Discharge-Stage and Discharge-Inundation Relationships for the Boise River at the Boise Hydrogeophysical Research Site

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ABSTRACT

River stage, river discharge, and river bank inundation have been measured at the Boise Hydrogeophysical Research Site at specific times in spring 2009, and at two week intervals from May 2010 to November 2011, for the purpose of monitoring and modeling aquifer dynamics and effects of river boundary conditions. From these data, empirical relationships have been developed relating discharge to river stage and river bank inundation. These relationships were used to predict river behavior from discharge data in the absence of measurements. These relationships can also be used to predict river stage and bank inundation based on discharge measurements alone.

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LIST OF ACRONYMS AND ABBREVIATIONS

AMSL	Above Mean Sea Level
BHRS	Boise Hydrogeophysical Research Site
C.I.	Confidence Interval
DSG	Downstream Staff Gauge
DSRE	Downstream Rive Edge measurement location
GPS	Global Positioning System
MSE	Mean Squared Error
MSRE	Midstream River Edge measurement location
P4	Piezometer 4
P4RE	Piezometer 4 River Edge measurement location
P5	Piezometer 5
P5A	Piezometer 5A
P5RE	Piezometer 5 River Edge measurement location
P6	Piezometer 6
P6RE	Piezometer 6 River Edge measurement location
Q_{BHRS}	Discharge in the Boise River at the BHRS
Q_{LUC}	Discharge from Lucky Peak Dam
Q_{NYC}	Discharge in the New York Canal
USG	Upstream Staff Gauge
USRE	Upstream River Edge measurement location

INTRODUCTION

The Boise Hydrogeophysical Research Site (BHRS) is located ~15 km southwest of Boise, ID on a 0.091 km^2 gravel bar adjacent to the Boise River (figure 1). The site is less than 1 km downstream from Diversion Dam and within a few kilometers of Lucky Peak Dam, both of which control discharge in the river. One focus of research at the BHRS is groundwater dynamics and aquifer states and fluxes, which includes influences of river boundary conditions (river stage and bank inundation). The combined management of dams upstream provides distinct, stable river discharges at the BHRS that range from low winter levels to high spring levels. Changes in river discharge occur at specific times and with defined changes, and discharge values are nearly stable between changes. Changes in discharge lead to changes in river stage and river bank position (river inundation) which influence well water levels and hydrology of the site. Over a typical year, discharge can vary by >200 m^3s^{-1} (7000 ft^3s^{-1}), river stage can vary by >1 m, and river inundation can change by >30 m. At several times the BHRS has been the site of high-resolution, high-precision hydrologic and hydrogeophysical testing and monitoring, and it is very important that the relationships between river discharge, river stage, and river inundation are well understood and can be accurately predicted. This report describes the use of data collected from 2009 – 2011 to determine a stage-discharge relationship (referred to as a rating curve) and a stage-inundation relationship for the BHRS, and the use of these relationships to predict river behavior in the absence of observed data.

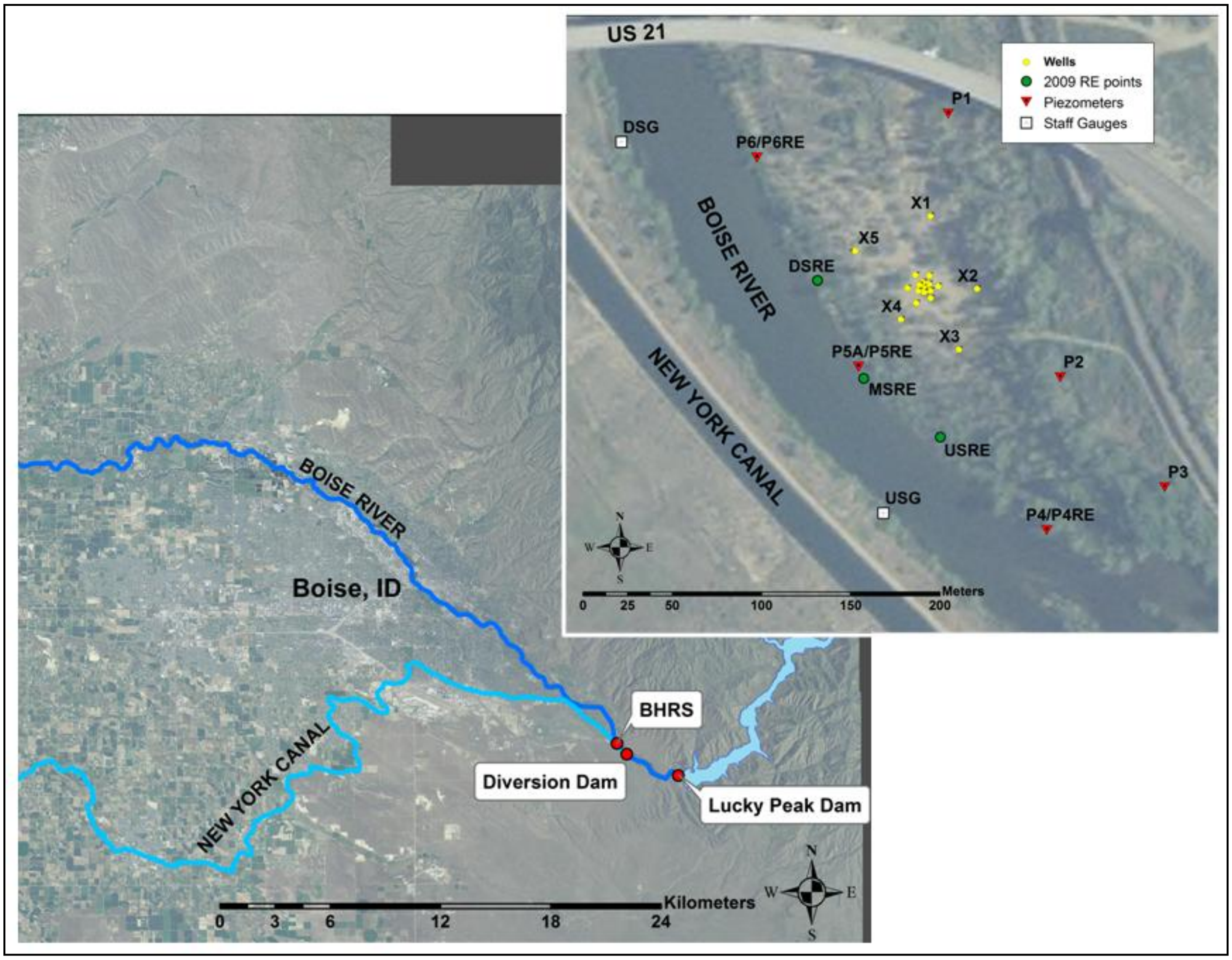

Figure 1: Overview of Boise area and BHRS measurement locations (inset).

The two main dams that control discharge in the Boise River along the BHRS are Lucky Peak Dam and Diversion Dam (figure 1). Lucky Peak Dam is a large, earthen dam used to maintain Lucky Peak Lake for winter runoff storage, flood control, power generation, and recreation. Diversion Dam is used to divert water from the Boise River into the New York Canal where it is routed throughout the Treasure Valley for irrigation. These two dams provide primary control of flow in the Boise River at the BHRS and downstream through the City of Boise. The river discharge varies seasonally as reservoirs are filled and drained in response to seasonal changes (e.g., spring snowmelt) and water needs downstream. Discharge in the Boise River typically follows a pattern of low winter flow; ~15 m^3s^{-1} (500 ft^3s^{-1}), slightly higher summer flow for irrigation and recreation; 30 – 60 m^3s^{-1} (1000 – 2000 ft^3s^{-1}), and highest flows during spring snowmelt; reaching >250 m^3s^{-1} (> 9000 ft^3s^{-1}) (figure 2). Discharge in the New York Canal maintains between 40 and 60 m^3s^{-1} (1400 and 2000 ft^3s^{-1}) in the summer (April – October) and the canal is dry through most of the winter (figure 2). Diversion Dam has a very small reservoir and, for almost the entire year, flows into this reservoir are equal to flows out and there is no net change in storage (figure 3). Water entering the Diversion Dam reservoir is either diverted into the New York Canal, passed through the turbines at the dam, or spilled over the dam. Both Lucky Peak Dam and Diversion Dam are maintained by the United States Bureau of Reclamation (USBR) which controls and measures discharge and reports data at regular intervals, ranging from 15 min to 8 hr.

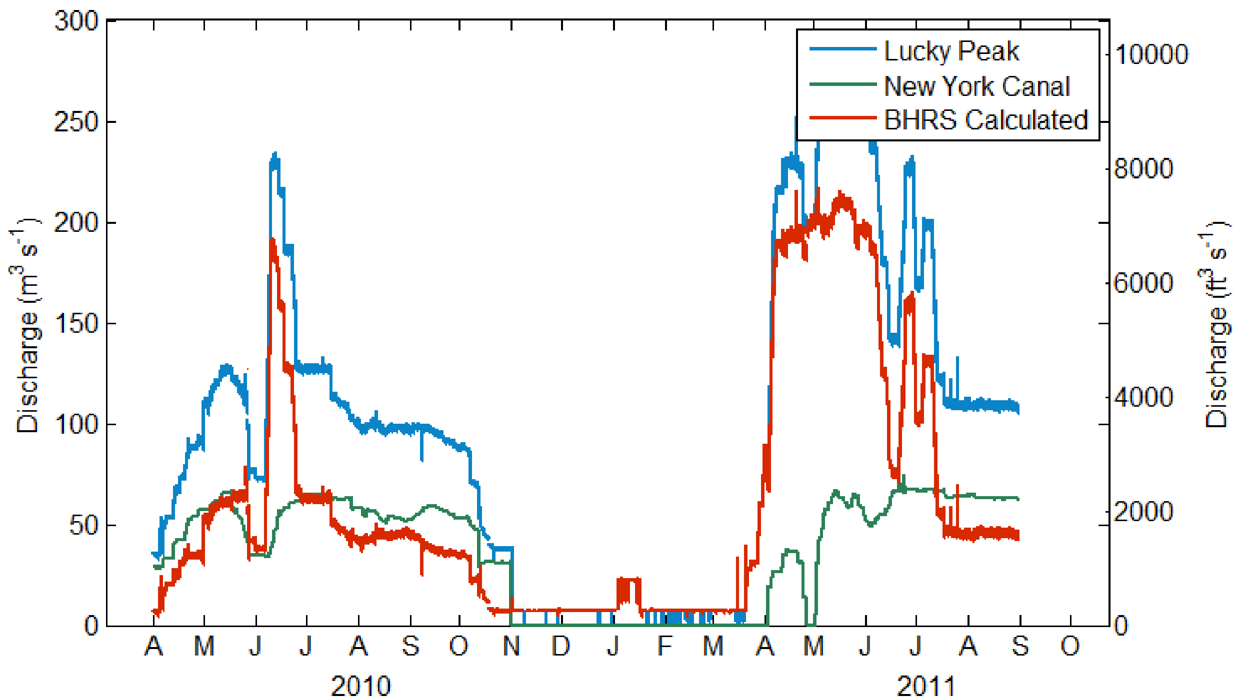

Figure 2: Reported Lucky Peak and New York Canal discharge from USBR, and calculated discharge at the BHRS (Q_{BHRS}) for April 2010 – Sept 2011.

