82%	0.008	0.090	0.52%	2.37%	0.024	77%
9	12-14	0.024	0.18%	0.88%	0.009	0.028	0.21%	1.02%	0.010	53%
10	14-15	0.048	0.59%	1.69%	0.017	0.080	0.98%	2.84%	0.028	63%
11	15-17	0.123	0.73%	4.31%	0.043	0.094	0.55%	3.29%	0.033	41%
12	17-18	0.106	0.83%	3.08%	0.031	0.030	0.23%	0.87%	0.009	22%
13	18-19	0.014	0.15%	0.48%	0.005	0.014	0.15%	0.48%	0.005	50%
14	19-21	0.036	0.24%	1.20%	0.012	0.036	0.24%	1.20%	0.012	50%
15	21-22	0.010	0.12%	0.35%	0.003	0.090	1.11%	3.19%	0.032	90%
16	22-24	0.003	0.03%	0.10%	0.001	0.026	0.23%	0.95%	0.010	90%
17	24-25	0.000	0.01%	0.01%	0.000	0.003	0.05%	0.12%	0.001	90%
Sum		**0.653**	**0.28%**	**1.08%**	**0.184**	**0.835**	**0.39%**	**1.44%**	**0.244**	**60%**

C: Constant Losses (Seepage)

U: Variable losses (Unmetered)

The figures below show comparison of the different types of losses as total and per kilometer for the different reaches under investigation. This visualization pointed directly to the reaches with the highest losses for each type and the reaches with the potential to face problems in the near future. Red and orange areas indicate KAC reaches with higher losses according to different metrics. The upper few reaches show both significant losses and unmetered/illegal use. Reaches 10-12 also stand out as outliers that could be a potential area to focus rehabilitation actions.

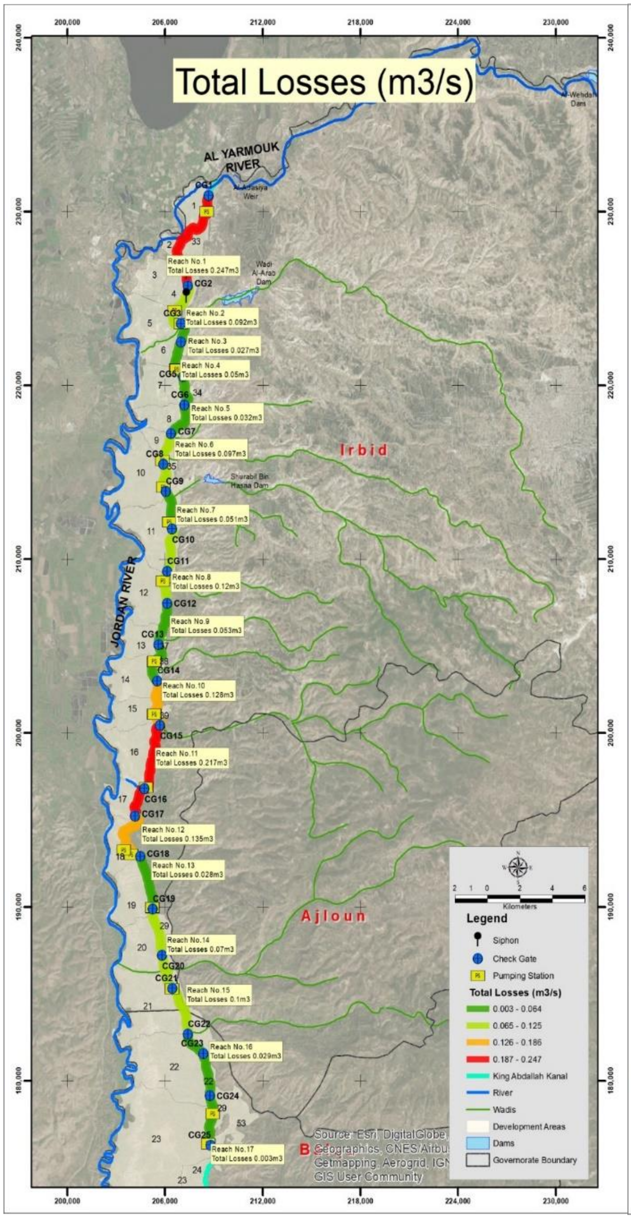


Figure 27: Upper KC Total Losses (m3/s)

