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Title: Evaluating Downstream Channel Changes in Response to a Small Dam Removal on the Calapooia River, Oregon with Respect to Measurement Errors and Prior Aerial Photo Observed Changes.

Abstract approved:

Desiree D. Tullos

The objective of this study was to evaluate the use of aerial photos as a substitute for multiple-year pre-removal field data to assess the downstream channel changes associated with a small dam removal. The Brownsville Dam, a 2.1 m tall concrete dam on the Calapooia River, Oregon, was removed in 2007. We surveyed cross sections below the dam during the summers prior to (2007) and follow (2008) removal, and we analyzed aerial photos from 1994 to 2006. The field surveys and aerial photos were used to map the low flow channel and bars over 1.3 km downstream from the dam and in an upstream control reach. Three types of measurement error (position error, identification error, and wetted boundary datum error) were assessed for the field surveys and aerial photos in order make the two methods of measurement more comparable. The first year after the dam removal, we observed changes in bar width, wetted width, and wetted width midpoint as large as 17 m ± 3 m immediately below the dam. We inferred that channel changes below the dam after removal were a result of the removal through comparison with pre-dam removal aerial photos, where changes up to 67 m ± 24 m were predominantly far from the dam, and an upstream control, where changes were only as large as 9 m ± 5 m. We conclude with suggestions of best practices for reducing errors, including establishment of permanent monuments for field surveys, taking measurements at similar, well-known discharges, and generating the highest-quality digital aerial photos through source and scanning choices.

Evaluating Downstream Channel Changes in Response to a Small Dam Removal on the Calapooia River, Oregon with Respect to Measurement Errors and Prior Aerial Photo Observed Changes

by
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APPROVED:

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Director of the Water Resources Graduate Program

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Cara Walter, Author

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1. Introduction

In the United States, 80 percent of dams will reach the end of their design life by 2020 (Evans et al., 2000). There are a myriad of problems associated with the aging of dams: reservoir sedimentation leading to reduced storage and flood control capacity, lack of compliance with fish passage requirements, impaired structural integrity, and increased maintenance (Evans et al., 2000; Heinz Center, 2002). While some of these problems may be addressed with repairs or maintenance, removal has become the favored option in many situations due to cost of repair and the increasingly negative public opinion of dams associated with affects on ecosystems (Doyle et al., 2003). In addition to contributing to a broader goal of habitat restoration, dam removal also provides a unique opportunity to study ecological and geomorphological processes (Bushaw-Newton et al., 2002; Doyle et al., 2003). However, the majority of the more than 450 dams removed in the last century, primarily small dams storing less than 123,000 m^3 of water, were relatively unstudied (Heinz Center, 2002; Stewart and Grant, 2005).

The general expectations for geomorphic outcomes in the reservoir and downstream after a dam removal have been established based upon studies of dam removals and geomorphic analogies, including landslides, incised channels, and sediment pulses in flumes (Doyle et al., 2002; Pizzuto, 2002; Stewart, 2006). Previous dam removal and sediment pulse studies have found that the extent of geomorphic changes associated with a small dam removal is limited both in time and space (Doyle et al., 2005; Pizzuto, 2002). It appears, from flume experiments, landslides, and dam removal studies in gravel-bed rivers, that dispersion is the dominate process influencing downstream deposition (Lisle et al., 2001; Stewart, 2006; Sutherland et al., 2002). In the limited areas affected by dam removal, studies have also found downstream deposition primarily on channel margins and in the thalweg (Stanley et al., 2002; Stewart, 2006). In the reservoir area, dam removal studies have found that modified channel evolution models are a good approximation of observed changes in reservoirs after the removal of dams (Ahearn and

Dahlgren, 2005; Cantelli et al., 2004; Doyle et al., 2002; Evans, 2007; MacBroom, 2005; Pizzuto, 2002). Reservoir erosion is typically initiated at the former dam site with a knickpoint which propagates upstream, and formation of an equilibrium channel in the reservoir can take upwards of a decade (Pizzuto, 2002). However, after the recent removal of the Marmot Dam on the Sandy River, a knickpoint migrated at least 400 m upstream and eroded possibly 15 % of reservoir sediments during the first flow event for which sediments were available to move (O'Connor et al., 2008).

