A Low-Cost, Real-Time, and Stand-Alone Hydrological Monitoring System

Journal of Atmospheric and Oceanic Technology – Paley, J.B. and Bonner, J.S. – 2-11-2014 Rev. 1

Abstract

Hydrological scientific studies require high resolution data with respect to time and space to resolve the inherit frequency of episodic events. Funding availability is a major factor that limits the establishment of environmental monitoring networks. To address these concerns, an inexpensive hydrological monitoring system was designed to collect real-time data with adequate performance to support watershed modeling and small scale scientific studies. The designed system uses both commercially available and custom engineered components, using enabling technology to reduce capital costs as well as operations and maintenance costs. In-expensive stage height, water temperature, and all-season precipitation sensors were designed, fabricated, and tested in-house. Integration of components into a comprehensive hydrological monitoring system required custom hardware designs and software routines. Controlled laboratory calibrations and field evaluations with a co-located research grade sensor indicated that the designed precipitation gauge provides a low cost alternative with comparable performance to commercially available off the shelf sensors. The designed stage height sensor also performed well in the laboratory, and co-location with external organizations making continuous stage height measurements at six independent stations in the Hudson River watershed demonstrated a strong correlation between stage height datasets, attesting to the field merit of the in-house designed sensor.

1. Introduction

Hydrological datasets are most useful to researchers when the temporal resolution is sufficient to capture the inherent frequency of episodic events. Many interesting hydrologic events occur quickly and without warning, thus the need for real-time and high temporal resolution monitoring. The spatial resolution of a hydrologic monitoring scheme needs to provide adequate initial conditions, forcing functions, and boundary values for hydrologic models. High spatial resolution datasets can capture localized hydrologic events as well as aid in watershed model calibration and verification. A study involving a compilation of over 250 historical studies involving the Soil and Water Assessment Tool (SWAT), a hydrological modeling program, has been conducted by (Gassman, Reyes, Green, & Arnold, 2007). It was found that some of the studies indicating poor results (Nash-Sutcliffe model efficiency (NSE) < 0.5) were partially attributed to inadequate representation of spatial rainfall estimates or watershed delineation configurations too course to capture the spatial variability of rainfall. In hydrology, gauge precipitation data is the driving input dataset for watershed modeling research such as flood forecasting (Chiang, Hsu, Chang, & Hong, 2007), sediment transport and fate (Hicks, McSaveney, & Chinn, 1990), and water resource management (Hannah & Gurnell, 2001). A major challenge in achieving the desired spatial and temporal resolution is funding restraints (Harmancioglu & Alpaslan, 1992). Recent advancements in communication and sensing technology have allowed for an increased remote monitoring effort at a low cost (Glasgow, Burkholder, Reed, Lewitus, & Kleinman, 2004).

This paper presents the design and results of testing a new Real-Time Hydrological Station (RTHS). The environmental parameters sampled by the RTHS are air temperature, relative humidity, wind speed, wind direction, barometric pressure, precipitation, stage height, and water temperature. The design criteria for the RTHS includes minimal power requirements, low-cost, rugged, real-time, autonomous, stand alone, 4-season, low-maintenance, and versatile system. A low cost system has been achieved by reducing capital costs as well as operations and maintenance (O&M) costs. Capital costs have been reduced by in-house fabrication of sensors and systems through the use of enabling technology available at a low cost. Examples of low-cost technologies utilized in the RTHS include single board computers, microcontrollers, cellular modems, pressure transducers and other specialty low cost integrated circuits. The RTHS is designed for solar or on-grid power, and is adaptable to various mounting styles and configurations dictated by site restrictions. Precipitation, stage height, and water temperature parameters are sampled by custom designed sensors. Aerodynamic properties of precipitation gauges limit the achievable measurement uncertainty to the larger of 5% or 0.1mm for daily accumulations (World Meteorological Organization, 2008). We used an accuracy performance criterion equal to the larger of ±4% or 0.508mm as defined by the National Weather Service (NOAA NWS, 2010). The performance criterion used for the stage height sensor is an absolute accuracy equal to the larger of 3.05mm or 0.2% of stage, as defined by the U.S. Geological Survey (Sauer & Turnipseed, 2010). By co-locating these sensors with other research grade sensors in the field we can evaluate the data for discrepancies larger than the stated accuracy performance criteria to provide insight towards the field merit of each sensor. We use the term discrepancy in the field data because amongst environmental factors it is not clear which sensor is of lower accuracy, yet the laboratory calibrations attest to the in-house designed sensor accuracy. The final RTHS product resulted from a design, build, test, and redesign approach. Redesign was conducted if the performance criteria were not adequately met. Consequently this iterative process resulted in a reliable and rugged design suited for harsh environmental conditions, which leads to a low failure rate, in turn reducing O&M costs. Site visits for inspection, cleaning, calibration, and swapping of system components reduces the number of failures, hence reducing overall O&M costs. The RTHS is modular and versatile in that as emerging enabling technology becomes available, the RTHS can be easily upgraded to a faster, less expensive, lower power, and more reliable system. The RTHS is flexible and allows the addition of other types of sensors (e.g. Dissolved Oxygen, pH, Chlorophyll ‘a’ and other water quality sensors). This added capacity is underway in our laboratory.

The stage height sensor has been tested and calibrated in the laboratory and material costs amount to $200 U.S. Dollars (USD) and require four man-hours for fabrication and calibration. The construction and calibration procedures have been designed for batches of three sensors at a time, and can be completed by a person with an associate’s degree level of experience. Load and temperature calibration linear regression curves have resulted in R^2 as high as 0.9999. The sensor was field tested through co-location with existing monitoring networks. The stage height sensor has been field deployed at 13 sites in New York State, all of which lie within the Hudson River watershed. Of the 13 sites, three are co-located with U.S Geological Survey stations, two are co-located with Hudson River Environmental Conditions Observing System (HRECOS) stations, and one is co-located with a River and Estuary Observatory Network (REON) station that contains an Acoustic Current Doppler Profiler (ADCP) with a depth measurement. The field sites range from rivers with shallow riffle areas in the mountainous terrain of the upper Hudson River to a tidal estuary in the lower Hudson River. A total of 149 days of data collection at co-location sites resulted in discrepancies between the RTHS and external organizations datasets larger than the performance criteria on average 65% of the measurements. Plotting RTHS gauge height versus USGS/HRECOS/REON gage height for each site resulted in linear regression curves with R^2 as high as 0.999. With eight failures during 105 total months of field operation in diverse environmental conditions, the stage height sensor demonstrates high reliability.

The designed precipitation gauge has been tested and calibrated in the laboratory and material costs amount to $380 (USD) and require three man-hours for fabrication and calibration. The fabrication and calibration has been designed to be as simple and streamlined as possible, and can be completed by a person with an associate’s degree level of experience. Laboratory calibrations result in R^2 as high as 0.9999. The precipitation gauge has been field tested via co-location with a NOAH II, a research grade precipitation gauge manufactured by ETI Instrument Systems Inc. The NOAH II is a high accuracy, reliable, all-season precipitation gauge (Gordon, 2003). During the testing, there were 63 days in which precipitation occurred and results show discrepancy between the two sensors larger than the performance criteria 51% of the days. A linear regression curve of daily accumulation reported by the two gauges results in R^2 equal to 0.97. Field testing revealed that the precipitation gauge falsely reported precipitation events with an average magnitude of 0.87mm and duration of 1.1 hours, occurring 10 times over the 126 day study. This false reporting is attributed to temperature induced errors and is not expected to significantly affect a hydrologic model relying on point precipitation measurements. With over 100 total months of operation, only two precipitation gauge failures occurred, amounting to a downtime of under 0.7%.

Results of field testing the precipitation gauge and stage height sensors indicate each sensor is a viable alternative with adequate performance to commercial off the shelf sensors. The sensors have been designed to be low-cost and quick to replace in the field, yet the failure rate observed in the field is extremely low. The RTHS is a highly capable monitoring system with applications in hydrological modeling. Achievement of a low-cost system allows for a high spatial resolution monitoring scheme under a limited budget, and therefore increasing the accuracy of a hydrological model which can provide many assets to the scientific community.

2. Materials and Methods

a. Design

A basic overview of the RTHS is shown below in Figure 1. The RTHS can be categorized into three partitions; sensors, computing infrastructure, and communications.