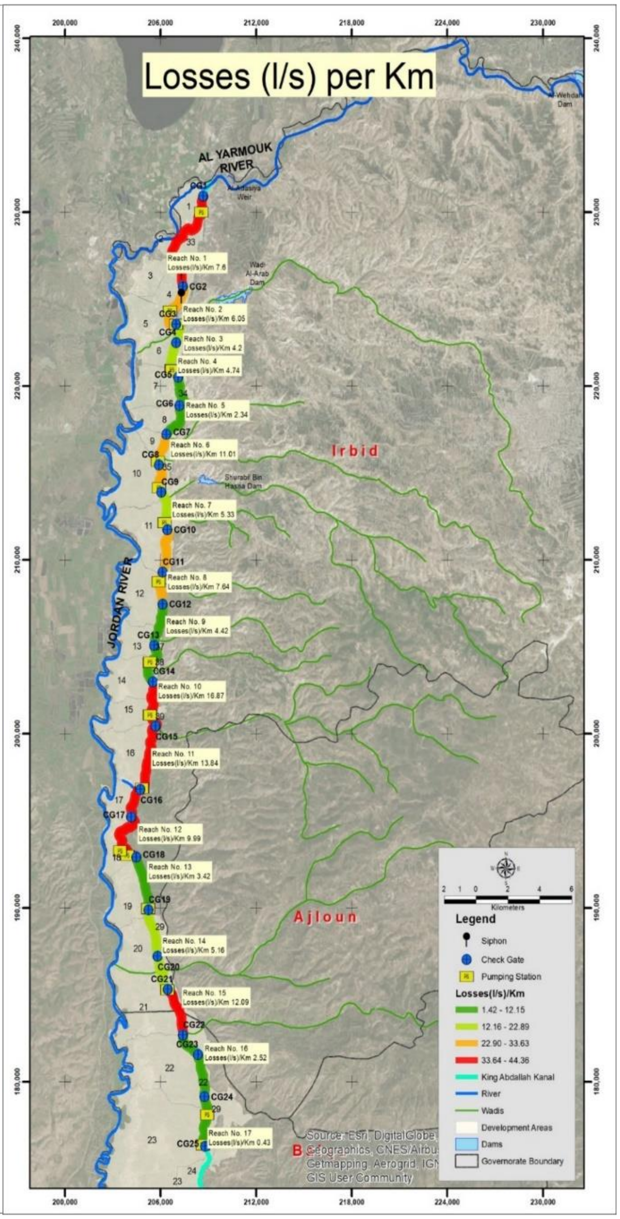


Figure 28: Upper KAC Losses per Kilometer

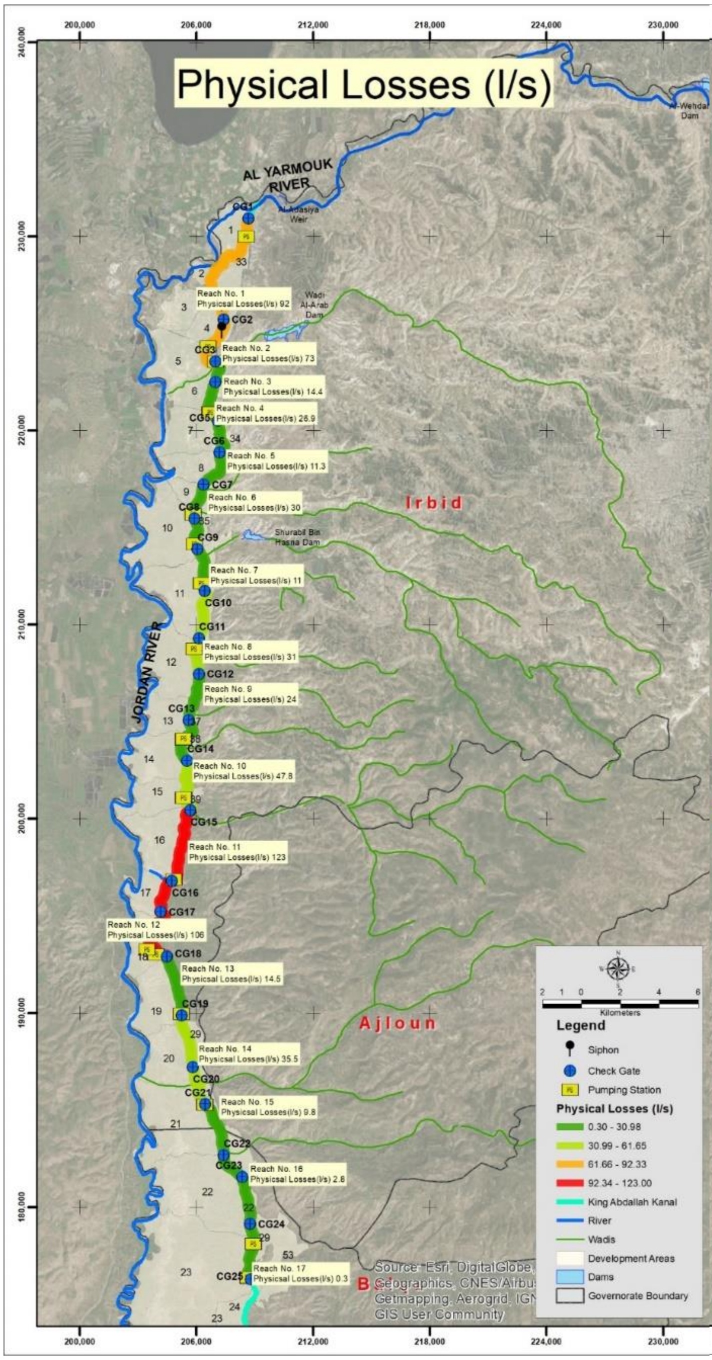


Figure 29: Upper KAC Physical Losses

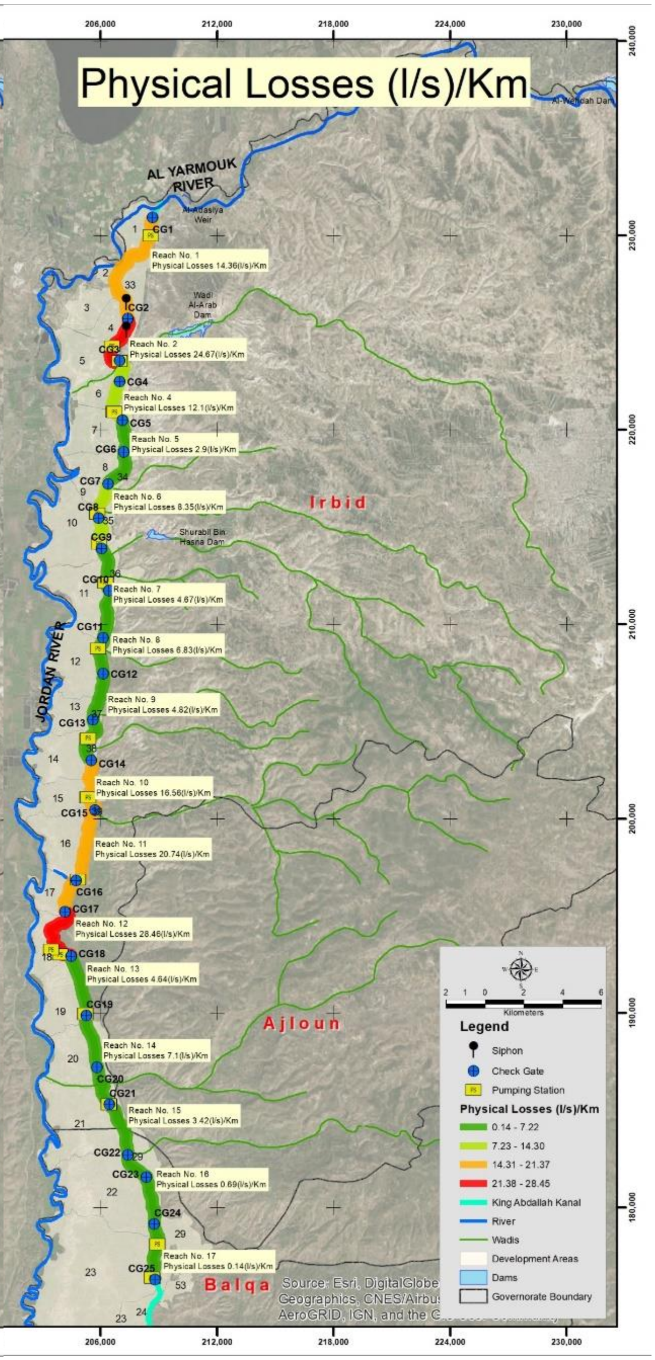


Figure 30: Upper KAC Physical Losses per Kilometer

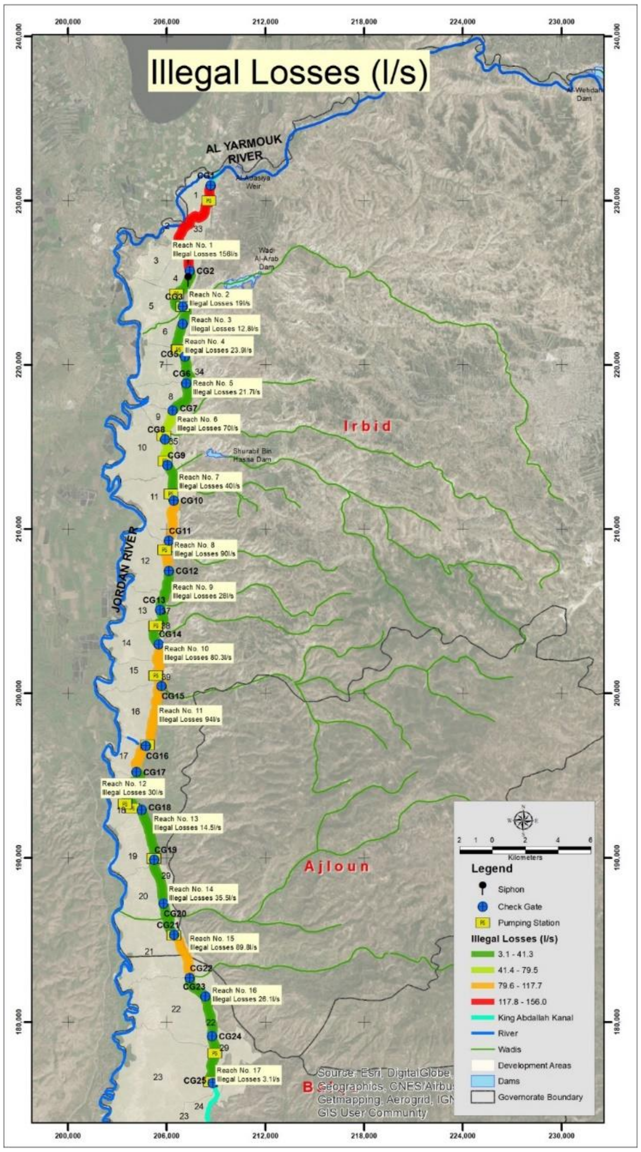


Figure 31: Upper KAC Unmetered/Illegal Losses

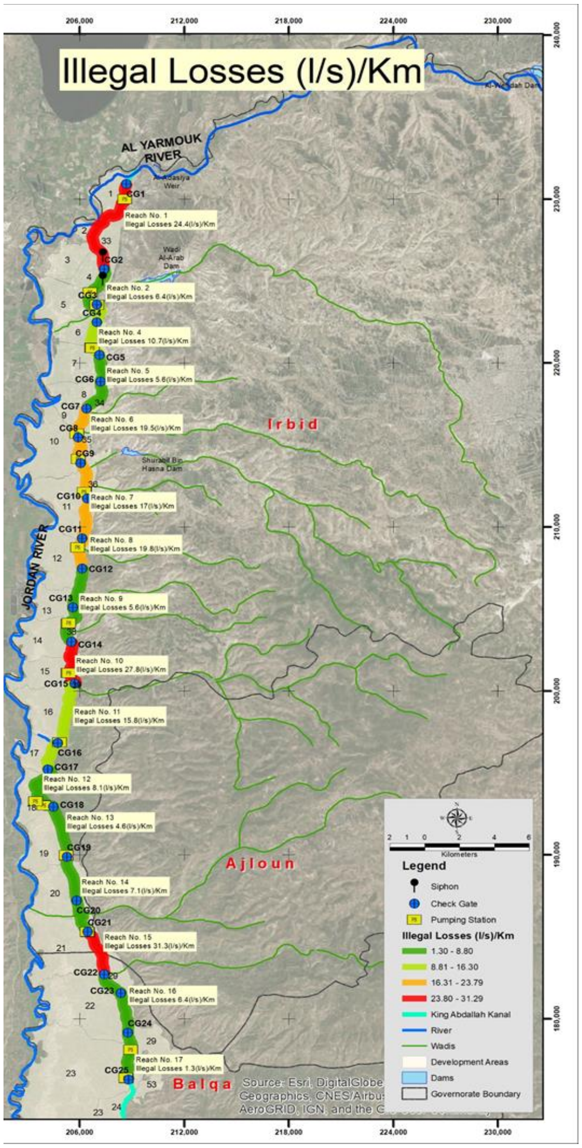


Figure 32: Upper KAC Unmetered/Illegal Losses per Kilometer

6.0 RECOMMENDATIONS

6.1 MEASURES TO OVERCOME THE LOSSES

The KAC is in relatively good condition, but is showing its age, and some relatively inexpensive actions could result in significant water savings. Due to the relatively low evaporation loss, the constant seepage and unmetered/illegal usages should be addressed at a higher priority.

Highest priority recommendations:

- Refurbish lining and fix cracks in older sections showing higher constant losses.
- Refine canal policies and security to discourage or eliminate illegal abstractions.
- Require all abstractions to be monitored by SCADA. You cannot manage what is not measured.