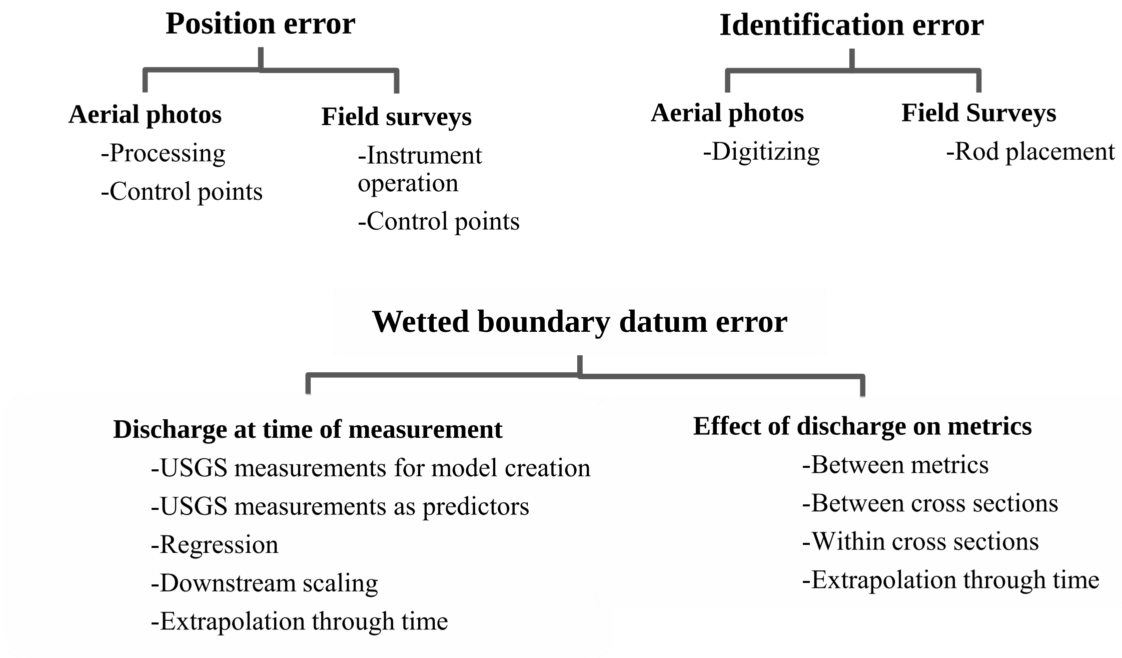
Geomorphological studies of events similar to dam removals, and those removal studies that have been performed, allow us to predict the trends and processes, but specifics will continue to elude scientists and managers until there is a greater body of research performed in a standardized fashion (Pizzuto, 2002). Unfortunately, the science of dam removal is evolving as a collection of uncoordinated case studies with usually no more than 1 year of data collected before removal (Bushaw-Newton et al., 2002; Doyle et al., 2005; Stewart and Grant, 2005). Rigorous studies of downstream deposition patterns within the context of previously observed changes have been largely absent. Error analysis of observations associated with channel change has also been missing (Mount and Louis, 2005). Without the qualifiers of natural variability, provided by multiple-year pre-removal data, and an estimate of measurement error, inferences regarding changes observed with a dam removal are challenged by a lack of appropriate context.

In this paper, we present methods for detecting and evaluating the physical effects of a small dam removal on the Calapooia River in Oregon within the context of natural variability and measurement error. The primary objective of this study was to evaluate the use of aerial photos as a substitute for multiple-year pre-removal field data to assess the downstream impact of a small dam removal. Multiple-year pre-removal data from analysis of aerial photos was used to evaluate changes in features (e.g. low flow channel, bars) following dam removal within the context of natural variability over time. We also evaluated the downstream effects of the dam removal relative to an upstream control using field surveys.

Metrics comparable between aerial photos and field surveys were restricted to those in planform, such as width, because extraction of depth from aerial photos was not possible for this study. We compared the width and location of the low flow wetted channel and exposed gravel bars, instead of the bankfull or active channel, because geomorphic changes as a result of the dam removal were expected to be small and because identification of bankfull boundaries in aerial photos is problematic (Mount and Lewis, 2005). Specifically, we calculated the changes in bar and wetted widths for cross sections, and the change in the wetted width midpoint for cross sections.