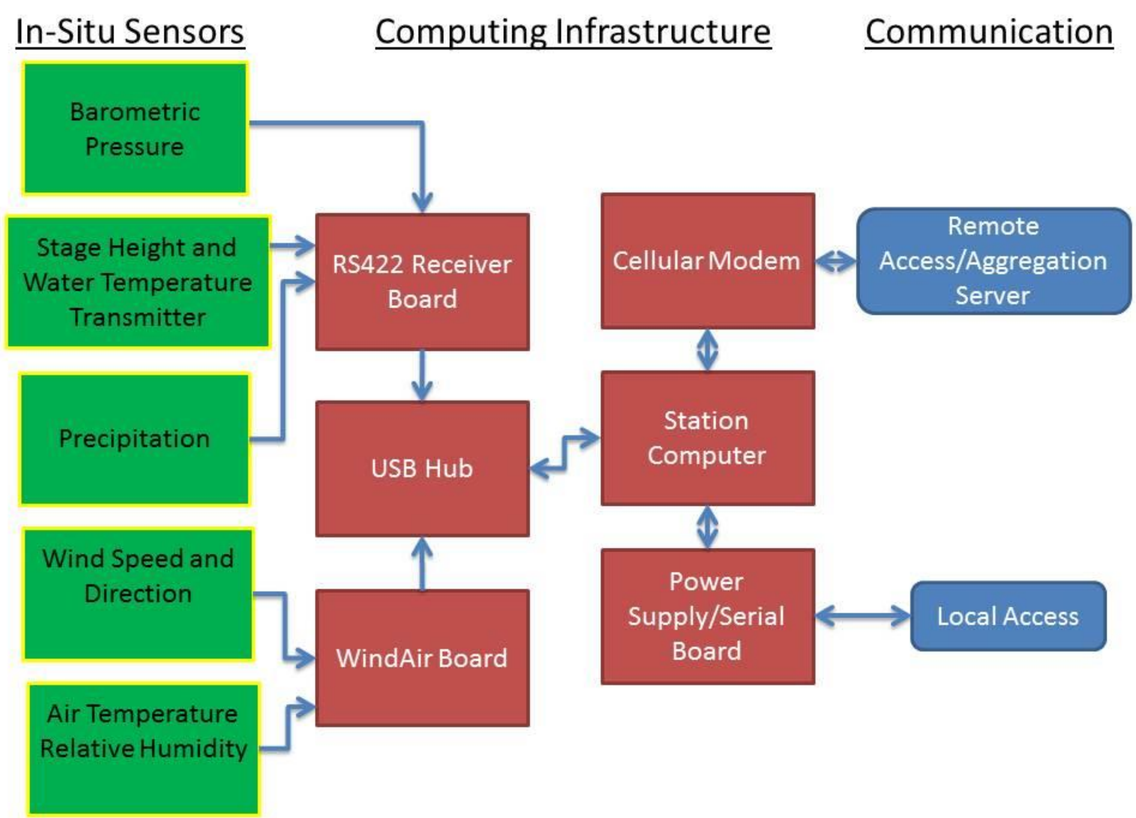

Figure 1: RTHS system overview

1) Computing Infrastructure

The RTHS computing infrastructure consists of sensors, microcontrollers (Teensy 2.0 and 3.0®), custom designed printed circuit boards, a single board computer (Raspberry Pi Model A), and a cellular modem. The station computer runs Linux version 3.6.11 from a Secure Digital (SD) card and logs the data locally as well as uploading in near real-time via the cellular modem. The station computer is also capable of data transmission via Wi-Fi or Ethernet.

The software design of the RTHS provides reliable real-time communication with each station, data backup, and a common accessible format for data storage. Each station keeps a unique secure shell (SSH) port open with an aggregation server located in the laboratory. Through the SSH port, users can access a station remotely. Currently, all of the sensors are being sampled by Teensy 2.0 or 3.0® microcontrollers, which have been programmed to output in a comma separated variable format. Through the use of sensor model names and serial numbers programmed into the microcontrollers, the station computer logs data from each sensor into a separate text file, and uploads to the aggregation server once an hour. A custom designed RS422 board utilizes a Teensy 3.0® to interleave data streams from the precipitation gauge, stage height sensor, and barometer to the station computer, while preserving the model names and serial numbers of each sensor. The receiver also utilizes a 12V to 12V DC-DC converter to supply power to the stage height sensor and precipitation gauge, thus ensuring a stable supply voltage regardless of the system voltage (which varies daily from solar charging). An electrical schematic of the RS422 receiver board is shown in Figure 2.

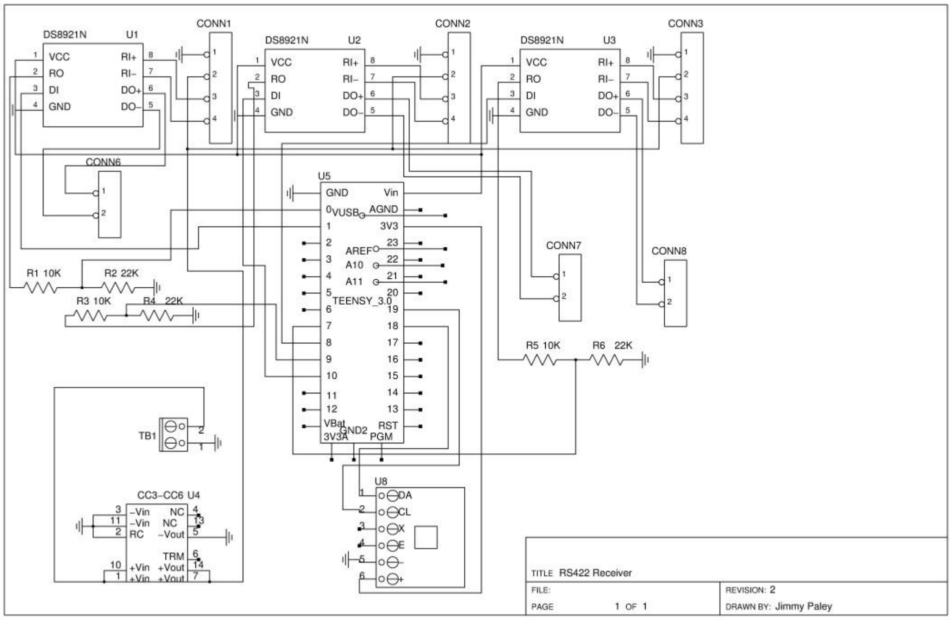

Figure 2: Custom RS422 receiver board electrical schematic

The RTHS may be powered either on-grid via direct tie-in to an existing AC power source or off-grid using a photovoltaic (PV) charging system. A 185W, 24V solar panel is used to charge a 12V 160 reserve capacity deep cycle battery, via an 8 amp maximum power point tracking (MPPT) charge controller. A fully charged battery will run the RTHS for about 12.5 days with no solar charging, which is necessary in the winter when solid precipitation can cover the solar panel for extended periods of time. Configured as an on-grid system, a 120VAC to 12VDC 1.5A power supply is used. At our test site latitude, a vertical alignment of the solar panel was determined to be optimal with adequate solar power during summer and winter by reviewing a 30 year insolation record (30-Year Average of Monthly Solar Radiation, 1961-1990 Massena, NY). The impact of solid precipitation on PV arrays is significant (Becker, Schiebelsberger, Weber, Vodermayer, Zehner, & Kummerle, 2006), and a vertical alignment proved advantageous for shedding off frozen precipitation at our test site latitude.

The structural design of the RTHS varies based on field site restrictions. Some sites are conducive to a stand-alone aluminum frame, while others require a timber post or direct mounting to an existing structure. Figure 3 below shows some examples of RTHS mounting styles.

Figure 3: RTHS mounted to a timber pole (left), aluminum frame (center), and tripod (right).

2) Precipitation Gauge

A weighing type precipitation gauge has been chosen for low power consumption and use in sub-freezing conditions. The power requirement of a traditional heated tipping bucket is 320 watts, which could not be provided without a massive PV array or grid-tied system, thus drastically limiting the versatility of the system and increasing the total cost. The designed sensor draws less than 1 watt at 12 volts. The precipitation gauge design includes an aluminum collection chamber (19.685cm inside diameter), low range pressure sensor, high range pressure sensor, amplifier circuit, 16-bit analog to digital converter (ADC), and microcontroller. The primary pressure sensor (low range) is sampled by a 16-bit ADC for a measurement range of 177.8mm of precipitation. The secondary pressure sensor (high range) is sampled by a 10-bit ADC. A Teensy 2.0® microcontroller is used to communicate via a differential line driver/receiver chip to the RS422 receiver board. The electrical block diagram and electrical schematics of the precipitation gauge are illustrated below in Figure 4 and Figure 5 respectively.