- Regularly inspect and document canal liner and embankments for sloughs, slumps, bulges, depression, and cracks. Inspections following floods and high flows is especially important. Geolocated photographic evidence is recommended.

Other recommendations based on observations:

- Increase security, including fence repair to discourage illegal use.
- Safety is largely overlooked in the KAC, with numerous children playing in the canal, and livestock falling into the canal. Measures should be taken to increase safety.
- Actively remove illegal structures and abstractions from the KAC.
- Perform routine cleaning of canal sediments and trash, especially in check gates.
- Systematically remove vegetation from the canal as its roots open cracks and leaks.
- Decrease trash load in the canal, which can obscure SCADA observations, flow estimates, and control. Improved fencing could help here.
- Repair and calibrate SCADA system – there are many malfunctioning instruments, and inaccurate flow calibrations.
- Repair leaks in pump stations, repair trash racks, and automate pump stations.

The consultant also recommends considering converting the conveyance system of the upper KAC from an open canal to a pipe for the following reasons:

1. Reserving the lives of many children that drown yearly in the canal due to its open nature and its closer to the inhabited localities
2. Maintain the quality of the fresh water and prevent any possible contamination incident
3. Eliminate the illegal abstraction of water and reduce the cost of continuous guarding and fencing of the canal
4. If the pipe maintains good pressure, the cost of operation and maintenance of pumping stations will be saved, in addition to the saving that will be obtained from the continuous fencing and guarding of the canal.

6.2 NEW TECHNIQUES USED TO FIX THE PHYSICAL LOSSES WITHOUT INTERRUPTING THE SERVICE

There are many established techniques to reduce physical losses in cement lined canals. These largely rely on relining the canal with cement or geotextile. However, most of these require interruption of canal service.

The Bureau of Reclamation, U.S. Department of the interior (Jay and Jack 2002), constructed 34 canal-lining test sections in the USA to assess durability and effectiveness (seepage reduction). They compared three types of canal linings: concrete, exposed geomembrane and concrete with geomembrane under liner. They assessed the performance after 1 to 10 years of service. The geomembrane with concrete cover offers the best long-term performance. The geomembrane under liner provides the water barrier and the concrete cover protects the geomembrane from mechanical damage and weathering. The system offers a durability of 40 – 60 years. The effectiveness (% seepage reduction) of the system is 95%. It effectively acts as barrier for the water loss through seepage, is highly flexible to withstand stresses, differential settlement, thermal stresses and high hydraulic pressures. The geotextile prevents the possibility of vegetation root growth through the liner, which may impede the water flow, and enables low maintenance and easy cleaning of canal.