In order to compare measurements of channel changes using different techniques relative to a discharge dependent datum, we evaluated the measurement error associated with aerial photos and field surveys. We identified three components to error when representing and comparing natural features using topographic surveys or aerial photos: 1) position; 2) identification; and 3) wetted boundary datum (Figure 1) (Downward, 1995). Position error is a result of disparities between the coordinates used and the actual coordinates for a given location. Identification error is a result of sampling a continuous feature using discrete points. Wetted boundary datum error is due to comparing discharge dependent metrics between aerial photos or field surveys with different discharges. In this paper, we present our investigations of the reliability in analyzing and relative importance of these errors, and the subsequent limitations of using aerial photos and field surveys to assess the impacts of a small dam removal. Through inclusion of measurement error, we strove to reconcile possible differences between changes observed from aerial photos and field surveys as a result of the different measurement techniques.

Figure 1. Errors in the representation and comparison of topographic data.



2. Background

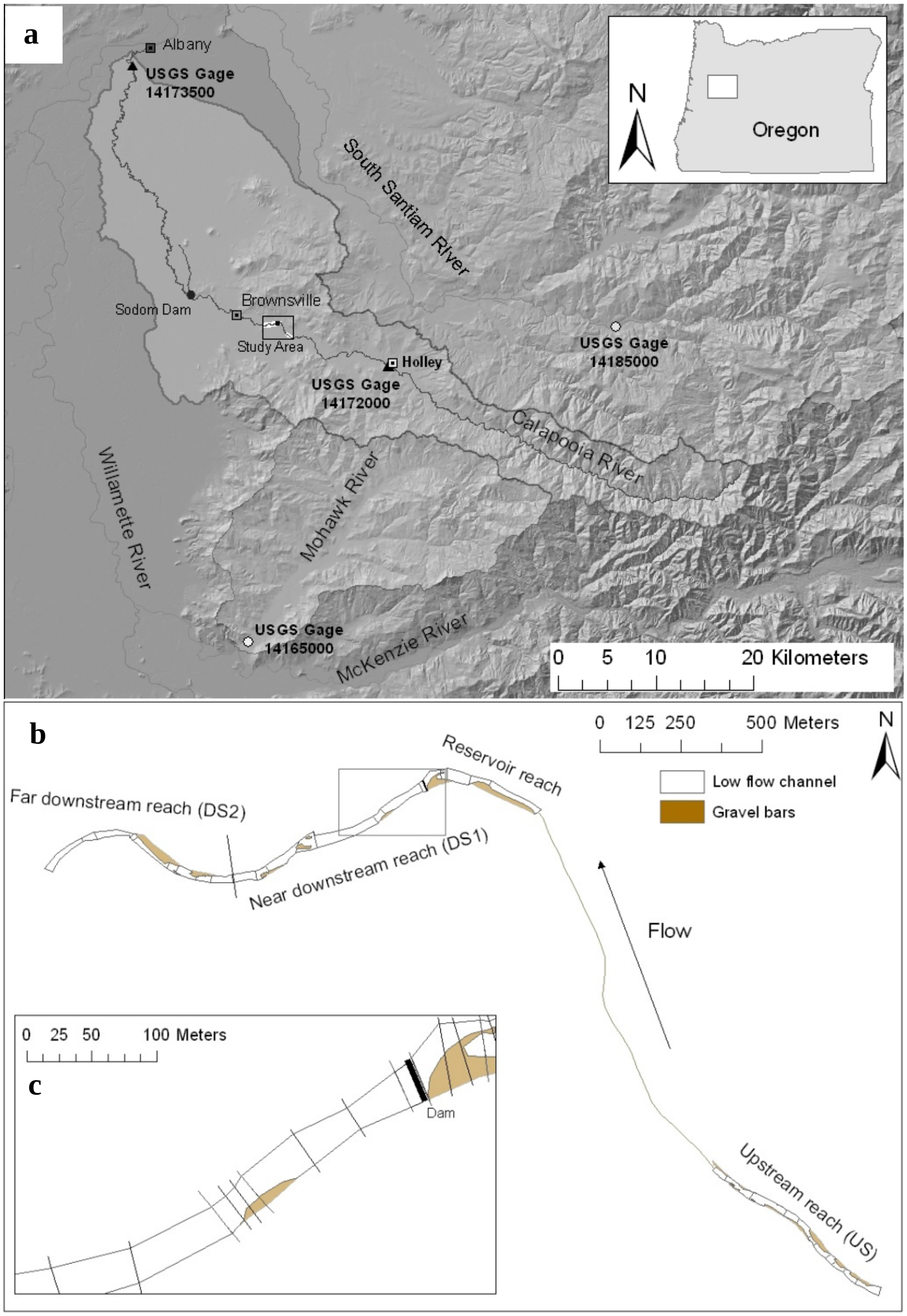
2.1 Geography of the Calapooia River Basin