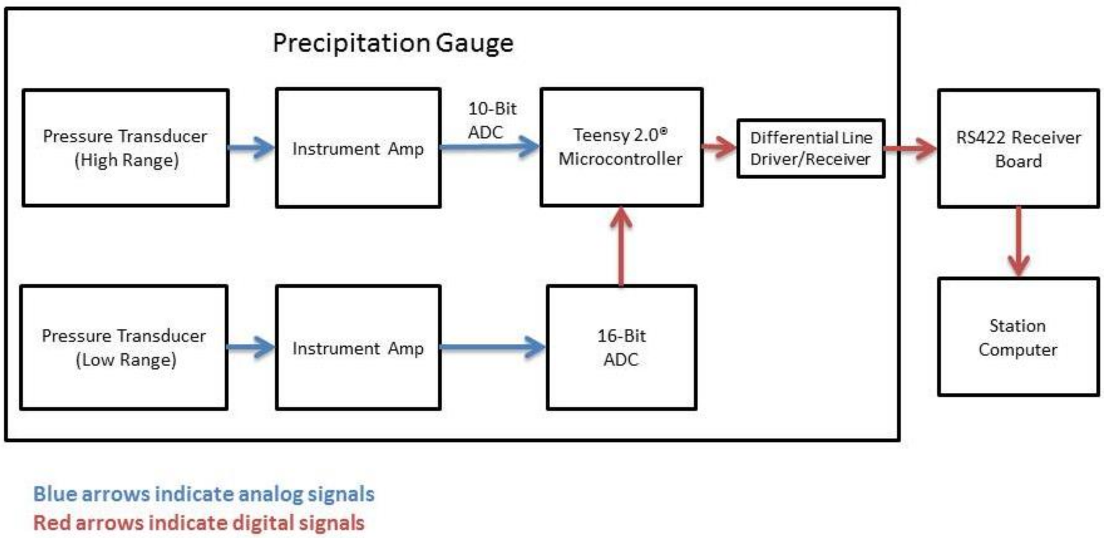

Figure 4: Precipitation gauge electrical block diagram

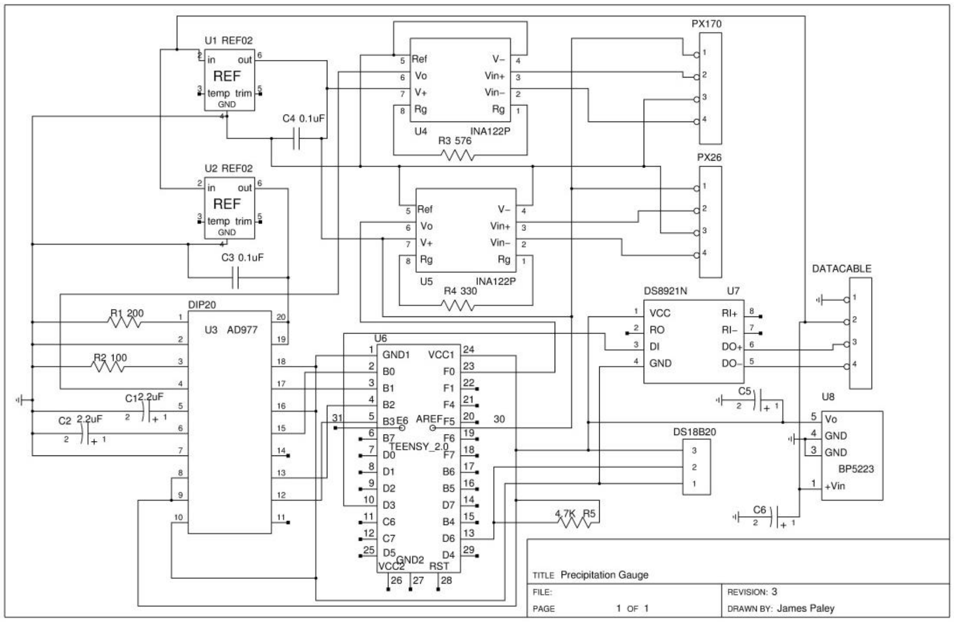

Figure 5: Precipitation gauge electrical schematic

Omega PX170-07DV and Omega PX26-001GV solid state piezoresistive pressure transducers are used to detect water level within the collection chamber. The low pressure sensor is the primary level detector and is used under normal conditions for high accuracy measurement. In cases where this low range pressure sensor becomes saturated due to an extreme rainfall event, the secondary high range pressure sensor captures the remainder of the rainfall event. During the summer months, a thin film of light oil is used to reduce evaporation to prevent the water level from dropping below the pressure sensing ports. During the winter months, propylene glycol is used to melt solid precipitation in the collection chamber. The collection chamber must be drained and cleaned periodically throughout out the year, on average about every 1.5 months in a watershed that receives 1250mm annual precipitation. This maintenance schedule is typical for weighing-type precipitation gauges, although a remote/automatic draining feature could be implemented to reduce O&M costs.

3) Stage Height Sensor

The stage height sensor also utilizes two pressure transducers. A high accuracy pressure transducer (Omega model PX-26-005GV) is used to capture stage variation under normal conditions. A high range pressure transducer (Omega model PX-26-015GV) is used to measure stage during extreme flood events when the low range sensor may become saturated. The load limit of the high range pressure transducer is 1055cm of H_2O, although due to temperature induced internal pressure changes and atmospheric pressure changes, the total range of the sensor is limited to 932cm of H_2O. The stage height sensor consists of electronics mounted inside a 1.25 inch trade size schedule 80 PVC pipe, which is submerged in the water below the minimum expected stage height. The mechanical housing has been tested in a pressure chamber delivering the equivalent of 35 meters of hydrostatic head. The pressure sensors are sampled by a Teensy 2.0® microcontroller which employs a 10-bit ADC. A Dallas Semiconductor DS18B20 1-wire® potted temperature sensor is used for water temperature measurement. This type of temperature sensor is calibrated at the factory and has proved to be an accurate yet inexpensive environmental sensor (Hubbart, Link, Campbell, & Cobos, 2005). The stage height sensor operates on 12VDC and draws 250mW. An electrical block diagram and electrical schematic are illustrated below in Figure 6 and Figure 7 respectively.

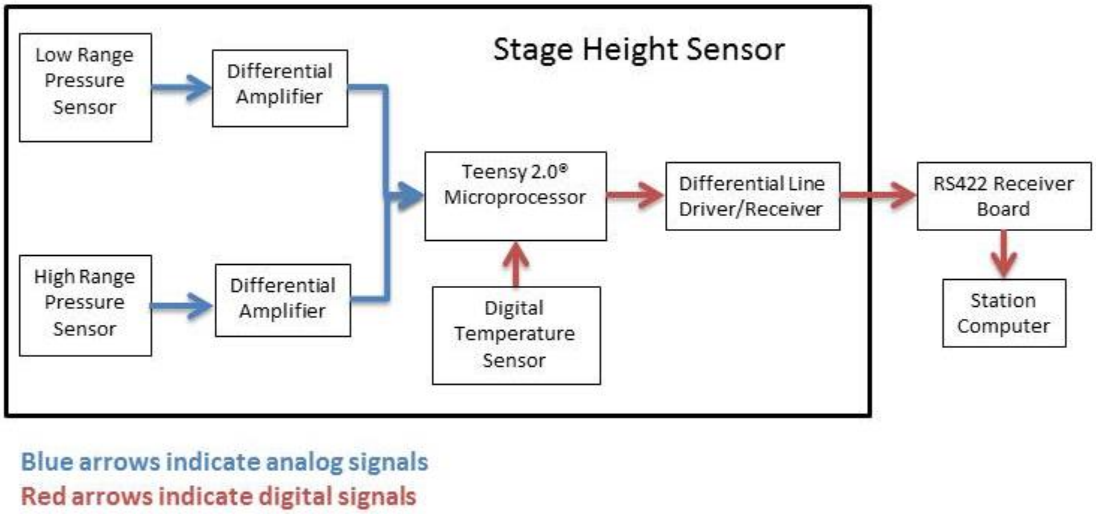

Figure 6: Stage height sensor electrical block diagram

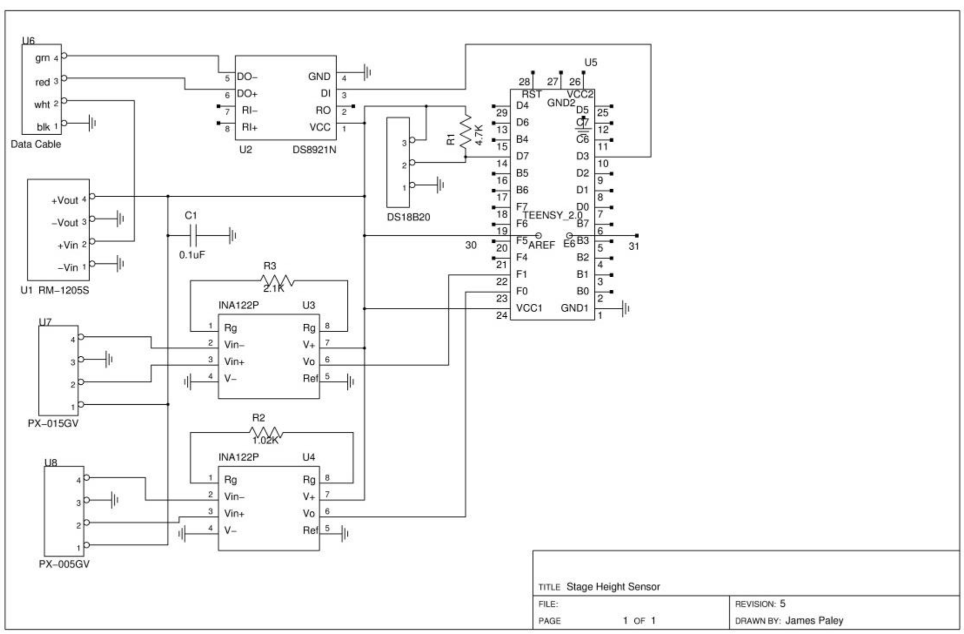

Figure 7: Stage height sensor electrical schematic

b. Laboratory Evaluations

1) Precipitation Gauge

The precipitation gauge was calibrated in the laboratory via load testing of the pressure transducers. To calibrate the precipitation gauge, a known volume of water at room temperature is added to the collection chamber, while the output of the pressure transducers is monitored. This calibration is used to determine the linear calibration coefficient used in converting raw 16-bit ADC counts to millimeters of precipitation. We generated a five point calibration curve using 1L additions of deionized water at room temperature to increment the water level by 32.77mm. The output was allowed to stabilize (typically < two minutes) and was recorded. A linear regression was performed to determine the linear calibration coefficient. The calibration was performed at room temperature, as it is shown below in Figure 8 that calibration temperature does not significantly affect the linear calibration coefficient (slope of linear regression curve).

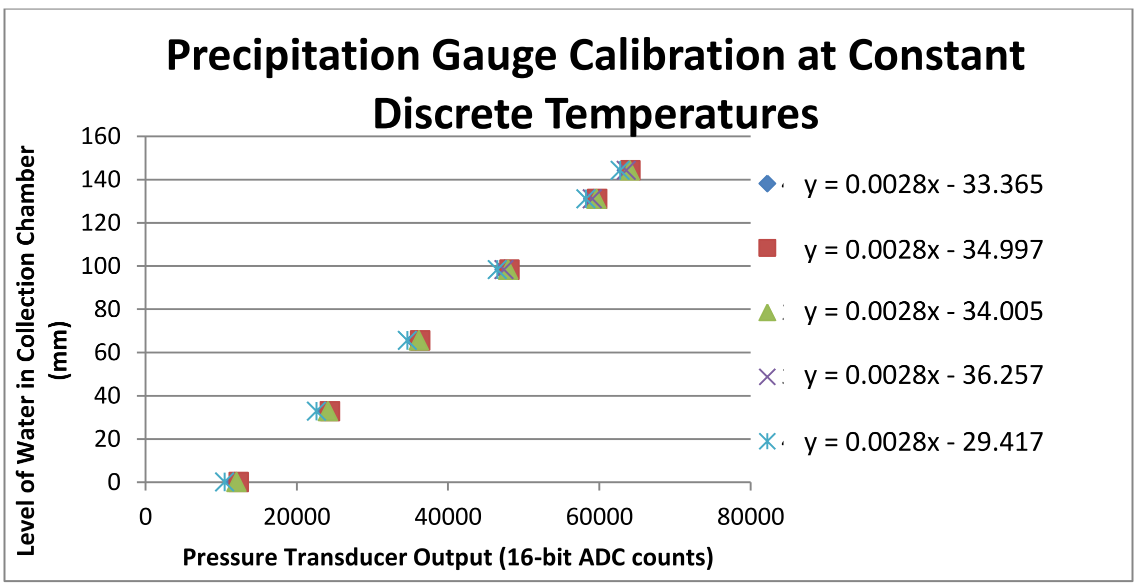

Figure 8: Precipitation calibration performed at 5 discrete constant temperatures.