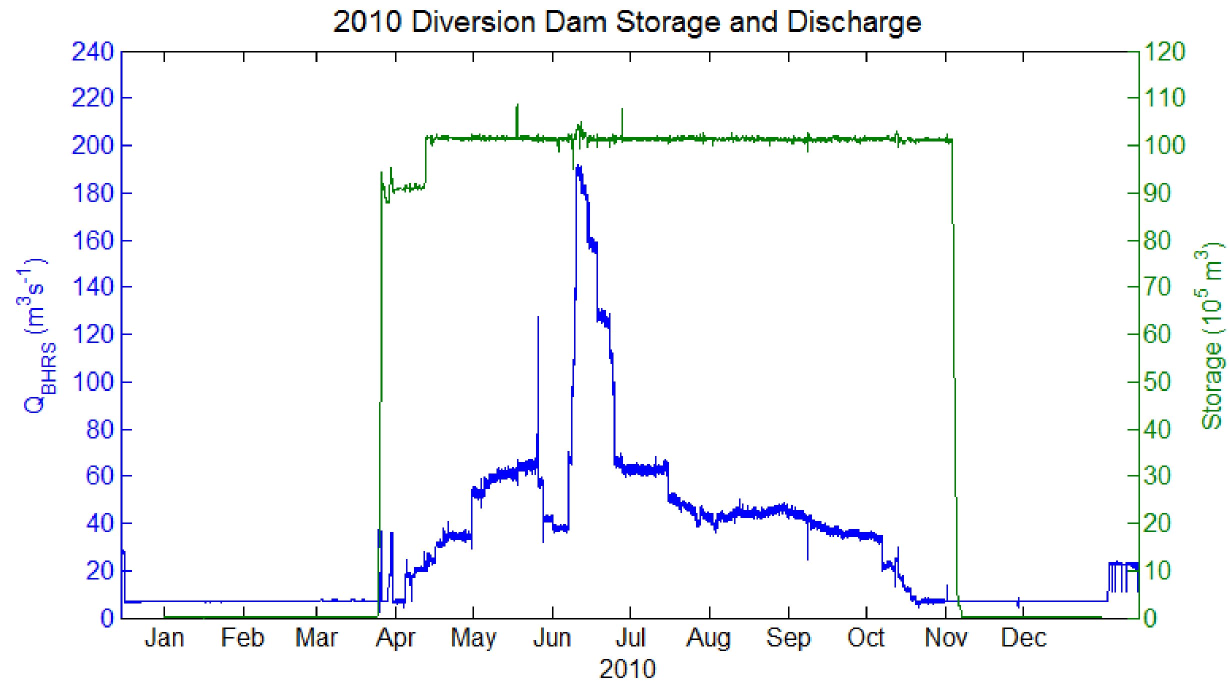

Figure 3: Diversion Dam reservoir storage and Q_{BHRS} for 2010 showing rapid filling and draining of the reservoir and stable summer levels.

METHODS

This section provides a description of the data collection and processing techniques used to develop the relationships between river discharge, river stage, and bank inundation. The section is divided into two sub-sections: 1) data collection and processing, and 2) model development.

Data Collection and Processing

Boise River Discharge at the BHRS

Since no direct measurements of Boise River discharge are available directly below Diversion Dam at the BHRS, BHRS discharge (Q_{BHRS}) is calculated as discharge from Lucky Peak (Q_{LUC}) minus discharge in the New York Canal (Q_{NYC}) (equation 1). Both sets of data are taken from the USBR website as discharge averaged over 15 min intervals. These two data sets are reported at the same times making subtracting canal discharge from river discharge a simple procedure. In winter months (November –

March) when the New York Canal is inactive and no water is flowing (this can be observed visually), values reported are often erroneous, such as negative values or values greater than Lucky Peak discharge. During these times, Q_{BHRS} is calculated to be equal to Q_{LUC}.

$$Q_{BHRS} = \begin{cases} Q_{LUC} - Q_{NYC} & spring - fall \\ Q_{Luc} & winter \end{cases}$$

(1)

Equation 1 assumes there is no net change in storage in the Diversion Dam reservoir. For much of the summer, Diversion Dam reservoir stage is greater than the spillway elevation and water can be observed flowing over the dam. At these high flows there is no question that increases in reservoir storage directly produce increases in Q_{BHRS} or Q_{NYC}.

River Stage

River stage is measured visually at two staff gauges located upstream (USG) and downstream (DSG) from the main BHRS well field (figure 1). Both staff gauges consist of sections of white plastic rulers marked with 0.02 ft (0.61 cm) increments (figure 4). The absolute readings on the staff gauges are arbitrary but the elevation at the top of each gauge has been surveyed using high-resolution GPS (Johnson et al. 2012), and the ruler marking on the top of each gauge is also known. A staff gauge reading is taken by recording the level of the river stage on the gauge and river stage elevation at the staff gauge is calculated using equation 2. River stage measurements have been taken at least every two weeks from spring 2010 to fall 2011. Prior to 2010, measurements were taken during experiments only, the most extensive of which was a multi-week monitoring campaign of river stage and well water levels that took place in spring-early summer of 2009 (figure 5).

$$river\ stage\ [m\ AMSL] = gauge\ top\ elev\ [m] - (gauge\ top[ft] - gauge\ reading[ft]) \cdot \left(\frac{0.3048\ m}{1\ ft}\right)$$

(2)

Figure 4: Downstream river staff gauge and stilling well at low stage, gauge increments are 0.02 ft.

River stage measurements have also been recorded using a submerged Solinst pressure transducer placed in a stilling well attached to the downstream gauge. The Solinst logger has been recording pressure (water level) and temperature at 15 min intervals since July 2010 and was also used during the multi-week monitoring campaign in 2009 with a sampling interval of 3 min. From May 2010 to July 2010 an Odyssey pressure transducer was used; this logger was replaced with a Solinst logger in July 2010. Data from this sensor have been downloaded every two weeks in conjunction with records taken of visual staff gauge measurements (figure 5). River stage elevation (equation 2) is used to determine transducer elevation at the time of download using equation 3, and river stage elevations during the period prior to download are determined using equation 4. These steps are repeated every two weeks so continuous corrections of transducer elevation can be made and applied to transducer recordings of river stage (figure 5).

$$transducer\ elevation\ [m\ AMSL] = river\ stage\ [m\ AMSL] - \ final\ water\ level\ measurement[m]$$
(3)

$$river\ stage\ [m\ AMSL] = transducer\ elevation\ [m\ AMSL] + \ water\ level\ [m]$$
(4)

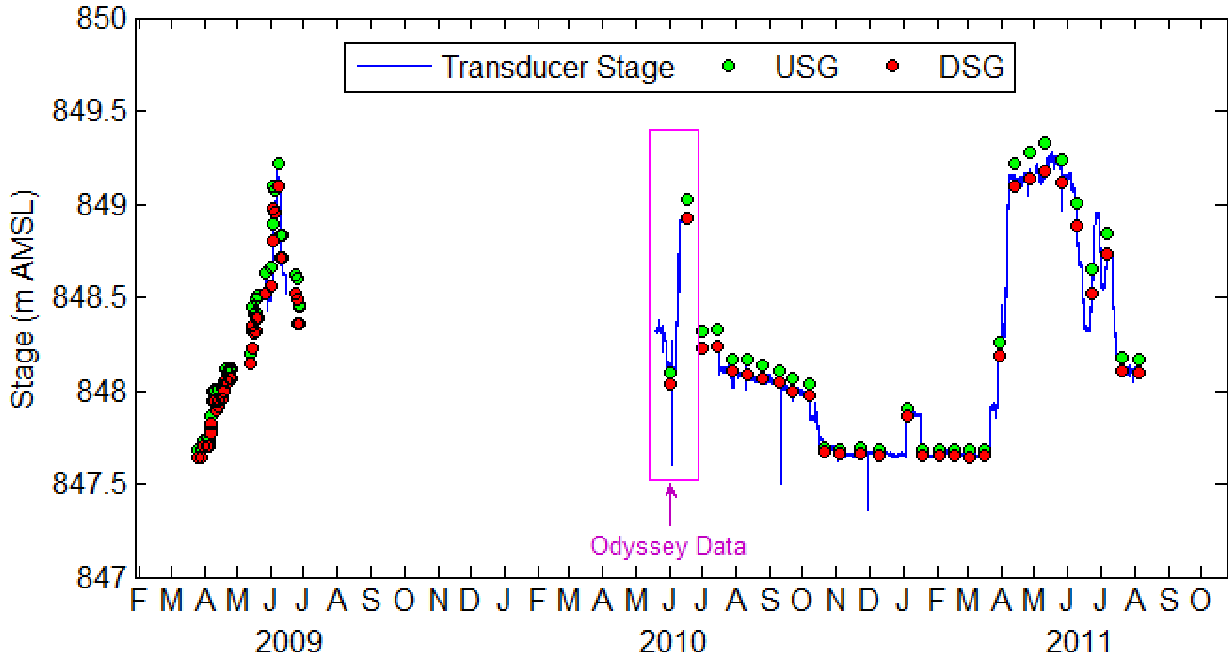

Figure 5: River stage elevation (2010 – 2011) from transducer data (at DSG) and visual gauge readings (from both USG and DSG) from 2010 – 2011 and the 2009 monitoring campaign.