The Calapooia River is a major tributary of the Willamette River in Oregon with a drainage area of 947 km^2 (Figure 2) (Runyon et al., 2004). It is a gravel-bed river that flows 121 kilometers from east to west starting at Tidbits Mountain in the Cascade Mountain Range and joining the Willamette River at Albany. The headwaters are in the Western Cascades, which consist of steep and highly dissected terrain of basalt and andesite (Sherrod and Smith, 2000). The upper portion of the watershed, from the headwaters to the town of Holley, is mostly private land managed for forestry (Runyon et al., 2004). In the middle portion of the watershed, from Holley to the Sodom Dam diversion downstream of the Brownsville Dam, the river is meandering and the valley opens into flat agricultural and rural residential lands. The peak flow of record at Holley was 357 cms on December 22, 1964 (Tippett, 1990).

2.2 Dam History, Location, and Demolition

The Brownsville Dam was located at river km 62 in the middle portion of the watershed about 4 km southeast of Brownsville. It was first built as a log crib dam in the late 1800s to divert water into the Brownsville Canal to bring water to a variety of mills (Runyon et al., 2004). The dam fell into disuse in the 1940s when the mills closed, and the dam failed during the 1964 flood (McCowan, 2007). It was rebuilt in the late 1960s as a concrete shell filled with sand and gravel to divert flow into the Brownsville Canal for aesthetic purposes. The dam was 33.5 m wide with a 4.3 m apron (Figure 3). The upstream height of the dam was increased from 2.4 to 4 meters using flashboards from the end of May to the beginning of October to enable diversion into the canal. During the summer, the ratio of reservoir width to channel width was 2.2, which reflects the wider reservoir section. The run-of-river reservoir was filled with sediment and stored approximately 14,000 m^3 of gravel ($D_{50} = 59$ mm). The river dropped 1.5-2.4 m from the downstream edge of the dam apron into a scour pool with large boulders placed against the dam to control scour under the sill (Runyon et al., 2004).

Figure 2. Location map of study reaches.
(a) Map of the Calapooia, South Santiam, and Mohawk Rivers within the Willamette Basin with the locations of current and former USGS gage locations. (b) Extent and layout of study reaches with 2007 bars and wetted channel broken into channel units. (c) Wetted channel and bars for part of the reservoir and immediately downstream showing cross sections.



The dam partially blocked the passage of spring Chinook, which are listed as threatened under the Endangered Species Act, winter steelhead, and other fish. The dam was also a safety hazard due to erosion under the sill on the downstream face of the dam (Runyon et al., 2004). The dam was removed with a jackhammer and excavator at the end of August 2007 in two stages (Martin, 2007). A 4.5 m section from the right, north, side of the dam was removed in the first stage. For the second stage, the river was diverted into the breach, and the remaining section was removed behind a coffer dam (Figure 3) (Martin, 2007).

Figure 3. Brownsville Dam from the north abutment after the first stage of removal. Photo courtesy of John D. Martin, Cascade Earth Sciences

2.3 Study Area

The study area consisted of four reaches (Figure 2). Two consecutive 0.67 km (20 times active channel width) reaches were established downstream from the dam, and one control reach was established 1.6 km upstream from the reservoir. A fourth, 0.4 km-long reach was defined within the reservoir that terminated at the first riffle upstream of the dam. Each of the four study reaches was divided into four types of channel units: riffles, pools, glides and runs (Figure 2). The slower flow channel units were defined as pools or glides. Pools were deeper with clear boundaries of the head and tail (Kershner et al., 2004). Glides had moderately shallow and tranquil flow (Nielsen and Johnson, 1983). The faster flow channel units were defined as riffles or runs. Shallow and turbulent stream units with gradients higher than pools or glides were riffles (Nielsen and Johnson, 1983). Runs were moderate gradient and average depth units that occurred downstream of riffles.