Type of Lining System	Concrete Alone	Exposed Geomembrane	Geomembrane with Concrete Cover
Construction Cost ($\$/ft.^2$)	1.92–2.33	0.78–1.53	2.43–2.54
Anticipated Lifetime (years)	40–60	10–25	40–60
Maintenance Costs ($\$/ft.^2/yr,$)	0.005	0.010	0.005
Seepage Reduction (% Effective)	70	90	95
B/C Ratio	3.0–3.5	1.9–3.2	3.5–3.7

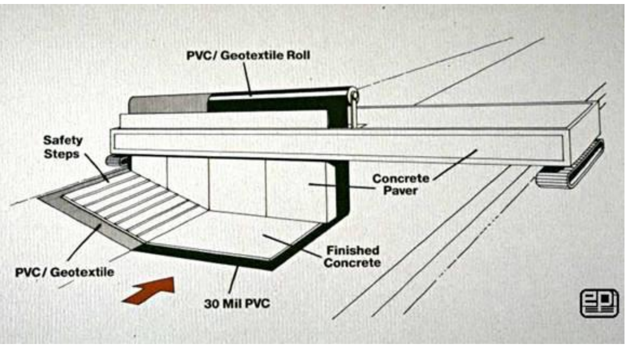


Figure 33: Geotextile under Concrete, Liner Placement Schematic (Rohe, 2004)

Leakage through cracks in concrete canal liners and seepage through damaged embankments have both operational and safety concerns. Most corrective actions require dewatering the reservoir to inject various chemical and/or cement base grouts or installation of protective geomembranes. Minor canal cement liner repairs can be accomplished by lowering canal water levels and patching the damaged sections. However, canal relining or extensive cement repair require dewatering the canal. To enable continued canal operations, this can be accomplished with the installation of cofferdams and a temporary siphon or bypass.

Figure 34: Roza Irrigation District Polyura Application

In 1989 the U.S. Bureau of Reclamation successfully implemented a PVC-based canal lining project in the operational Coachella Canal. The PVC geotextile was deployed in sections and sealed with a tetrahydrofuran underwater adhesive. The PVC geotextile was then sealed with a 75mm thick concrete cover using a concrete mix that would cure underwater. The process used a specially built crawler-mounted dredge/trimmer and a underwater paver. The dredge/trimmer cleans the canal, trims the old liner to a specific dimension, and fills any gaps. The paver deploys the geotextile and concrete liner cap (Morrison, 1990).

Alternatively, several irrigation districts in Washington State, USA have successfully used a polyurea product (brand name AquaLastic) to seal cracks in canals, even underwater using divers. The polyurea product has an elongation factor of nearly 900% and its adhesive qualities and tensile strength. Applicator experience and skill is an essential element of efficient use of polyurea substances on concrete for underwater applications and that other products, such as fillers, can be utilized to increase the places that polyurea can be used to save money and prolong the life of canals, flumes and ditches. The product has a proven track record and lifespan (Winfield, 2009). Depending on the nature of the cement liner repair need, there are many different products available on the market that can be used to successfully repair the compromised lining (see http://www.arconsupplies.co.uk/uses/repair-materials-for-canals-rivers-reservoirs).

6.3 NEXT STEPS REQUIRED

This Phase I preliminary assessment of losses focused largely on the upper 65km of the KAC. There was also a steep learning curve on how to measure in the unique conditions of the KAC, including non-steady state conditions, issues with sediment and trash, and reliability issues with the SCADA. The best M9 measurements were made in October 2017, in combination with manual stage measurements. However, more measurements of the upper KAC are highly recommended to help refine these loss estimates. Loss estimates in the lower KAC are also highly recommended, including for the Talal conveyance, to get help prioritize investments across the system.