River Inundation Measurements

River inundation measurements record the position of the wetted perimeter of the Boise River at specific locations across the site. River inundation has been measured at three locations during the spring 2009 monitoring campaign and every two weeks from May 2010 to November 2011. During the 2009 campaign, three locations were chosen for river inundation measurements located at upstream, middle, and downstream positions relative to the central well field (table 1, figure 1). In 2010, with the installation of piezometers further upstream and downstream from the central well field, two of the 2009 locations were replaced with the locations of two new piezometers (P4 and P6). The middle measurement location changed slightly from the 2009 landmark (a tree) to a permanent piezometer (P5) in 2010. In 2011, P5 was replaced with a piezometer nest, P5A, but the location did not change significantly and P5A became the new reference measurement location for mid-stream river inundation. All mid-stream river edge measurements have been corrected to the P5A measurement location. River inundation measurements are made by measuring from the center of the permanent piezometer to the river edge in a direction perpendicular to the river (see table 1). River bank inundation often passes beyond the location of the piezometers at high stage, and such measurements are reported as negative values. At very high stage, measurements at P4 cannot be taken do to extensive flooding at that location. Figure 6 shows river edge measurements from 2009 to 2011 and how the river edge measurements change in response to changes in river discharge.

Table 1: River measurement locations and bearing.

Name	UTM E [m]	UTM N [m]	True Bearing for River Edge Measurement [°]
DSG	572722.60	4821524.18	NA
DSRE	572831.02	4821445.98	240
P4	572957.81	4821305.22	200
P5/MSRE	572854.63	4821396.84	240
P5AS	572856.16	4821394.63	250
P6	572798.03	4821514.41	250
USG	572868.18	4821314.83	NA
USRE	572900.00	4821357.98	240

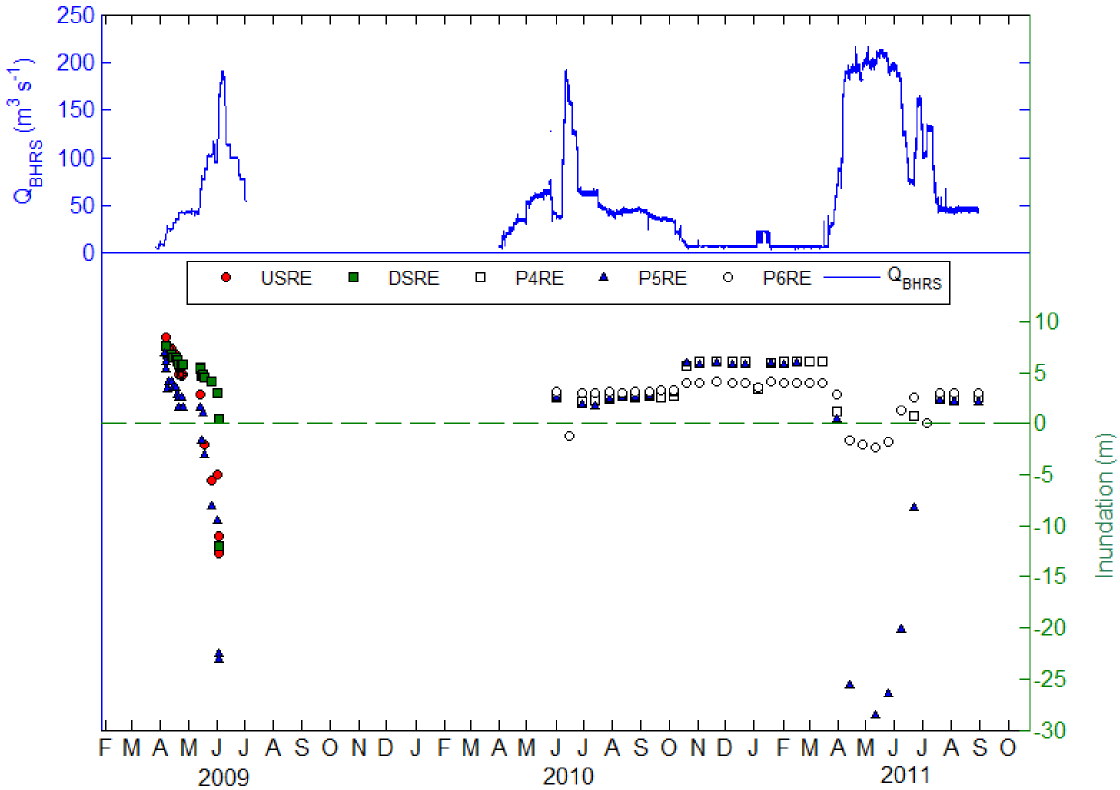

Figure 6: River inundation measurements at all five sites (lower plot) and Q_{BHRS} (upper plot) from 2009 – 2011.

Model Development

Stage – Discharge Relationships

The relationship between river discharge and either river stage or river inundation is directly controlled by the shape of the river channel and bank. As river discharge increases, the excess water causes the river to swell and river stage to rise. This rise in stage will be accompanied by a widening of the river onto the banks (and often an increase in velocity in the channel). In general, when multiple data points are plotted on a discharge vs. stage graph they form a highly correlated relationship (referred to as a rating curve (Dingman 2002). Such relationships can typically be fit using a regression equation which then can be used to model river stage in the absence of measured data. In a later section we show how this relationship is used to predict river stage during a time of transducer failure.

Development of the rating curve begins by finding individual data pairs of stage and discharge measurements taken at the same times. Although both discharge and stage are recorded at 15 min intervals, the times do not always match (difference less than 2 min) and a linear interpolation of the stage data is conducted to match the discharge data times. The high sampling rate of both data types implies there will be little change over 15 minutes and that a linear interpolation is appropriate. Once stage-discharge data pairs are found they are plotted as discharge versus stage (figures 7 and 8). A trend line can then be fit to the data using regression. For this study we used a non-linear curve fitting algorithm provided by the MATLAB function *nlinfit* and the power equation shown in equation 5.

$$Stage[m] = C_1 \cdot Q_{BHRS}[m^3 s^{-1}]^{C_2} + C_3$$
(5)

where C_1, C_2, and C_3 are the regression parameters. All three years of DSG transducer data (2009 – 2011) were used to find the coefficients in equation 5 and the result of the regression is shown in figure 7 with the coefficients presented in table 2 along with 95% confidence ranges on the parameters. The same technique was used for USG visual stage measurements which provided far less data (72 points compared to 38,484 points for DSG), but yielded a similar trend line (figure 8) and similar coefficients (table 3). The difference in coefficients between USG and DSG rating curves is primarily the result of differences in channel shape between the two locations. It should be noted that the offset coefficient (C_3) is a fitting parameter and does not represent the zero-discharge elevation as equation 5 implies.

Table 2: Rating curve coefficients from the inversion of USG and DSG data.

	C_1	C_2	C_3	MSE
DSG	0.0391 ±0.0003	0.7072 ±0.0016	847.513 ±0.0014	6.24E-4
USG	0.0505 ±0.0165	0.6744 ±0.0580	847.501 ±0.0587	3.26E-4

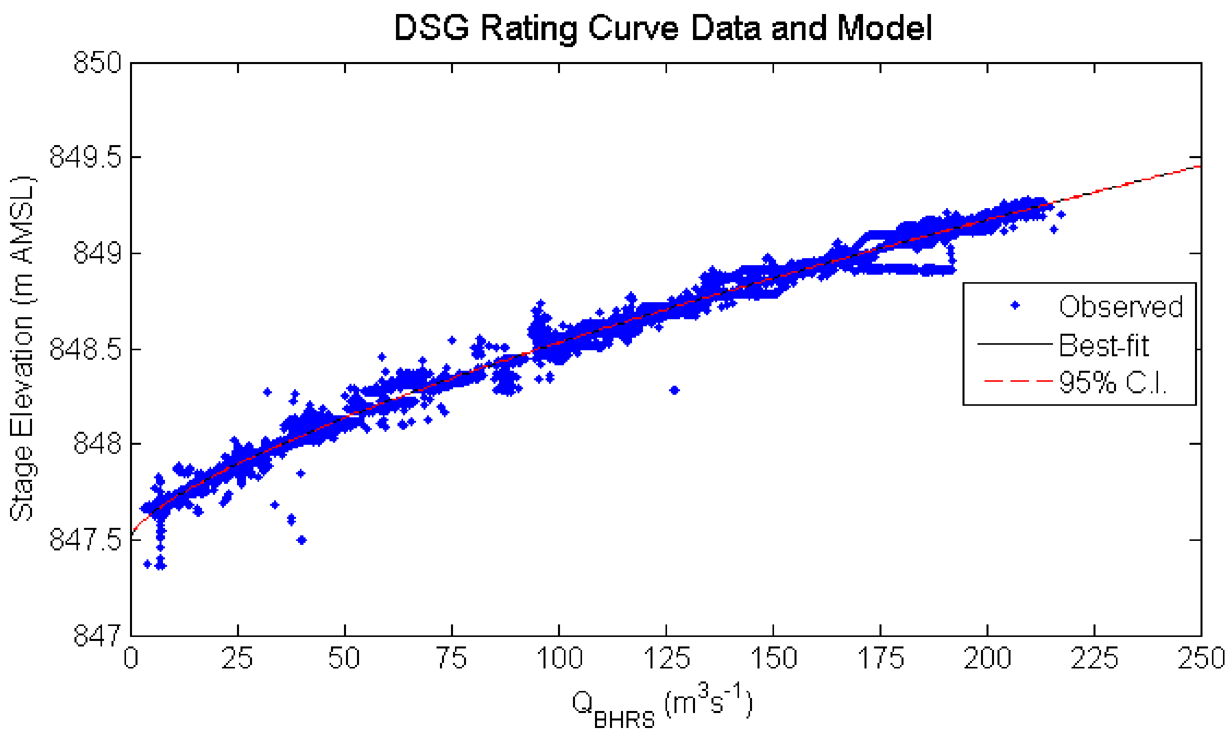

Figure 7: DSG rating curve data from 2009 – 2011 and best-fit line with 95% confidence interval (C. I.) on predicted measurements.