2) Stage Height Sensor

The stage height sensor was calibrated in the laboratory for both load response and temperature dependence. The load response was calculated by lowering the sensor in a 305cm test chamber.

The sensor output was monitored at five evenly spaced depths from 30.5cm to 274.3cm. The sequence of depths is then reversed, and a second set of five depth readings is recorded to check for hysteresis effects. From the 10 depth readings, a calibration curve is generated and the slope of the curve serves as the linear load calibration coefficient.

The temperature dependence of the stage height sensor is significant due the watertight design, and is dominated by changes in internal pressure of the sensor due to temperature changes according to the Ideal Gas Law. The temperature dependence is analyzed by applying a constant load to the sensor, while varying the temperature. This is accomplished by placing the sensor into the bottom of the collection chamber with approximately 1m of water and varying the temperature by placing the assembly into an incubator with a programmable temperature controller. The water serves as a constant load as well as a buffer to minimize transient temperature effects in order to observe only absolute temperature effects. The incubator is set to ramp from 5C to 35C over 12 hours, hold at 35C for 8 hours, ramp down to 5C over 12 hours, and then hold at 5C 8 hours. This cycle is performed twice, while monitoring the output of the sensor. A small amount of oil is added to the water chamber to minimize evaporation effects, thus applying a constant load.

After correcting for barometric pressure changes, the output from the pressure sensors can be plotted against the internal sensor temperature to determine the linear temperature calibration coefficient. Finally, with a known load on the sensor during the temperature calibration, a final offset “C” is calculated. Using the linear load and temperature calibration coefficients and offset, the final equation to convert raw counts (10-bit) to stage height (cm) is as follows:

$$Stage\_Height = \left[raw\_counts - \frac{(Baro - 1013) * 1.020 \frac{cm}{hPa}}{A} + \frac{temperature - 35}{B} \right] * A + C$$

Where:

Stage_Height = level of H_2O above sensor (cm)

raw_counts = 10-bit ADC value from pressure transducer

A = linear load calibration coefficient (cm/count)

B = linear temperature calibration coefficient (degrees/count)

Baro = barometric pressure (hPa)

Temperature = internal sensor temperature (degrees Celsius)

C = offset (cm)

c. Field Evaluations

1) Precipitation Gauge

The precipitation gauge was field tested from September 2011 to April 2012 near Potsdam, NY for validation purposes. The latitude/longitude of the site is 44.728955,-74.944358. The precipitation gauge was field tested alongside a research grade precipitation gauge manufactured by ETI Instrument Systems, Inc. model NOAH II. The two sensors were co-located in a 1700m^2 field with grassy vegetation about 1m tall. Small trees lie along perimeter of the field, reducing the magnitude of wind in the test area. Using a RTHS system, data was collected and logged from both precipitation gauges.

A software filtering algorithm has been developed to minimize false precipitation reports induced by errors driven by temperature fluctuations. To minimize false reports, a precipitation rate threshold has been determined to be 0.884mm/hr. This threshold has been calculated by using the NOAH II as a reference gauge, and optimizing both false positive and false negative precipitation events reported by the in-house designed gauge. The algorithm treats precipitation rates above the threshold as actual precipitation, and all rates below the threshold are assigned a rate of 0mm/hr. This software filtering algorithm is currently performed at the database level. The temperature induced errors set the minimum detection rate of the precipitation gauge to 0.884mm/hr.

2) Stage Height Sensor

The stage height sensor has been field deployed at six RTHS locations in the Hudson River watershed with co-location datasets available. Table 1 provides an overview of the test site locations.

Site Location	Latitude	Longitude	Secondary Measurement	Dates of Validation
North Creek, NY	43.701923	-73.98648	USGS Site 01315500	1 Nov 2013 to 30 Nov 2013
Lock 8 Mohawk River, NY	42.8281	-73.9904	USGS Site 01354330	18 Oct 2013 to 6 Dec 2013
Schodack Island, NY	42.4989	-73.7771	HRECOS Schodack Island Hydrologic Station	18 Oct 2013 to 18 Nov 2013
Newburgh, NY	41.51180	-74.00550	REON ADCP	8 Sep 2013 to 14 Sep 2013
West Point, NY	41.38605	-73.95502	USGS Site 01374019	13 Nov 2013 to 30 Nov 2013
Piermont, NY	41.04303	-73.89643	HRECOS Piermont Pier Hydrologic Station	13 Nov 2013 to 23 Nov 2013

Table 1: Stage height sensor field study locations

At each of the validation field sites only gauge height is analyzed, as the stage height measurements are not referenced to a common elevation datum. The variance in the gauge height of each dataset is used to verify the accuracy and field merit of the stage height sensor. All of the sites have co-located sensors within 100m of each other, with the exception of North Creek where the USGS sensor is located about 500m downstream of the RTHS sensor.

3. Results

Laboratory calibrations of the precipitation gauge and stage height sensor were performed throughout the development of each sensor. The strength of the calibration curve attests to the accuracy of each sensor and was an essential element to the design, build, test, and redesign strategy. If a RTHS component did not meet the laboratory evaluation criteria, it did not proceed to field evaluation but rather was redesigned and fabricated and then subjected to a new round of testing. Several iterations of this were conducted and the calibration curves from the latest revision of each sensor are presented.

Field evaluations of the in-house designed sensors demonstrate the reliability and ruggedness of each sensor. The stage height sensor was subjected to harsh environmental conditions such as 100-year floods and significant ice formation and movement. With over 105 total months of field operation, eight stage height sensor failures occurred, all of which were mechanical failures. Precipitation gauge failures in the field totaled two from over 100 total months of operation. Comparisons with research grade co-located sensors further attest to the overall accuracy of each sensor.

a. Laboratory Results

1) Precipitation Gauge

Precipitation gauge laboratory calibrations correlate accumulated precipitation level to raw 16-bit counts, and resulted in correlations as high as R^2=0.9999 (Figure 9). The y-intercept of the linear regression is attributed to the physical connection of the pressure transducer to the collection chamber.

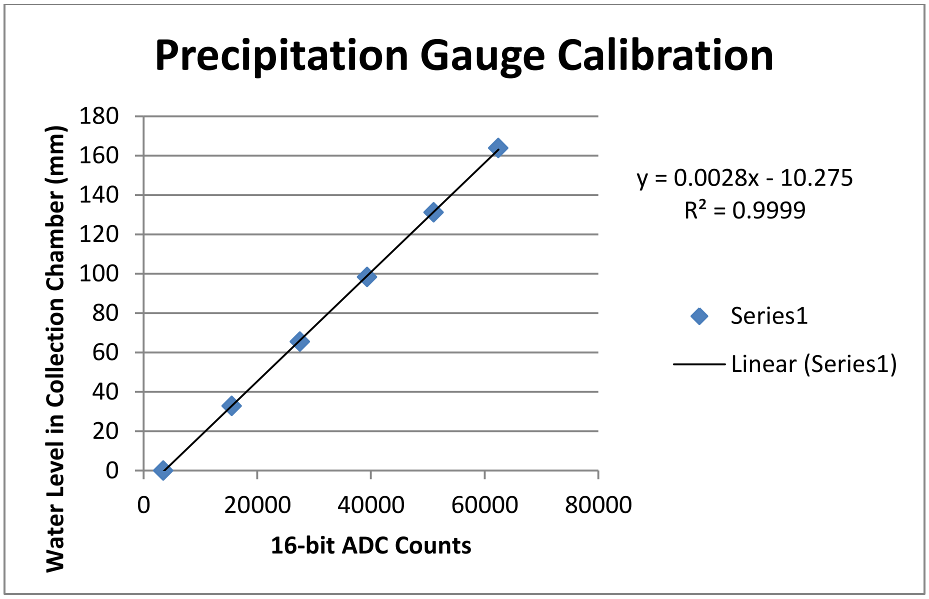

Figure 9: Example precipitation gauge calibration

2) Stage Height Sensor

The stage height sensor laboratory load calibration also resulted in R^2 as high as 0.9999 (Figure 10). A total of 16 stage height sensors have been fabricated and calibrated. For the low range pressure transducer, mean and standard deviation of calibration coefficients among the 16 sensors are 0.3447cm/count and 0.0232cm/count respectively. The high range transducer load calibrations over the 16 sensors resulted in a mean and standard deviation of calibration coefficients of 1.0000cm/count and 0.0070cm/count respectively. The low variance in calibration coefficients demonstrates repeatability of the electrical and mechanical fabrication of the sensor. The temperature calibration resulted in R^2 greater than 0.99 (Figure 11). Similar to the load calibration, the variability of temperature calibration coefficients between sensors was very low.