Prior to the dam removal, the first 400 meters downstream from the dam in the first downstream reach (DS1), was a straight, plane-bed channel with exposed bedrock/hardpan and few small bars (Table 1). In the second downstream reach (DS2), the river became wider and more open with large, alternating gravel bars. DS2 had secondary channels up to 100 m from the main channel, and transitioned to a braided channel downstream of DS2. The upstream control reach was narrower than both downstream reaches with an even distribution of channel units, long lateral bars, and no side channels.

Table 1. Reach attributes for the study area prior to dam removal (2007).
The “active channel” width is the combined width of the low flow wetted channel and bare or sparsely vegetated bars (O'Connor et al., 2003; Rappe and Abbe, 2003).

Reach	Active Channel Width (m)	Slope (%)	Sinuosity	Channel Units	D_{50} (mm)
DS1	31	0.3	1.0	1 pool, 3 riffles, 3 runs	6
DS2	38	0.2	1.2	4 pools, 2 riffles, 2 glides, 1 run	26
US	22	0.1	1.0	3 pools, 3 riffles, 3 glides, 2 runs	23

3. Methods

3.1 Field Surveys and Aerial Photography: Data Collection and Processing

The stream channel was surveyed during the summer of 2007, prior to the removal of Brownsville Dam, and during the summer of 2008, one year following dam removal. Within each channel unit of each reach, we surveyed four evenly-spaced cross sections (Figure 2). The bottom cross section of each channel unit was the same as the top cross section of the downstream adjacent channel unit. Within each cross section, points were surveyed at obvious slope breaks using a Nikon DTM-352 Total Station and prism. In addition to the cross sections, the thalweg of the wetted channel, and the boundaries and slope breaks of bars were surveyed. From each field survey, polygons were created for the bars and wetted channel of each channel unit and mapped in Environmental Systems Research Institute (ESRI)® ArcMap™ 9.2 in US feet in the Oregon North State Plane projection, North American Datum 83 (ESRI, 1999-2006).

In addition to the field pre-removal data, we performed an analysis of recent (1994-2006) aerial photography (see Table 2 and Section 3.4 for details). The photos from 1994, 1995, 1998, 2003, 2004, and 2006 were orthorectified with the Camera model in the Image Analysis™ for ArcGIS extension (Leica Geosystems Geospatial Imaging, 2007). We used bilinear pixel resampling during and after orthorectification to transfer pixel values from the original image to the orthorectified image, which was necessary due to warping of pixels during orthorectification and changing cell sizes after orthorectification (Hughes et al., 2006). The 1996, spring 2000, and 2005 photos were flown, scanned and aerotriangulated using stereo pairs and GPS located targets for Linn County GIS. The summer 2000 photo was processed as a Digital Ortho Quarter Quad (DOQQ) by the Oregon Geospatial Enterprise Office.

The wetted channel, backwaters and bars for the two downstream reaches and the upstream reach were delineated at a consistent scale from the aerial photos. Bars were defined in the photos as areas adjacent to the wetted channel that were bare or sparsely vegetated. Widths from surveyed and photo-mapped cross sections were calculated using the Identity tool in Analysis in ArcMap™ along consistent transects established from the 2007 field survey edges of water for cross sections (ESRI, 1999-2006).

Table 2. Summary of aerial photography sources, attributes, and processing.