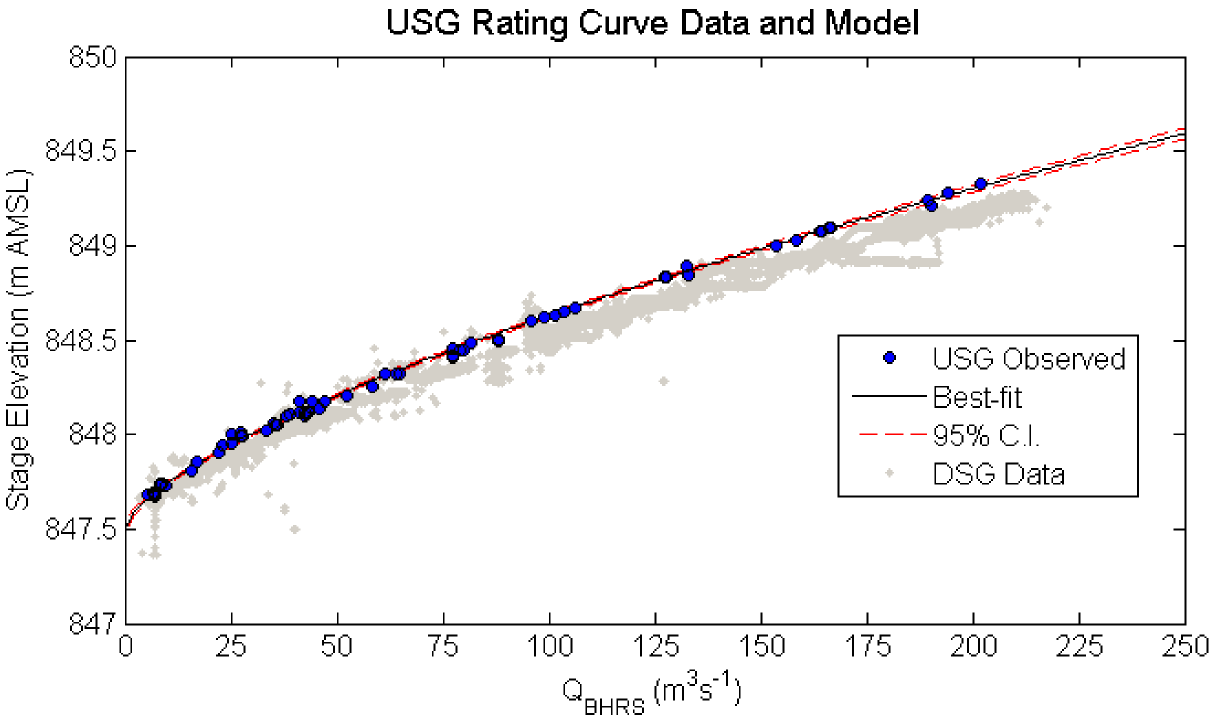

Figure 8: USG rating curve for 2009 – 2011 visual staff gauge data and best-fit line. Shaded points are the DSG data for comparison.

Stage – Inundation Relationships

River discharge – inundation relationships fit the same criteria as discharge – stage relationships, that is, they are controlled by river channel geometry and can thus be approximated with regression relationships. For the BHRS, river inundation measurements have been collected every two weeks from May 2010 to November 2011and during the spring monitoring campaign in 2009. These data were taken at locations P4RE, P5RE, and P6RE in 2010 and USRE, MSRE, and DSRE in 2009. For discharge – inundation data we approximated the relationship with a series of linear equations (equation 6) with coefficients of slope (C_1) and intercept (C_2) which are treated as fitting parameters rather than physical features in the natural system.

$$Inundation[m] = C_1 \cdot Q_{BHRS}\left[{m^3}/{s}\right] + C_2$$

(6)

where C_1 and C_2 are regression coefficients. Determination of coefficient values was accomplished using *nlinfit* in the same manner as the stage – discharge relationship. Due to the varied geometry of the Boise River bank at the inundation measurement locations, there are different coefficients for different ranges of discharge, which correspond to differences in slope of the river bank (figures 9 – 13). For example, the P5RE discharge – inundation relationship (figure 10) has a lower slope at lower discharge (Q_{BHRS} < 70 m^3s^{-1}) and a higher slope at higher discharge (Q_{BHRS} > 70 m^3s^{-1}). These different relationships correspond to different elevation gradients of the river bank.

Table 3: Coefficients for linear fit models of river discharge – inundation relationships of all measurement locations and at different flows. Mean squared error (MSE) is also reported.

Section	C_1 (slope)	C_2 (intercept)	MSE
$DSRE_{Q<40}$ 2009	-0.067	8.572	0.028
$DSRE_{40<Q<100}$ 2009	-0.028	6.980	0.004
$DSRE_{Q>100}$ 2009	-0.113	15.331	0.170
$P4RE_{Q<20}$	-0.295	8.078	0.005
$P4RE_{Q>20}$	-0.036	4.056	0.081
$P5RE_{Q<70}$	-0.092	6.507	0.281
$P5RE_{Q>70}$	-0.210	13.312	11.446
$P6RE_{Q<50}$	-0.027	4.201	0.004
$P6RE_{Q>50}$	-0.0353	5.102	0.782
USRE 2009	-0.155	11.276	0.560

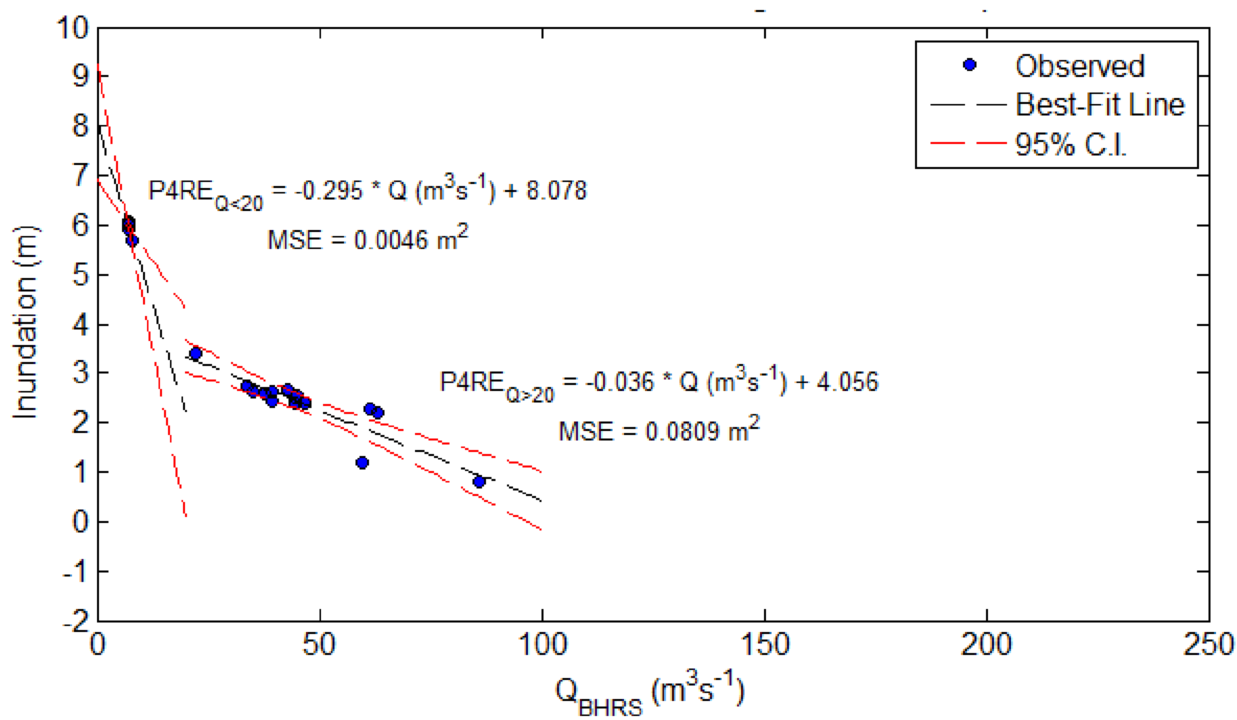

Figure 9: P4RE river discharge – inundation data and best-fit lines with final equations and MSE reported.