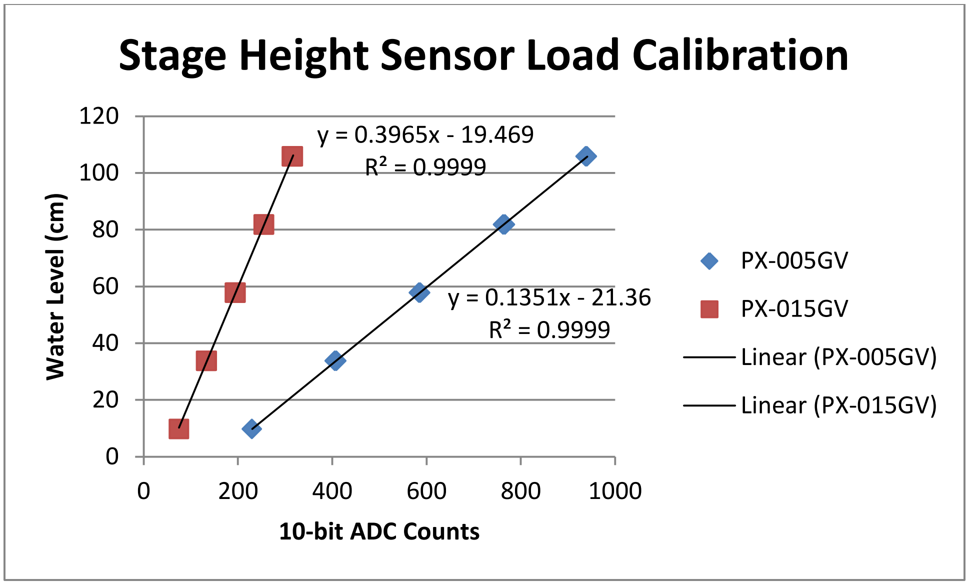

Figure 10: Stage height sensor load calibration – both high range (red) and low range (blue) pressure transducers shown.

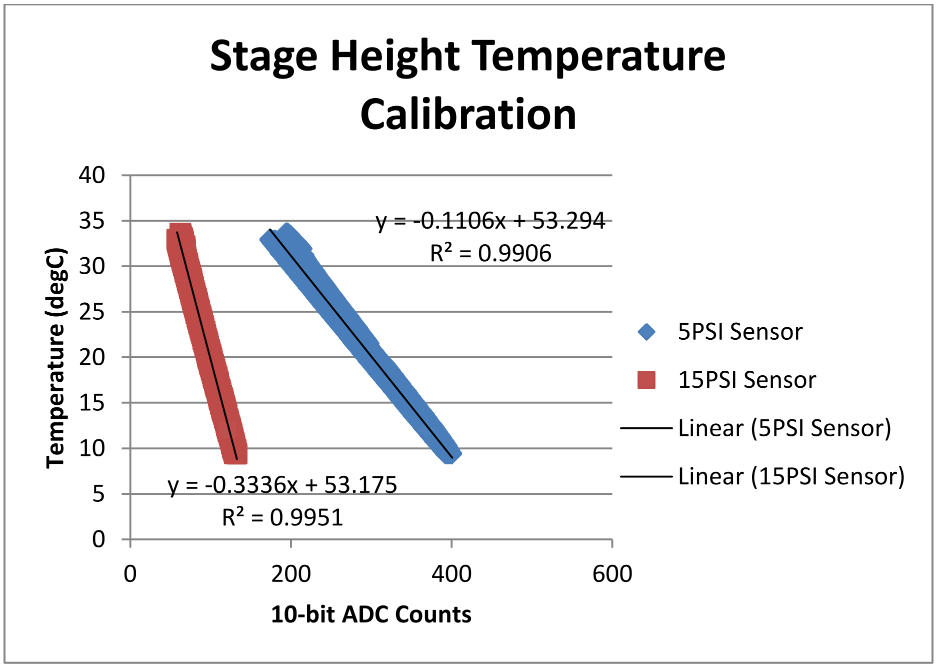

Figure 11: Stage height sensor temperature calibration - both high range (red) and low range (blue) pressure transducers shown.

b. Field Results

1) Precipitation Gauge

Results from the precipitation gauge field study demonstrate a strong correlation to the NOAH II reference gauge. During the study, a total of 63 days of precipitation were reported by the NOAH II. A linear regression of the co-located gauges daily, non-zero accumulation resulted in an R^2=0.9671 (Figure 12).The 0.0932mm y-intercept of the linear regression is very low, as daily precipitation under 0.127mm is considered trace precipitation by the U.S. National Weather Service (U.S. National Weather Service, 1989) and is treated quantitatively as zero (Yang, Goodison, & Metcalfe, 1998). The total precipitation reported by the RTHS and the NOAH II precipitation gauges over the study period was 336.9mm and 326.4mm respectively. Based on the aforementioned performance criterion of ±4% or 0.508mm accuracy, the RTHS gauge and NOAH II agreed to within the accuracy specification 49.2% of the days in which precipitation occurred.

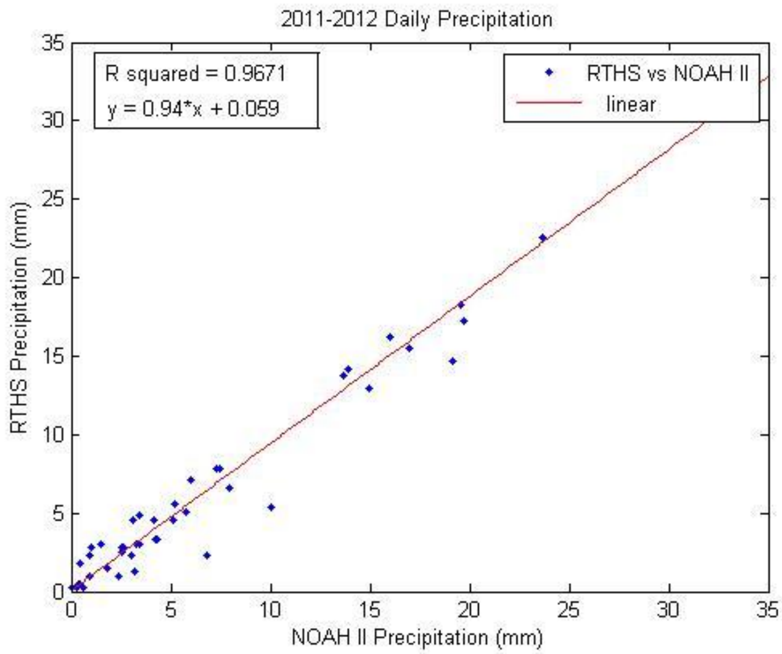

Figure 12: Daily accumulation of RTHS precipitation gauge and the NOAH II

Precipitation occurred during each week of the field study, a bar plot of the weekly precipitation reported by each gauge is shown in Figure 13. Precipitation events can be defined by a minimum inter-event time (Dunkerley, 2008), here we used 20 minutes which produced good results. Correlating precipitation events revealed that the RTHS gauge falsely reported precipitation on 10 days of the 126 day field study. We define a false event as the RTHS gauge reporting precipitation while the NOAH II gauge does not report precipitation within 3 hours. The average magnitude and duration of the false events was 0.87mm and 1.1 hours.

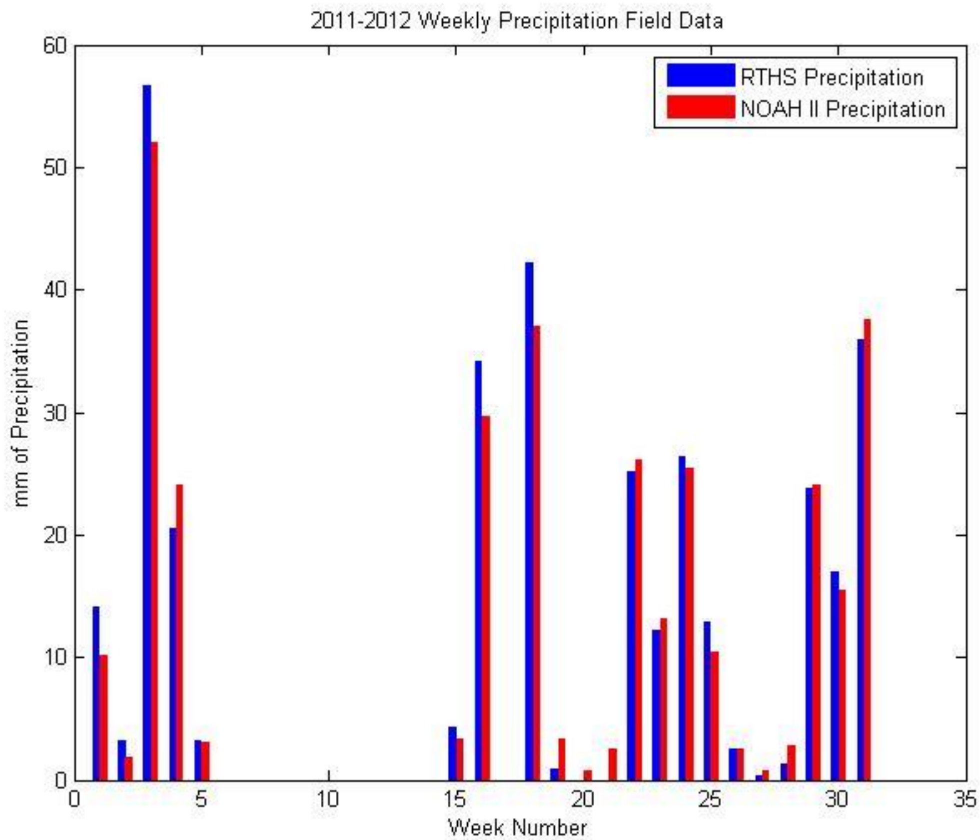

Figure 13: RTHS and NOAH II weekly precipitation during field study. There is no data for weeks 6-14.