Source	Scale/ Pixel Size	Type	Dates Flown	Comments
1994 National Aerial Photography Program (NAPP) (Available at the University of Oregon Map Library, Eugene, OR)	1:40,000/ 0.6 m	B&W	5/24/94	Scanned from contact print and orthorectified.
1995 NAPP (Available from the Earth Resources Observation Systems (EROS) Data Center (EDC), Sioux Falls, SD)	1:40,000/ 0.6 m	B&W	6/29/95	Scanned from contact print by EDC. Orthorectified by authors.
1996 Linn County, OR digital orthophotos (Available from Linn County GIS, Albany, OR)	1:20,000/ 0.3 m	B&W	4/30/96	Scanned and aerotriangulated by 3DiWest
1998 Linn County, OR (Available from WAC Corp, Eugene, OR)	1:24,000/ 0.6 m	Color	8/10/98	Scanned from contact print and orthorectified.
2000 Brownsville DOQQ (Available from Oregon Geospatial Enterprise Office, Salem, OR)	1:40,000/ 1.0 m	B&W	7/24/00	Processed by Oregon Geospatial Enterprise Office from NAPP photos.
2003 National Agricultural Imagery Program (NAIP) (Available from the Aerial Photography Field Office (APFO))	1:40,000/ 0.6 m	Color	6/26/03	Scanned from contact print and orthorectified.
2003 NAIP (Available from the APFO)	1:40,000/ 0.6 m	Color	6/20/04	Scanned from contact print and orthorectified.
2005 Linn County, OR digital orthophotos (Available from Linn County GIS, Albany, OR)	1:20,000/ 0.3 m	Color	7/3/05	Scanned and aerotriangulated by Mapcon Mapping
2006 NAIP (Available from the APFO)	1:40,000/ 0.6 m	Color	6/23/06	Scanned from contact print and orthorectified.
2000 Linn County, OR (Available from Linn County GIS, Albany, OR)[a]	1:20,000/ 0.3 m	B&W	4/1/00	Scanned and aerotriangulated by 3DiWest

[a] This photo was only used for wetted boundary datum error validation.

Because we compared wetted channel-based measurements between aerial photos and field surveys that were taken at different discharges, we introduced boundary datum error. To account for the error associated with different discharges, we estimated the average change in wetted width with discharge at a cross section within each reach (see Section 3.4.3). Further, we used the photo taken in spring, April 1st, of 2000 to validate the wetted boundary datum error (see Table 2 and Section 3.4.3 for details).

3.2 Analysis of Channel Changes

Changes in bar width, wetted width, and wetted width midpoint observed from both the field surveys of the upstream control reach, and the aerial photos of the downstream reaches were used to provide context for the changes observed in the downstream reaches using field surveys associated with the dam removal. The three metrics were relevant to changes previously observed downstream from a dam removal: channel widening occurred at other sites due to deposition on the channel margins and in the thalweg, and lateral migration was observed with the creation of alternating bars (Stanley et al., 2002; Stewart, 2006). In addition, all three metrics reflect changes in the active channel, the portion of the channel regularly scoured by flows (O'Connor et al., 2003; Rappe and Abbe, 2003).

We used the changes observed in the downstream reaches using the aerial photos as a control for the changes observed in the downstream reaches using the field surveys associated with the dam removal. We compared the magnitude and location of changes in bar width, wetted width, and wetted width midpoint between the aerial photos and field surveys for the downstream reaches. Using the changes observed from the aerial photos as a control for the changes observed from the field surveys, one of the important differences between the two sets of data was the peak flow between measurements (e.g. photos and surveys). It is well-recognized that high flow events drive channel change through the movement of sediment (Ham and Church, 2000). Thus, we evaluated observed changes relative to the peak discharge between measurements to account for discharge-related differences in the changes in bar width, wetted width, and wetted width midpoint at a cross section between the field surveys and aerial photos. We were thus able to evaluate the possibility of the field survey changes in the downstream reaches being due to the dam removal with respect to the previous extent and magnitude of changes.

We also analyzed the changes observed in the downstream reaches with the field surveys relative to the changes observed in an upstream control reach with the field surveys during the same time period. As a study control, the upstream reach should experience and respond similarly to the same basin conditions as the downstream reaches in the absence of the dam removal (Bushaw-Newton et al., 2002). The upstream reach was picked for its proximity, accessibility, and relative similarity to the downstream reaches. We expected there to be few differences in the conditions and responses for the upstream reach and downstream reaches. If the reaches were similar, differences between the changes observed in the downstream reaches and upstream reaches using the field surveys (pre-removal in 2007, post-removal in 2008) could indicate a dam removal effect. However, there could also be inherent differences between the upstream and downstream reaches unrelated to the dam. Thus, we also analyzed the aerial photos to assess differences not related to the dam removal between the upstream and downstream reaches.