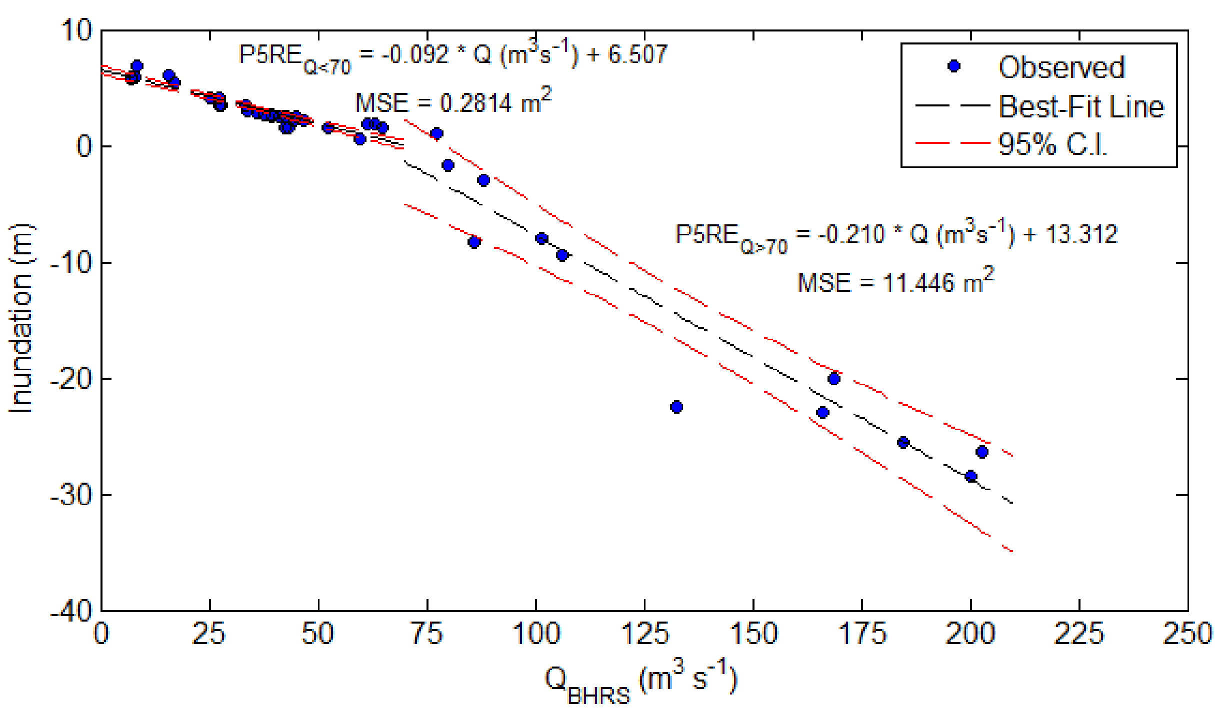

Figure 10: P5RE river discharge – inundation data.

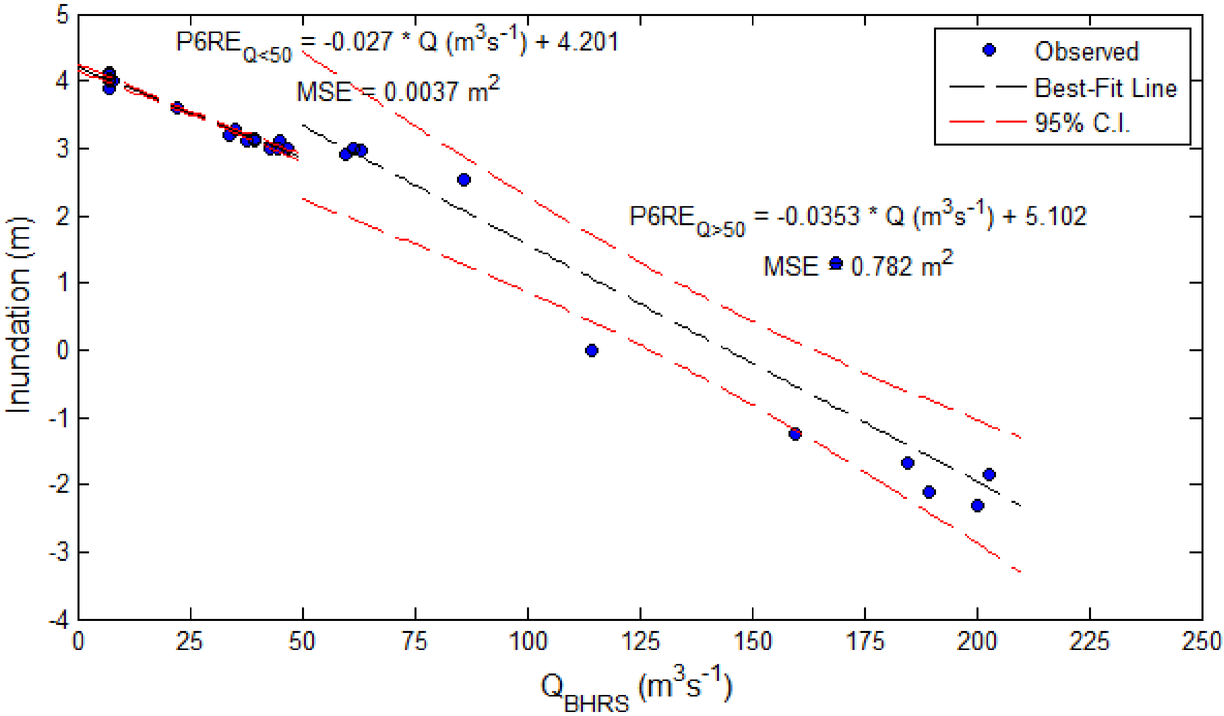

Figure 11: P6RE river discharge – inundation data.

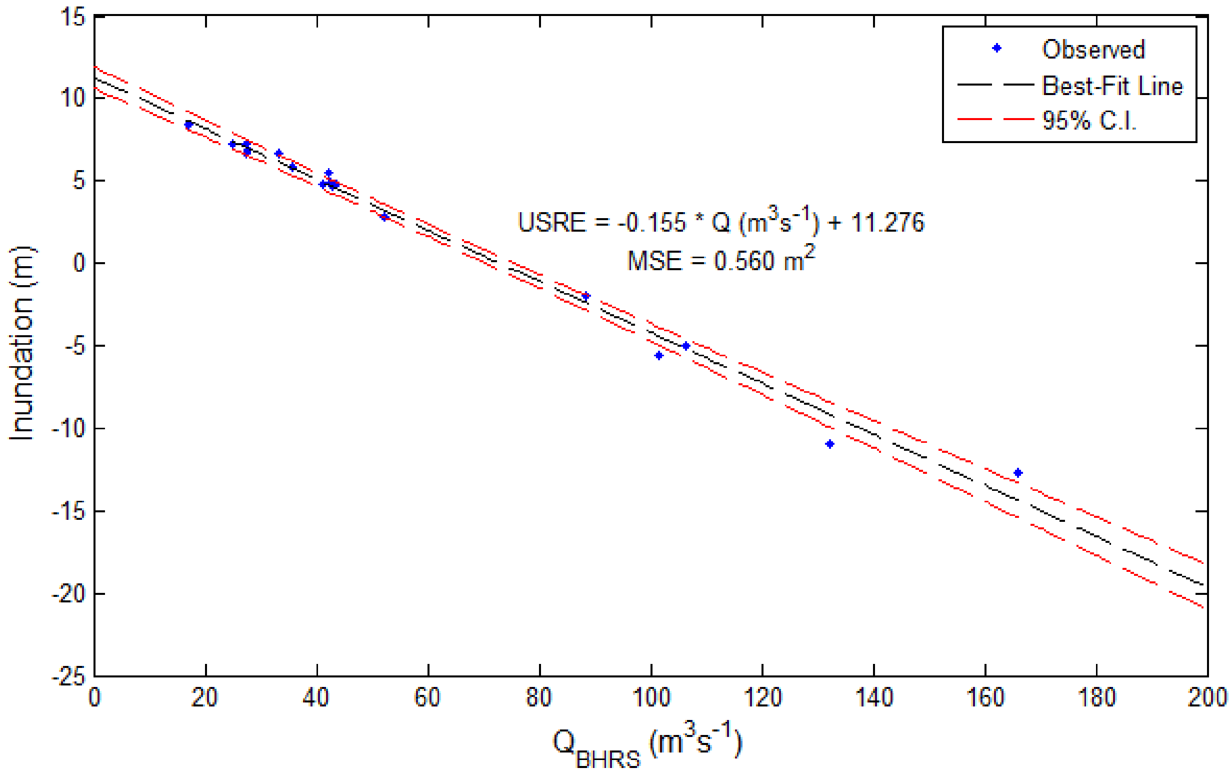

Figure 12: USRE river discharge – inundation data.

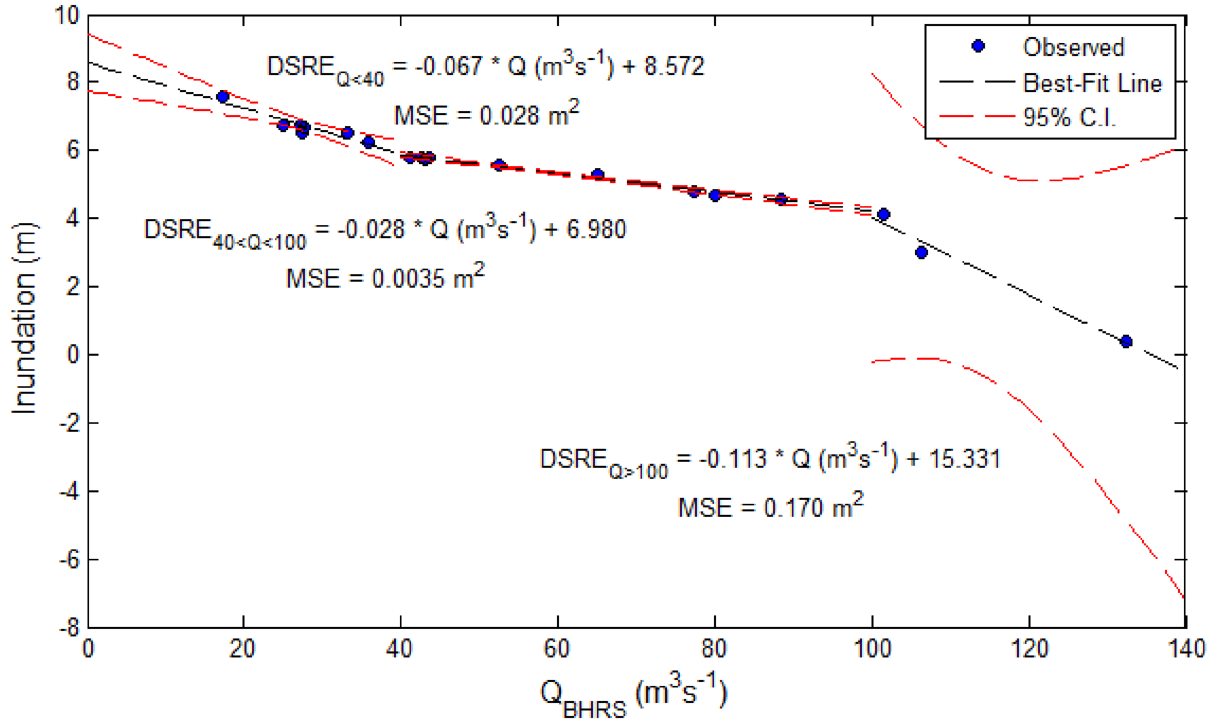

Figure 13: DSRE river discharge – inundation data.