2) Stage Height Sensor

Field testing the stage height sensor in diverse environmental conditions attests to the ruggedness of the sensor. Co-location sites included natural riverine systems (Figure 14), dam controlled rivers (Figure 15), and estuaries (

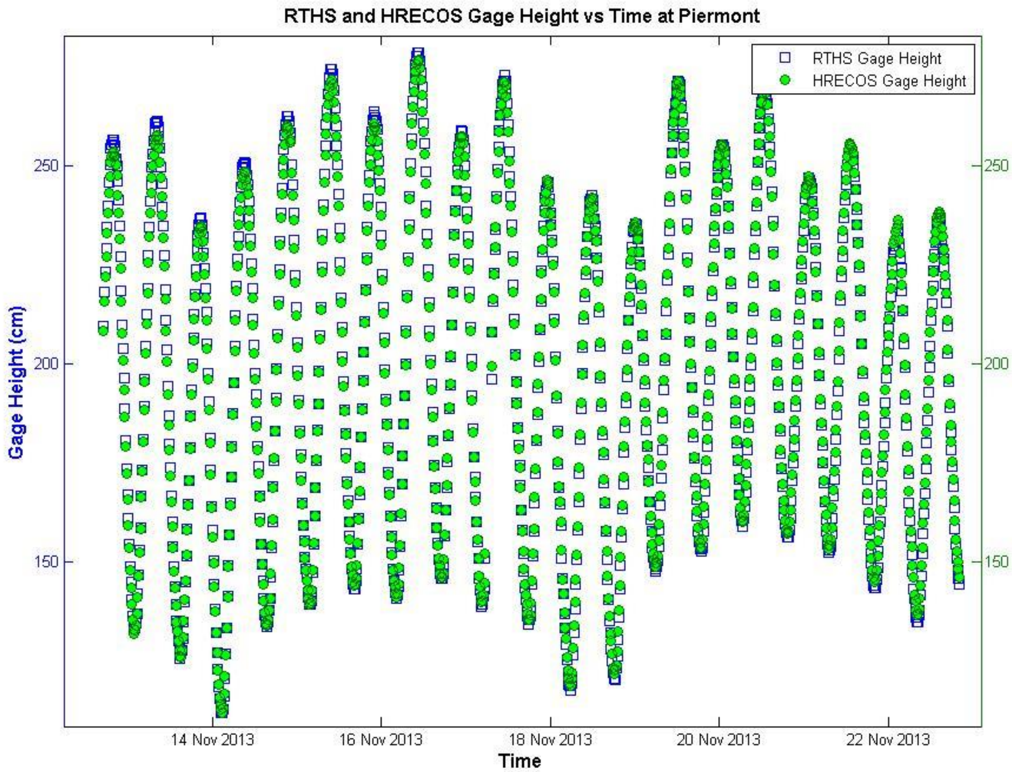

Figure 16), due to varying reference datums an offset was applied to the RTHS dataset for visualization purposes. The sampling interval of the RTHS stage height sensor is set to about 10 seconds, while the interval for the co-locating agencies ranged from one minute at Newburgh (REON ADCP) to 15 minutes at North Creek (USGS). Data analysis was performed by comparing the closest RTHS data value in time to each of the co-located stage measurements. Synchronizing the RTHS and co-locating agency datasets demonstrates the strong correlation between sensors, with R^2 ranging from 0.9896 to 0.9996 (Figure 17).

The slope of the linear regression curves range from 1.005 to 1.033 and the y-intercept reflects the bias in the reference datum between datasets. Discrepancies larger than the 3.05mm or 0.2% performance criteria ranged from 51.0% to 91.5% (Table 2).

Site Location	Minimum	Maximum	Length	Number of	Discrepancy Between

	Stage Observed (cm)	Stage Observed (cm)	of Study (days)	Co-located Samples	Datasets Larger than 3.05mm or 0.2% (% of Measurements)
North Creek, NY	7.09	73.90	31	2858	78.5
Lock 8 Mohawk River, NY	34.35	186.91	50	10693	76.2
Schodack Island, NY	42.02	285.73	32	3053	85.7
Newburgh, NY	125.82	260.91	7	9911	36.9
West Point, NY	61.34	254.27	18	1637	91.5
Piermont, NY	112.22	272.67	11	968	80.0

Table 2: Results of stage height sensor field testing

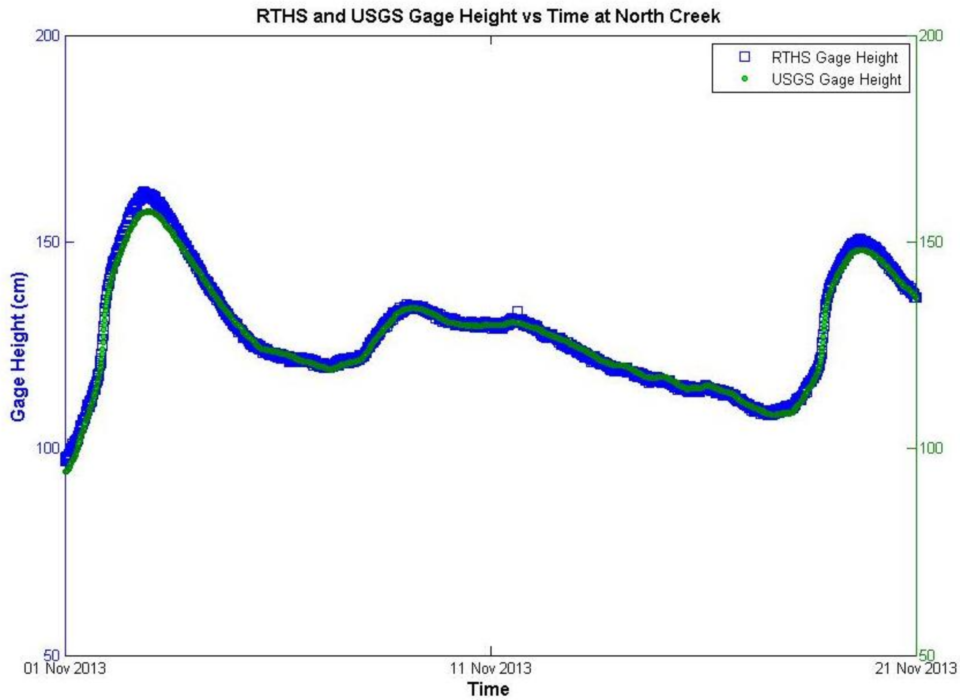

Figure 14: RTHS and USGS gage height at North Creek (natural riverine).

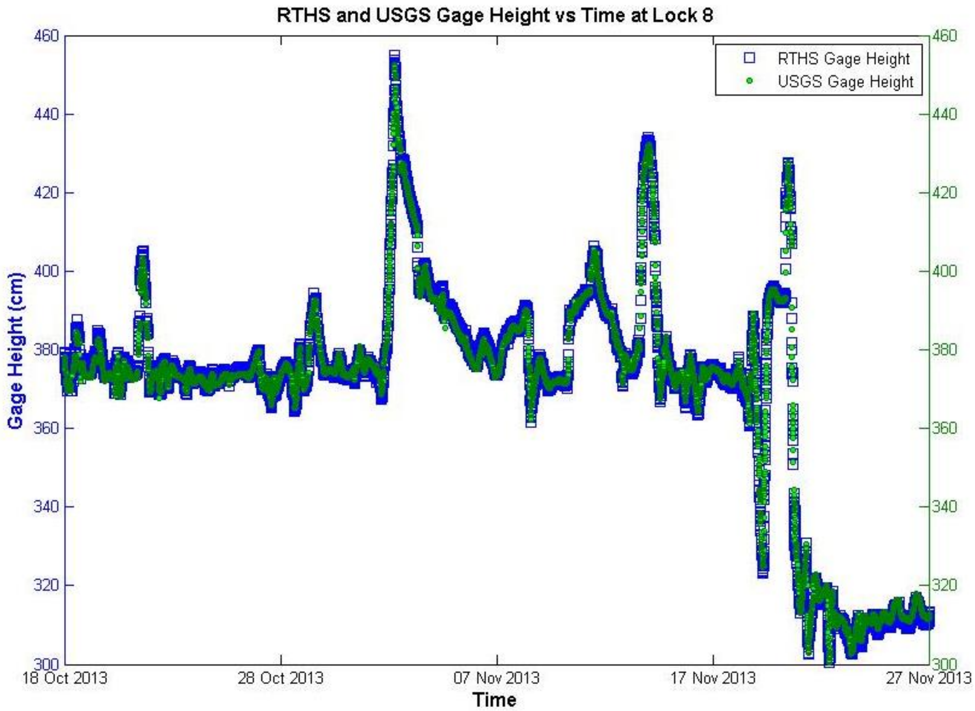

Figure 15: RTHS and USGS gage height at Lock 8 Mohawk River (dam controlled river)

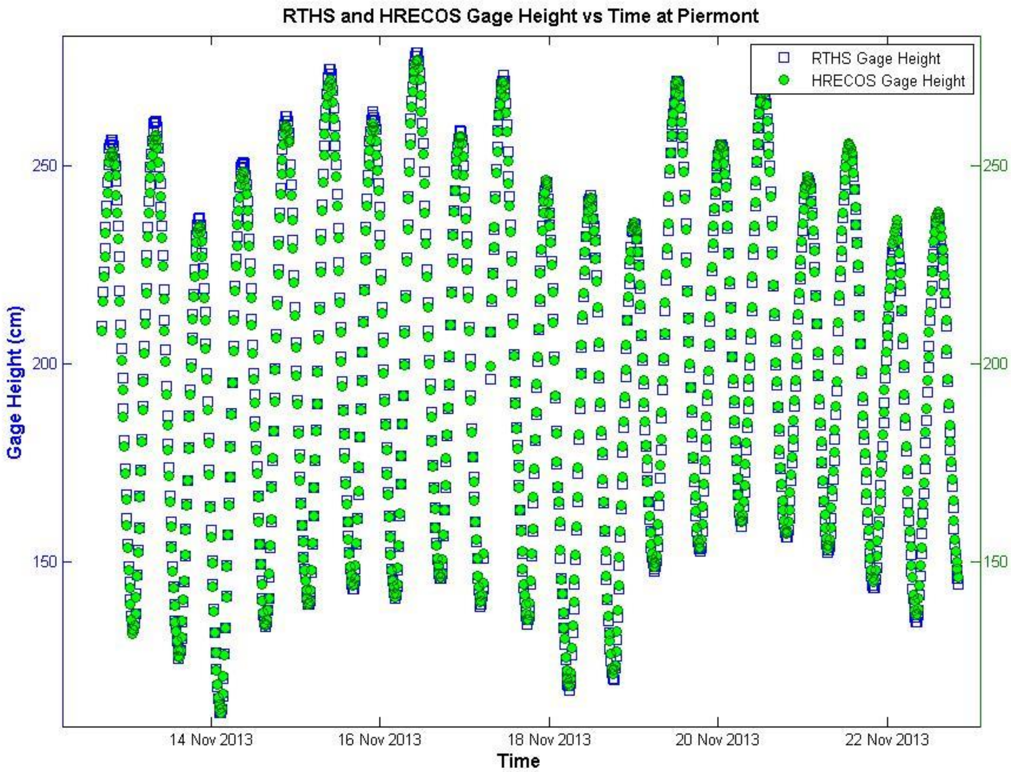

Figure 16: RTHS and USGS at Piermont (tidal estuary)