Both controls had errors of different magnitude than the field survey measurements for the downstream reaches, either due to location or measurement technique. Lack of inclusion of measurement errors could result in misleading results by over or under estimating differences. Therefore, we evaluated all changes relative to their measurement errors to express uncertainty in observations.

3.3 Discharge Extrapolation

We used linear regression to generate annual peak flows and average daily flows for our channel change and error analyses. No published record of discharge exists for the period of aerial photo and field survey analysis, 1994-2008, on the Calapooia River. The USGS gage at Albany (#14173500) ceased operation in 1980, and the USGS gage at Holley (#14172000), 16 km upstream from the dam, ceased operation in 1990 (Figure 2). Two nearby USGS gages on the South Santiam (#14185000) and Mohawk Rivers

(#14165000) were chosen to create regression models for the average daily and annual peak discharges at Holley (Table 3). The USGS gages on these two rivers were selected based on the following criteria: 1) within 40 km of the Holley gage; 2) a drainage area between 250 and 460 square km; 3) operational for at least 25 years concurrently with the Holley gage and from 1994 to the present; and 4) with similar hydrogeology, identified as rivers draining the Western Cascade Mountain Range (Tague and Grant, 2004). The gages were evaluated for a statistically significant relationship with the average daily low flow and annual peak flows from the Holley gage from 1963 to 1990.

Table 3. USGS and other discharge gaging stations on the Calapooia, South Santiam, and Mohawk Rivers.

Site Number	Station Name	Drainage Area (km^2)	Time Period Operational
USGS 14165000	Mohawk River near Springfield, OR	458	9/1/1935 - 9/30/1952[a], 10/1/1963 – 9/30/97 10/1/98 - Present
USGS 14185000	South Santiam River below Cascadia, OR	451	9/1/1935 - Present
USGS 14172000	Calapooia River at Holley, OR	272	10/1/1935 –10/6/63[a] 10/7/63- 9/30/1990
USGS 14173500	Calapooia River at Albany, OR	963	10/1/1940 - 12/10/1981
OSU gaging station	Calapooia River at Brownsville, OR	403	9/29/2007 - Present

[a]: Non-recording gage for this time period (Tippett, 1990; U. S. Geological Survey, 2008a)

To evaluate the current relationships between the Calapooia River and Mohawk and South Santiam River, stage for the Calapooia River was measured 4.6 km downstream from the dam using an in-stream Stevens PS 600 vented pressure transducer. The pressure transducer was installed on the side of a concrete slab, part of a former bridge. Starting September 29, 2007, water heights for the Calapooia River were measured every 15 minutes. Discharge measurements were taken according to USGS standard methods from the Brownsville Bridge using a crane for higher flows (Rantz and others, 1982). Discharge measurements for lower flows were taken using a top-setting wading rod at the site of the gaging station (Rantz and others, 1982). A total of 18 discharge measurements were used to create a rating curve for low flows and for high flows.

3.3.1 Annual Peak Flow

The coincident annual peak flows from 1963 to 1990 for the Holley, Mohawk, and South Santiam gages were used to create a multiple linear regression model[1] for the peak annual flow at the Holley gage. The model predictions were compared with measurements between 1988 and 1990, at Holley, and during the 2008 water year, at Brownsville Bridge, for the highest flow on the South Santiam and Mohawk from each storm that was not the annual peak for validation of the model. For the 2008 validation, we scaled the discharge measured at Brownville Bridge to be more comparable to the discharge predicted at Holley by multiplying the discharge at Brownsville Bridge by the ratio of the drainage areas of the two locations: 272 km^2/403 km^2. The peak discharge values predicted for 1994 to 2008 at Holley were not scaled to the study area because the peak discharges between measurements were used relative to each other and not as absolute values.