Estimating Stage and Inundation Data

Estimating Stage and Slope

Once relationships were established between discharge, river stage, and river inundation, these relationships were used to estimate river conditions where there are no data (either prior to monitoring or during instrument failure) or to get at a finer temporal sampling scale (as with USG stage which is only measured at two week intervals). The Bureau of Reclamation has been recording Lucky Peak discharge values since the dam was erected in 1955, and New York Canal discharge since 1927. Discharge data from these time periods can now be used to estimate both river stage and river inundation at the BHRS for any (or all) of that time period. First, however, it is necessary to confirm the accuracy of the relationships developed above. To do this, we used the discharge relationships (equations 5 and 6) to estimate river stage for both USG and DSG locations based on discharge data, and compared the estimated stage to the observed values. Figure 14 shows the observed DSG transducer river stage elevation from 2009 to 2011 and the stage estimated from the rating curve relationship and discharge data alone. Also shown is a plot of the error, or difference between the observed and the estimated stage, and the 95% C.I. on the estimated data. From figure 14 we can see that the mean error is around 0 m with a range commonly less than 0.1 m. Much of the noise associated with the difference plot is due to noise in the reported discharge, which can fluctuate by as much as 0.3 m^3s^{-1} (10 ft^3s^{-1}) during "stable" time periods. This range can lead to an average error in predicted stage of near 0.06 m at high stage and 0.12 m at low stage. Figure 14 also shows that, on average, there is larger error associated with the Odyssey transducer measurements than with the Solinst measurements, which is consistent with their rated accuracies.

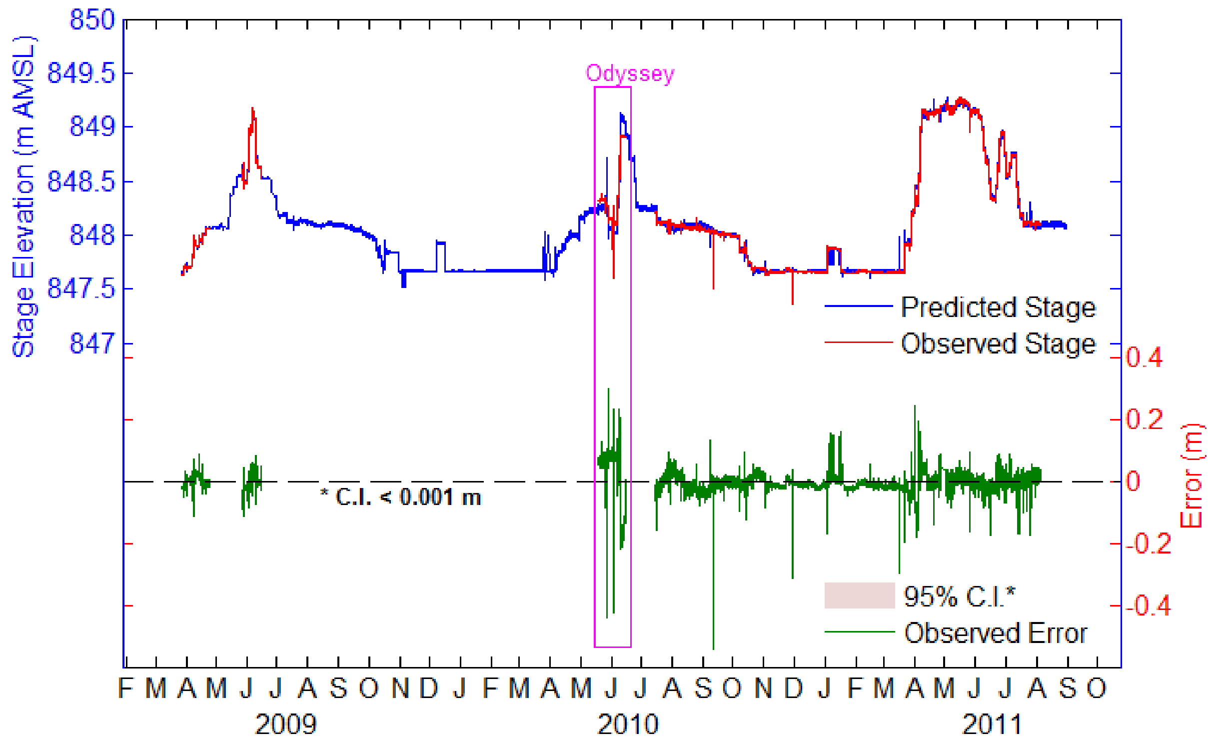

Figure 14: Estimated and observed DSG river stage from 2009 to 2011 for the times when DSG stage was recorded by either Odyssey or Solinst transducers. Also shown is the observed error (observed – predicted).

The same method applied to the DSG can be applied to the USG. Although the USG observed data are much more sparse, the product of this procedure is still very useful because it can be used not only to estimate the river stage elevation at the USG location for a continuous time period, as is shown in figure 15, but also to estimate the river slope between the USG and DSG locations (figure 16) and the river slope can potentially be used to estimate the river stage at any point along the BHRS river boundary. This method, however, assumes a constant linear slope along the river edge, which is not a correct assumption as visual observations indicate that the slope near the USG is slightly higher than at the DSG, especially at high river discharge. Based on the relationships developed for the USG and DSG rating curves, one would expect a similar relationship between the river slope and the discharge. This relationship was calculated using the same linear regression method as above and the results are shown in figure 17.

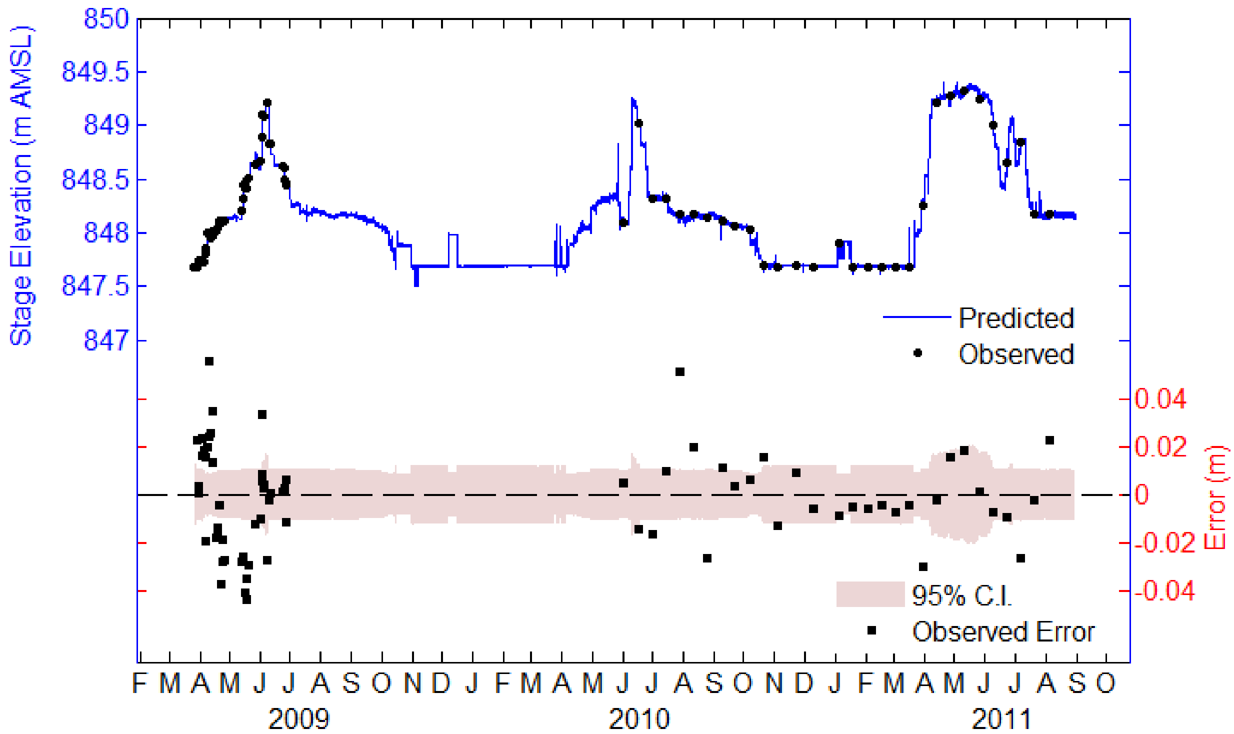

Figure 15: USG predicted and observed river stage from 2009 - 2011 along with the error. Note that errors for USG are about 10^{-1} that of DSG.