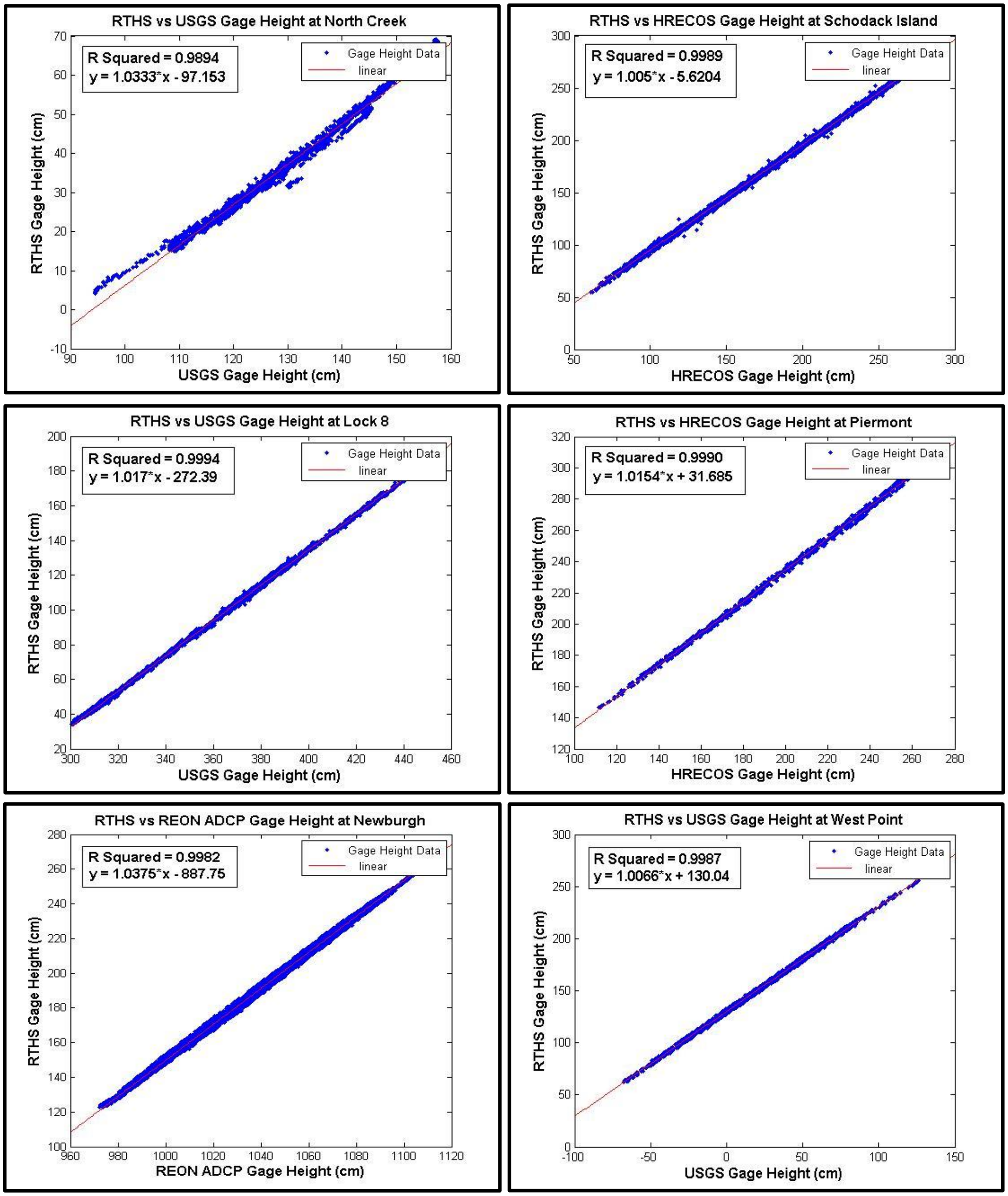

Figure 17: Gage height versus gage height at six field testing sites. The y-intercept reflects the difference in reference datum between datasets.

Stage height anomalies unveiled by high frequency sampling have been identified as a possible discrepancy at Schodack Island. HRECOS collects data by taking spot measurements on a 15 minute interval (New York State Department of Environmental Conservation, 2012), while the RTHS samples at a much higher rate of 10 seconds. Comparing the raw data from both sources indicates there is a very strong correlation between datasets, but with periods of anomalies which contribute to the high discrepancies between datasets at that site (Figure 18). The two datasets are collected completely independently from each other, suggesting the anomalies are not a sampling or systemic error. The anomalies are evident in both datasets, but are more clearly visualized in the RTHS data due to higher sampling frequency.

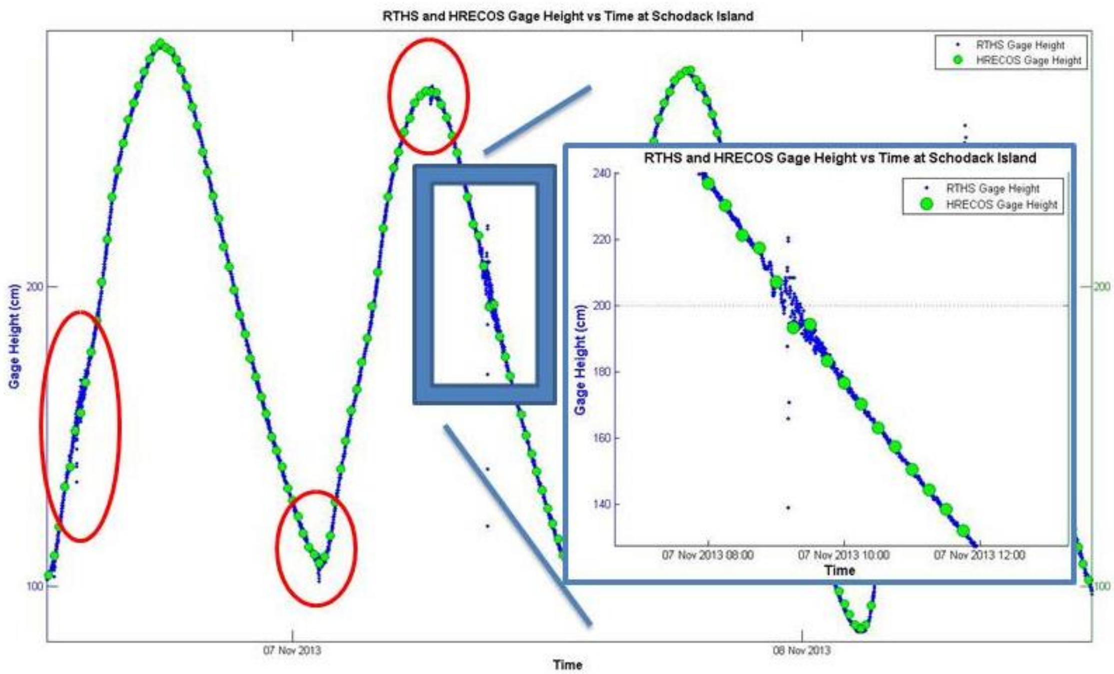

Figure 18: RTHS and HRECOS gage measurements versus time at Schodack Island. Note the brief periods of data anomaly (circled) recorded by both sensors. See boxed inset (blue) for expanded section of data anomaly.

At West Point the high number of discrepancies could be caused by factors such as sensor drift or insufficient temperature compensation. Graphing the relative error between datasets over time reveals a trend in the error (Figure 19). It is not clear if one or both sensors are drifting over time. Note that a shorter time period analysis at this site would result in fewer discrepancy values.

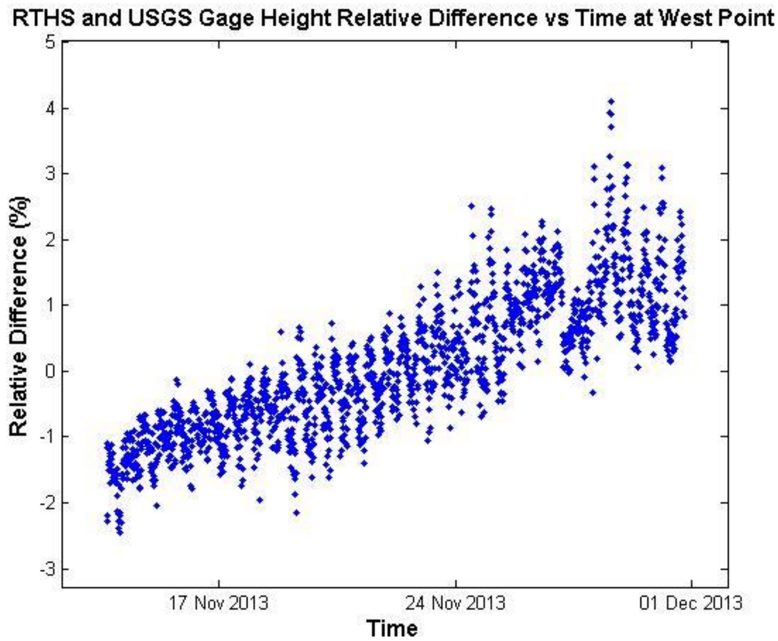

Figure 19: Sensor discrepancy over time at West Point.