There are also some additional techniques that could be applied to help track losses across longer-term. These include (a) using the M9 in combination with manual stage measurements to calibrate the SCADA system, and then use the calibrated SCADA data to recalculate losses over longer periods, and (b) using a hydrodynamic model to model KAC flows and losses.

A summary of the recommended next steps is below:

- **Lower KAC losses**: Measure and assess losses in the lower KAC.
- **Refine KAC loss estimates**: Refine the KAC loss assessments with measurements from more seasons and irrigation regimes.
- **Longer-term loss partitioning estimates**: Make IQ timeseries measurements over longer periods of time to capture more loss dynamics.
- **Improve IQ measurements:** Make IQ measurements with more M9 calibration points to account for accumulating bias.
- **SCADA calibration:** Make targeted M9 measurements to calibrate the SCADA, which would involve rebuilding rating curves for each gate (M9 measurements at different flows). Manual stage measurements and repair of SCADA sensors is also recommended.
- **Long-term loss assessments:** Use calibrated SCADA data to assess long-term loss dynamics in the KAC.
- **Hydrodynamic Loss Modeling:** Use a hydrodynamic model conditioned on M9, IQ, and SCADA data to model KAC losses.

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APPENDIX A: NORTH JORDAN VALLEY WATER BALANCE

Water Balance according to water budget: North Jordan Valley

Year	Water Resources										
	Wehda Dam	Wehda dam delivered to KAC	Yarmouk River	Mukheibah Wells	Total produced	Total Delivered to KAC	Tiberai	Wadi Al-Arab Dam (net)	Sharhabeel Dam	Total Water Produced	Total Water Delivered to KAC
2010	12.25	11.51	13.52	27.7	53.47	52.73	48.79	5.75	2.38	110.39	109.65
2011	11.16	10.08	12.64	25.56	49.36	48.28	49.24	0.38	2.37	101.35	100.27
2012	17.66	16.77	18.52	27.92	64.1	63.21	54.26	0.22	1.78	120.36	119.47
2013	37.76	34.30	28.32	25.93	92.01	88.55	52.91	2.78	3.81	151.51	148.05
2014	41.39	38.70	16.04	23.81	81.24	78.55	55.15	-4.1	1.8	134.09	131.40
2015	53.2	49.47	19	23.32	95.52	91.79	48.25	2.3	1.6	147.67	143.94
2016	79.96	71.86	7.52	23.26	110.74	102.64	51.97	3.08	0.82	166.61	158.51

Year	Water Released					
	Total water released for irrigation	Water released for drinking	Water released to the canal South	Total water released	Metered irrigation water	Total metered water
2010	40.60	53.94	0.75	95.29	37.95	92.64
2011	28.24	53.54	1.06	82.84	27.9	82.5
2012	34.26	62.14	2.27	98.67	33.75	98.16
2013	47.67	70.06	5.16	122.89	43.82	119.04
2014	43.84	60.9	3.9	108.64	39.26	104.06
2015	45.70	66.23	3.82	115.75	42.05	112.1
2016	50.40	68.67	5.52	124.59	48.46	122.65

Year	Losses									
	losses in the whole network	Losses in KAC and distribution networks	Losses from source to KAC	losses in distribution network	losses in KAC	losses % in the whole network	losses % from source to KAC	Losses % in KAC and distribution network	Losses % in distribution network	Losses % in KAC
2010	17.75	17.01	0.74	2.65	14.36	16.1%	0.7%	15.5%	6.5%	13.1%
2011	18.85	17.77	1.08	0.34	17.43	18.6%	1.1%	17.7%	1.2%	17.4%
2012	22.2	21.31	0.89	0.51	20.80	18.4%	0.7%	17.8%	1.5%	17.4%
2013	32.47	29.01	3.46	3.85	25.16	21.4%	2.3%	19.6%	8.1%	17.0%
2014	30.03	27.34	2.69	4.58	22.76	22.4%	2.0%	20.8%	10.4%	17.3%
2015	35.57	31.84	3.73	3.65	28.19	24.1%	2.5%	22.1%	8.0%	19.6%
2016	43.96	35.86	8.1	1.94	33.92	26.4%	4.9%	22.6%	3.8%	21.4%

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