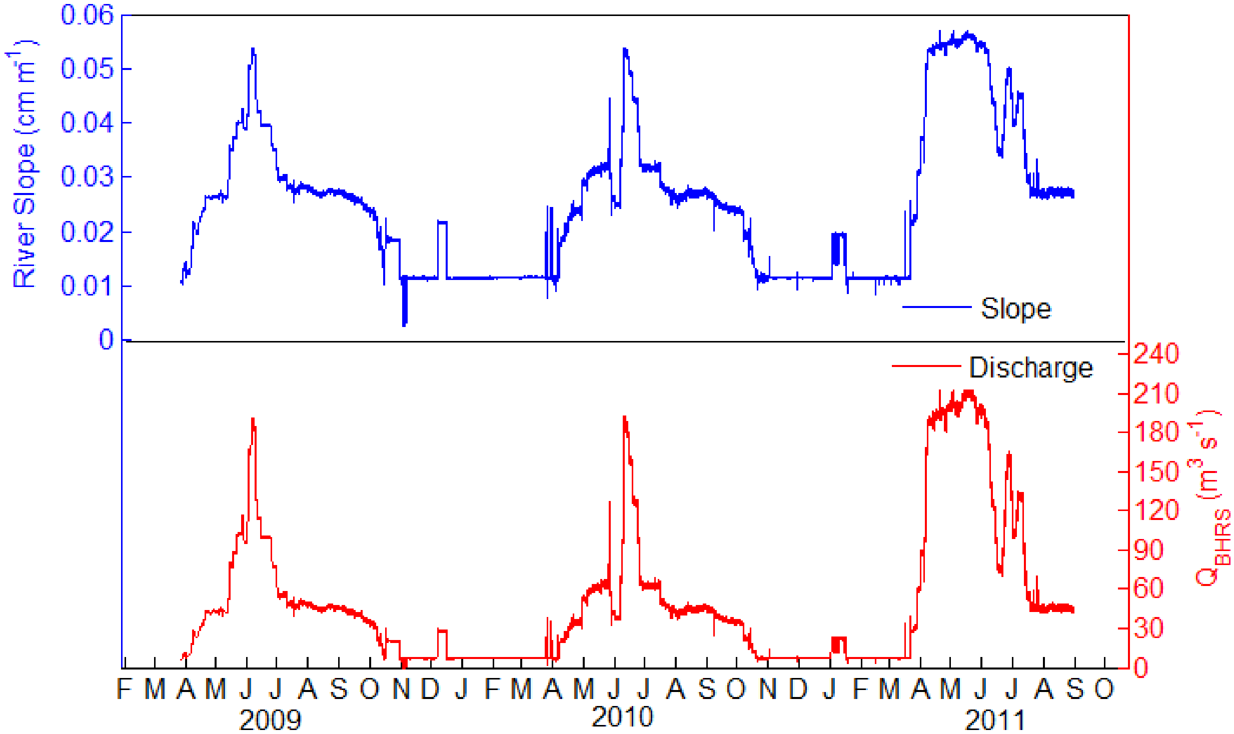

Figure 16: River slope (top) calculated from estimated USG and DSG stage values and Q_{BHRS} (bottom) for comparison.

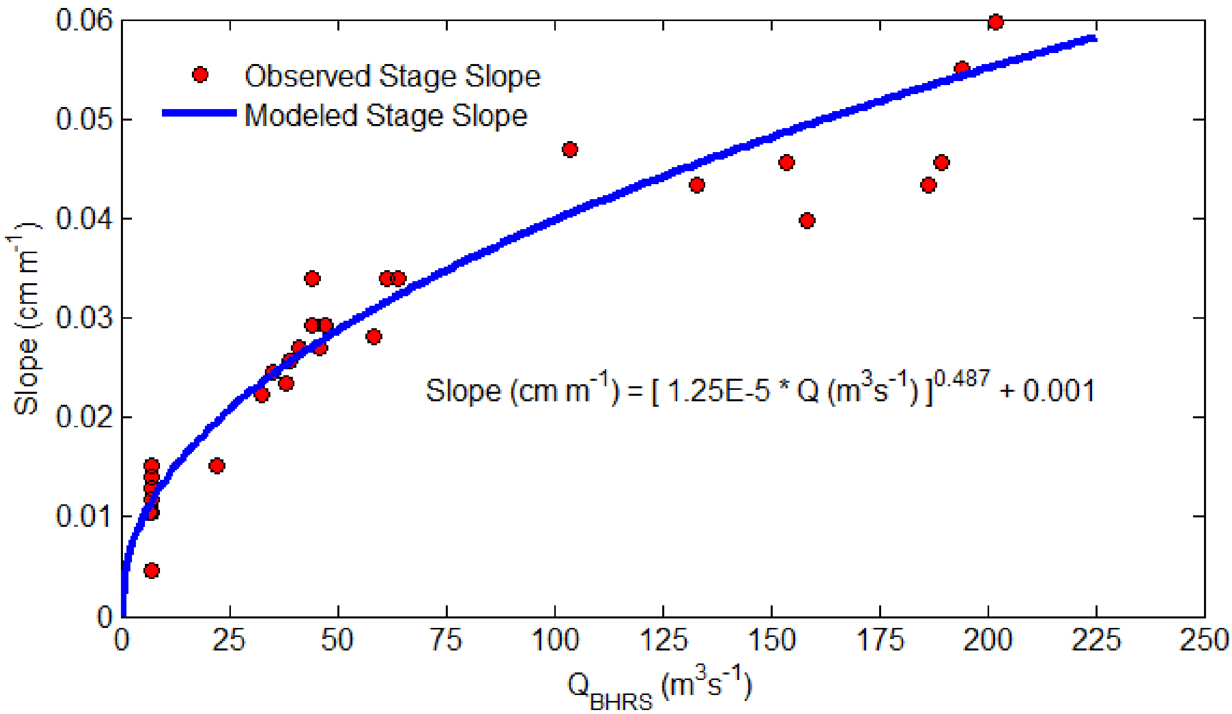

Figure 17: Discharge vs. slope relationship for the Boise River at the BHRS determined from modeled stage measurements at USG and DSG and slope estimates from observed stage data (visual records). This model assumes a linear slope between USG and DSG.

Estimating Bank Inundation

River inundation measurements are less accurate than river stage measurements (due mostly to inexactness in tape length over the ground, local river edge positions, and repeatability of bearing from reference point) but the same estimation process was applied to produce river edge estimates from 2009 – 2011 at a higher frequency than every two weeks (figures 18 – 22). These estimates can be used along with river stage estimates to more accurately model the interactions and mass exchanges between the Boise River and the aquifer at the BHRS given the changing vertical and lateral position of the river.

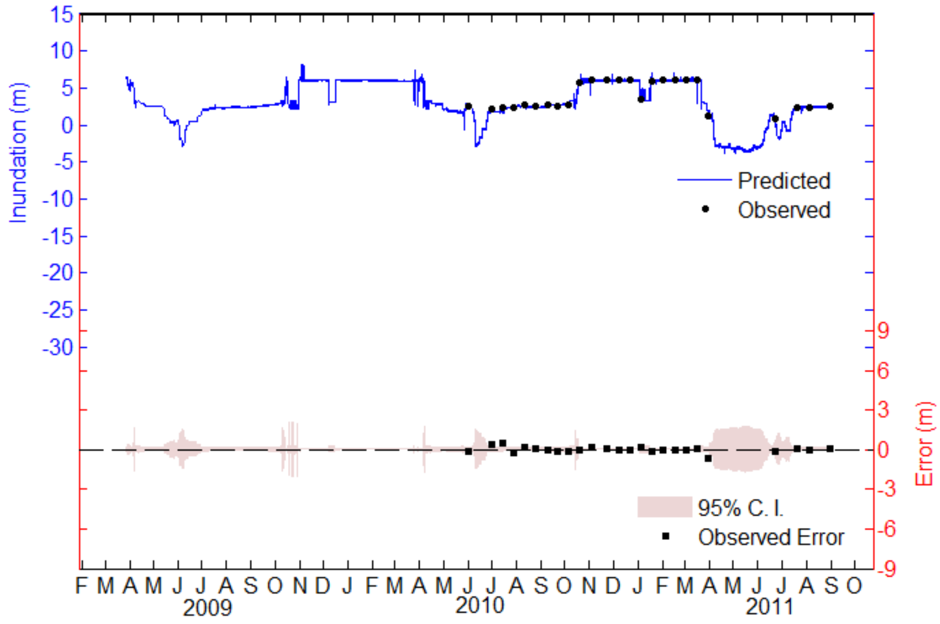

Figure 18: P4RE river inundation estimates compared to observed measurements and associated error.

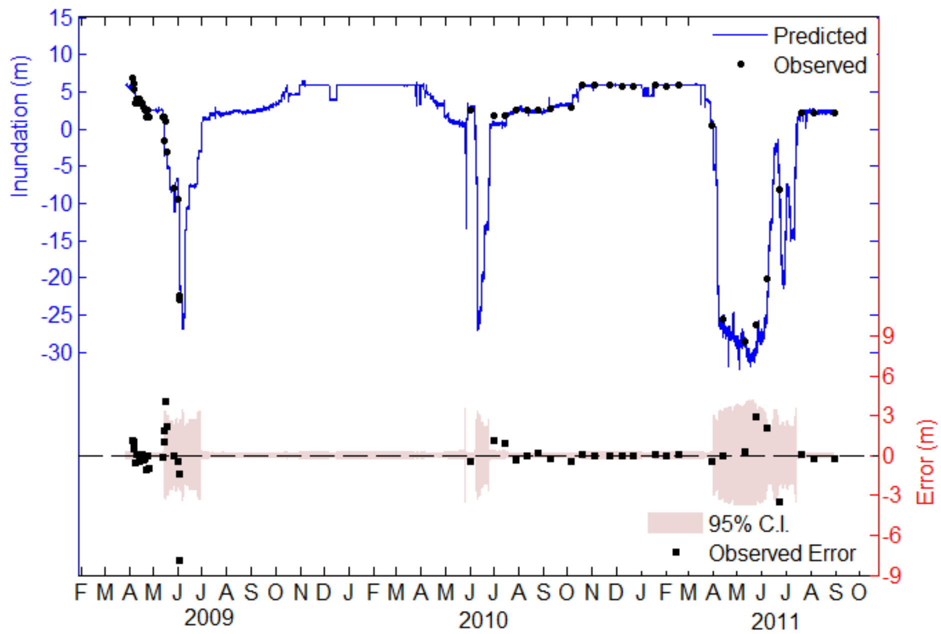

Figure 19: P5RE river inundation estimates compared to observed measurements and associated error.