4. Discussion

The Real-Time Hydrological Station has been designed, developed, fabricated, and tested in the laboratory and the field. Results of laboratory testing of the precipitation gauge and stage height sensor demonstrated promising accuracy and precision with calibration curves resulting in R^2 as high as 0.9999. In the field, both sensors performed well in terms of reliability, and compared well against co-located research grade sensors. The precipitation gauge field testing occurred during events of both liquid and solid precipitation, attesting to its all-season capability. Similarly, the stage height sensor field testing occurred in diverse aquatic systems throughout the summer and winter, demonstrating ruggedness and reliability.

The precipitation gauge field study showed the in-house designed gauge compared well to the research grade commercial sensor. The RTHS gauge reported some false events, although software filtering drastically reduced these errors stemming from the pronounced temperature dependence of the sensing element. The magnitudes of the false events were all less than 1.8mm and these precipitation errors are not expected to significantly affect the watershed hydrologic dynamics, thus the gauge is acceptable for producing a useful hydrological modeling input dataset. The precipitation gauge field testing demonstrated the gauge performed better on a daily scale rather than hourly or event based. On a larger scale, over the 22 week field study, the precipitation gauge reported 103.2% of the total 326.44mm precipitation reported by the NOAH II. It is important to note that wind-induced undercatch among other systematic errors are commonly accepted as the highest source of bias in precipitation measurements, causing errors up to 50% (Yang, et al., 1999).

Results from field testing the stage height sensor indicate strong correlations with sources at USGS/HRECOS/REON sites (Figure 17). The accuracy performance criteria of 3.05mm or 0.2% was met at varying levels based on the field site. The performance criteria were derived from USGS (Sauer & Turnipseed, 2010), and is considered a high standard as this organization has been making stream measurements for over 100 years. Nevertheless the stage height sensor agreed to within the performance criteria with external measurements on average 34.9% of the values, with a total of 29,120 co-located measurements taken. Some of the sites with higher discrepancies can be attributed to environmental conditions. In Figure 17, the North Creek stage height comparison resulted in a non-linear regression, which is most likely due to imperfect co-location of sensors. Due to site restrictions, the RTHS site is located about 500 meters upstream of the USGS station, at a significantly narrower section of river. At this site, comparing discharge would be a more applicable study, but without a stage-discharge relationship at this time, 22% of stage height measurements within the performance criteria indicate that the stage height sensor produces comparable data to USGS. At Piermont, discrepancies between the RTHS and HRECOS datasets are attributed to different sampling rates (Figure 18). If a higher sampling rate was invoked by HRECOS, software filtering both datasets could result in fewer discrepancies. The source of stage anomalies is unclear at this time, whether it is actual stage variations or biasing noise generated from an external source nearby, and high frequency sampling by the RTHS sensor has shed light on the magnitude and frequency of the anomalies. At West Point, the RTHS and USGS absolute stage error appears to be drifting over time (Figure 19). This could be due to imperfect temperature compensation, as water temperature is steadily decreasing during this period, and again it is unclear which sensor producing higher accuracy data.

Field testing the in-house designed sensors involved referencing to a research grade sensor (precipitation gauge) or co-locating with external organizations of high reputation (stage height sensor). The problem with comparing datasets from two independent sensors is that when discrepancies such as anomalies, drift, and false reporting become evident, it is not clear which sensor is at fault without taking manual measurements. Taking manual measurements at each of the test sites at an adequate temporal resolution was not feasible for this study.

Results of field testing conclude that these sensors provide a low-cost alternative with adequate performance to commercially available sensors and systems. Discrepancies greater than with 3.05mm or 0.2% accuracy performance criteria for the stage height sensor ranged from 51% to 92%, with some stations subjected to known environmental factors attributing to the discrepancies. Also it is important to note that the accuracy criteria are based on total system accuracy including load calibration, temperature compensation, and barometric pressure correction. The precipitation gauges agreed to within the accuracy criteria on 49% of the days in which precipitation occurred, with 10 false positive events over the 126 day study. The daily accumulation linear regression resulted in R^2=0.9671, demonstrating a strong correlation and adequate performance for hydrological monitoring and modeling. Both the stage height sensor and precipitation gauge show strong correlations to external data sources amongst the inhibiting environmental conditions, varying sampling frequencies, and varying measurement technologies.

Future work for the RTHS includes expanding the sensor suite to include water quality measurements. Basic water quality parameters such as dissolved oxygen, pH, turbidity, and conductivity are being implemented into the RTHS to provide a more comprehensive hydrological monitoring scheme. Also additional meteorological parameters could be measured such as solar radiation, snow depth, soil moisture, and evaporation rate. The RTHS is capable of easily integrating additional commercially available sensors, in terms of power, physical mounting, and data management.

The RTHS system has been designed and evaluated for use as a hydrological monitoring tool with applications in hydrological modeling. The following parameters are reliably measured using the RTHS: air temperature, relative humidity, wind speed, wind direction, barometric pressure, precipitation, stage height, and water temperature. Designing a custom stage height sensor and precipitation gauge for the RTHS has decreased system cost, while maintaining adequate accuracy and reliability. The system has been designed for quick installation and low operations and maintenance costs. The RTHS provides a low cost, high temporal resolution, high accuracy, real-time solution to high spatial resolution environmental monitoring under a fixed budget. High temporal and spatial resolution monitoring is necessary to capture episodic events, localized events, as well as to provide input datasets for quality hydrological modeling in diverse watersheds.

References

30-Year Average of Monthly Solar Radiation, 1961-1990 Massena, NY. (n.d.). Retrieved 9 24, 2013, from http://rredc.nrel.gov/solar/old_data/nsrdb/1961-1990/redbook/sum2/94725.txt

Becker, G., Schiebelsberger, B., Weber, W., Vodermayer, C., Zehner, M., & Kummerle, G. (2006). *An Approach to the Impact of Snow on the Yield of Grid Connected PV Systems.* Munich: Bavarian Association for the Promotion of Solar Energy.

Chiang, Y.-M., Hsu, K.-L., Chang, F.-J., & Hong, Y. (2007). Merging multiple precipitation sources for flash flood forecasting. *Journal of Hydrology, 340*, 183-196.

Dunkerley, D. (2008). Identifying individual rain events from pluviograph records: a review with analysis of data from an Australian dryland site. *Hydrological Processes, 22,* 5024-5036.

Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2007). The Soil and Water Assesment Tool: Historical Development, Applications, and Future Research Directions. *Transactions of the ASABE, 50*(4), 1211-1250.

Glasgow, B. H., Burkholder, J. M., Reed, E. R., Lewitus, A. J., & Kleinman, J. E. (2004). Real-time remote monitoring of water quality: a review of current applications, and advancements in sensor, telemetry, and computing technologies. *Journal of Experimental Marine Biology and Ecology, 300*, 409-448.

Gordon, J. D. (2003). *Evaluation of Candidate Rain Gages For Upgrading Precipitation Measurement Tools For the National Atmospheric Deposition Program.* U.S. Geological Survey U.S. Department of the Interior, Water-Resources Investigations Report 02-4302, Denver, Colorado.

Hannah, D. M., & Gurnell, M. A. (2001). A conceptual, linear reservoir runoff model to investigate melt season changes in cirque glacier hydrology. *Journal of Hydrology, 246*, 123-141.

Harmancioglu, N. B., & Alpaslan, N. (1992). WATER QUALITY MONITORING NETWORK DESIGN: A PROBLEM OF MULTI-OBJECTIVE DECISION MAKING. *Journal of the American Water Resources Association, 28*, 179-192.

Hicks, M. D., McSaveney, M. J., & Chinn, T. (1990). Sedimentation in Proglacial Ivory Lake, Southern Alps, New Zealand. *Artic and Alpine Research, 22*(1), 26-42.

Hubbart, J., Link, T., Campbell, C., & Cobos, D. (2005). Evaluation of a low-cost temperature measurement system. *Hydrological Processes, 19*, 1517-1523.

New York State Department of Environmental Conservation. (2012). *HRECOS Hydrologic and Meteorologic Stations Quality Assurance Project Plan.*

NOAA NWS. (2010). *National Weather Service Instruction 10-1301*.

Sauer, V. B., & Turnipseed, D. P. (2010). Stage Measurement at Gaging Stations. In *U.S. Geological Survey Techniques and Methods Book 3, Ch. A7, 45 p.*

U.S. National Weather Service. (1989). *Cooperative Station Observations NWS Observing Handbook No. 2.* Silver Spring, Md.

World Meteorological Organization. (2008). *Guide to Meteorological Instruments and Methods of Observation.*

Yang, D., Goodison, B. E., & Metcalfe, J. R. (1998, Feburary). Accuracy of NWS 8" Standard Nonrecording Precipitation Gauge: Results and Application of WMO Intercomparison. *Journal of Atmospheric and Oceanic Technology*, *15*, 54-68.

Yang, D., Goodison, B. E., Metcalfe, J. R., Louie, P., Leavesley, G., Emerson, D., et al. (1999, Feburary). Quantification of precipitation measurement discontinuity induced by wind shields on national gauges. *Water Resources Research*, *35*(2), 491-508.