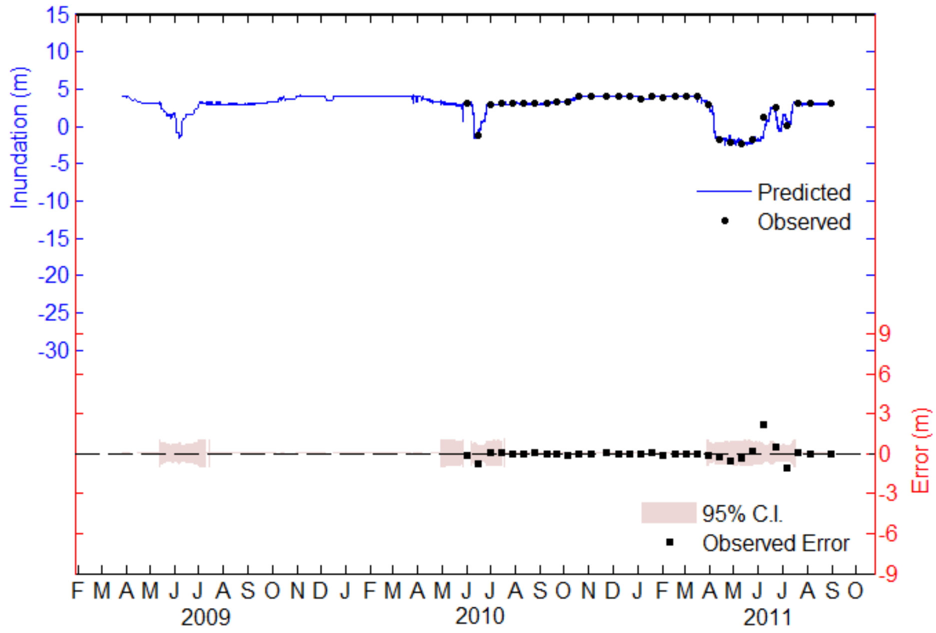

Figure 20: P6RE river inundation estimates compared to observed measurements and associated error.

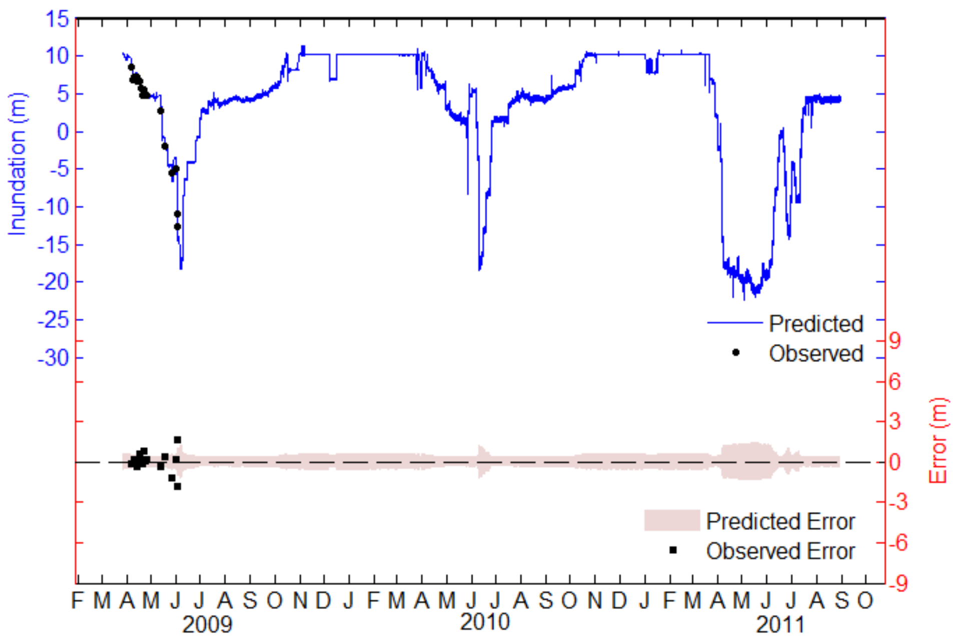

Figure 21: USRE river inundation estimates compared to observed measurements and associated error.

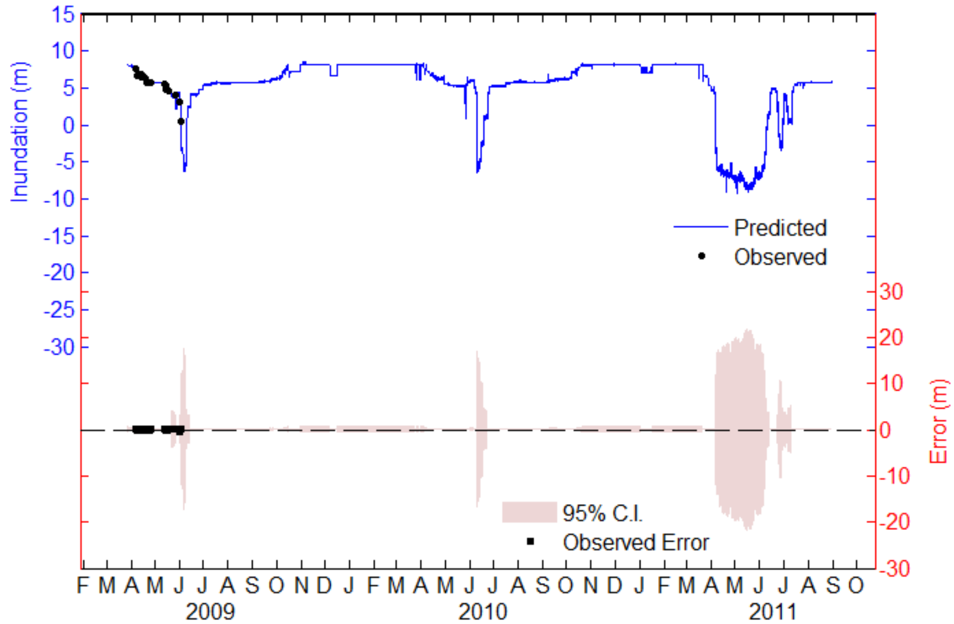

Figure 22: DSRE river inundation estimates compared to observed measurements and associated error.

Due to large errors in parameters of some of the best-fit lines of the discharge – inundation data, the errors in the estimated river edge measurements are also large, on the order of meters. Some error is attributed to a lack of data at certain discharge ranges, particularly when discharge values are near a break in slope of the best-fit lines. Some additional error in P4RE is due to a lack of observed high-flow inundation data. Visual observations indicate that, at high discharge, the entire upstream section of the BHRS is completely inundated and it is impossible to measure P4RE (figure 23). Due to this lack of data, the estimated inundation drastically under-predicts inundation and only reaches ~5 m. Figures 18 – 22 show river inundation estimated from discharge values since May 2009 at all five measurement locations. The bottom portion of each plot shows the difference between the predicted inundation and the observed inundation and also the 95% C.I. on the predicted measurements.

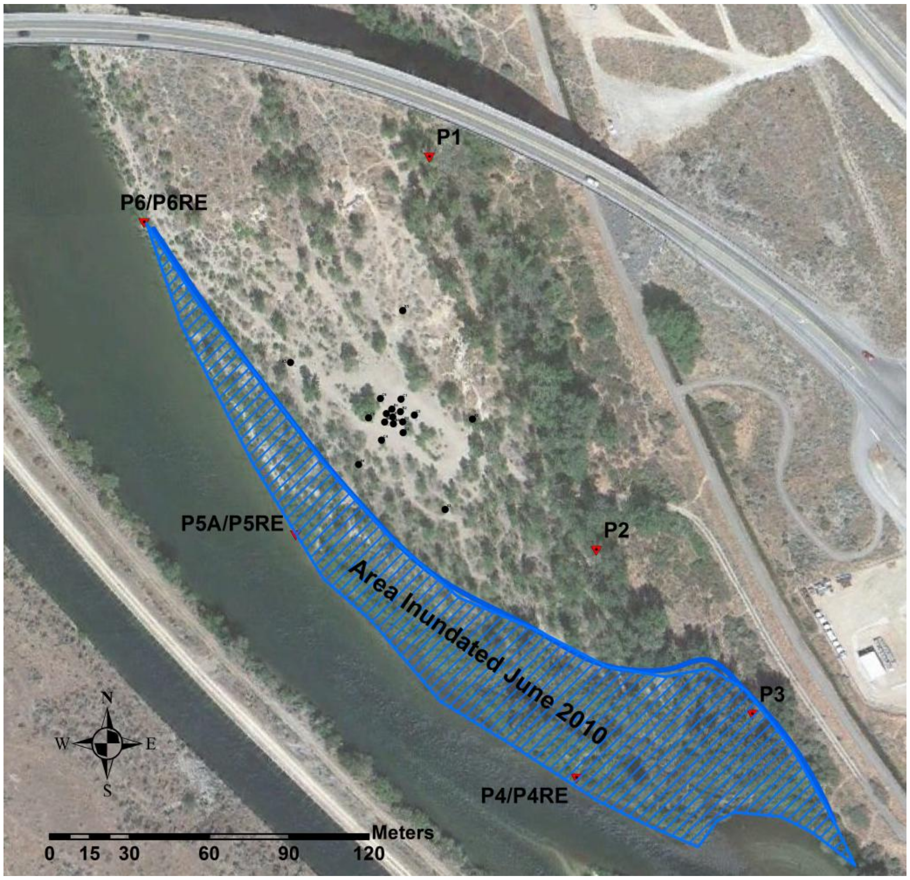

Figure 23: Measured river edge position on June 16, 2010 showing area of inundation

SUMMARY AND CONCLUSIONS

River discharge, river stage, and river bank inundation data have been used to develop empirical relationships relating these three hydrologic parameters. Rating curves for staff gauge locations both upstream and downstream of the BHRS were calculated and used to estimate river stage elevation and river slope for a continuous time period from May 2009 to August 2011. Estimated river stage values are commonly within 0.1 m of the observed data. River slope data assume a constant slope although the slope near USG is greater than the slope for the remainder of the reach. River bank inundation data were compared to discharge data to produce relationships for river edge position at five locations along the BHRS river boundary. These relationships were used to predict river edge position for the same period of May 2009 to August 2011. For most time periods estimated river edge show observed errors less than 2 m, but occasionally errors reach 4 m during periods of high river stage where measurements may be lacking. The data relationships developed in this report can be used for estimating river boundary conditions (stage and bank position) during aquifer tests, and can be incorporated into aquifer flow and transport models.

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