3.3.2 Flows during Measurements: Photos and Field Surveys

A simple linear regression model was developed between average daily flow at the Holley gage on the Calapooia River, and average daily data flow at the South Santiam River USGS gage using low flow data from 1963 to 1988[2]. The Mohawk gage was not used for the analysis of average daily low flows because it was not operational during the 1998 water year. The model-predicted flows for the summers of 1989, 1990, and 2008

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[1] $\ln(\hat{Q}_H / DA_H) = b_1 \ln(Q_M / DA_M) + b_2 \ln(Q_{SS} / DA_{SS}) + a$

[2] $\ln(\hat{Q}_H) = b_1 \ln(Q_{SS}) + a$

where Q_H is discharge on the Calapooia River at Holley, Q_M is discharge on the Mohawk River near Springfield, Q_{SS} is discharge on the South Santiam River below Cascadia, and DA is drainage area.

were compared to the measured flows on the Calapooia from the former USGS gage at Holley, during the 1989 and 1990 summers, and the average daily flow from our gage on the Calapooia at Brownsville during the 2008 summer for validation of the model. Consumptive use water rights, obtained from the Oregon Water Resource Department, were subtracted from the predicted average daily flow during the summer at Holley to scale flows for our discharge measurements at Brownsville for the 2008 validation. The average daily flow for all photo days and field survey days, except for 1996 and spring 2000, were predicted with the same simple linear regression model and South Santiam average daily discharge data from 1994-2008.

The 1996 and spring 2000 photos were taken during higher flows during the recession limb of spring storms in this snow-melt hydrologic regime. Thus, a different model was used to reflect the difference in the relationship between the spring runoff hydrographs and the summer low flow hydrographs between these three rivers[1]. The input data for the spring model included the average daily flows for the recession limbs of storms from January to May, 1964 to 1988 for the Calapooia River at Holley, the Mohawk River, and the South Santiam River. Multiple linear regression was performed on the natural log of the discharge divided by drainage area, similar to the annual peak flow extrapolation. The photo day flows, as well as the recession limbs of storms during 1989, 1990, and 2008 for validation, were then predicted using South Santiam and Mohawk average daily discharge data from 1994-2008. For the 2008 validation, we scaled the discharge measured at Brownville Bridge to be more comparable to the discharge predicted at Holley by multiplying the discharge at Brownsville Bridge by the ratio of the drainage areas of the two locations: 272 km^2/403 km^2.

3.4 Error Analysis

3.4.1 Position Errors

For the field surveys, we documented two parts of the position error: 1) initial control point coordinates for consistent location comparison with aerial photos; and 2) instrument operation for consistent coordinates between the field surveys. The position error assessment for the field surveys was different for the upstream reach and the downstream reaches. The two regions, upstream and downstream, had different sets of controls due to their physical separation. Surveying with a total station requires two control points: a base to set the coordinate datum, and a backsight to set the horizontal angle datum. The 2007 field surveys were located relative to the aerial photos by incorporating two control points, a base and a backsight, for the two distinct portions of the study area, downstream reaches and the upstream control reach, with GPS coordinates acquired with a Topcon HiPer® Lite + GPS base station and corrected using OPUS-RS (National Geodetic Survey, 2008).

For the downstream reaches in 2008, initial controls were located relative to the 2007 controls using a consistent base control, and a new GPS-acquired backsight control. Due to the consistent base control between surveys for the downstream reaches, the position error for the comparison of field survey data was not a direct function of the error in the GPS position of the control points. Instead, the error in coordinates for the downstream reaches was from the difference in horizontal angle datum due to error in the different initial backsight controls for 2007 and 2008, and the accuracy of station coordinates due to instrument operation throughout the reaches. Four monuments, aside from the initial control, were present in the downstream reaches during both the field surveys in 2007 and 2008. For those four stations, ranging from 340 to 730 m downstream from the control at the dam, the initial coordinates from the 2007 survey were compared to the coordinates from re-occupation in 2008. Both components (initial horizontal angle datum and instrument operation) of position error were included in the position error estimate based on error estimates from the four station re-occupations.

For the upstream reach, all control monuments from 2007 were missing in 2008, so new base and backsight controls were established in 2008 using GPS. Since no control re-occupation was possible for the upstream reach, the error due to station operation was assumed to be the same as for the downstream reaches. The lateral shift in coordinates for cross sections due to errors in the initial horizontal angles of both field surveys of the upstream reach was estimated at three cross sections, predominantly of bedrock, surveyed at consistent locations for both 2007 and 2008. For each of the three cross sections, we compared the coordinates for both the two left edges of water, and the two right edges of water between the two surveys relative to any difference in wetted width.

Instrument operation was also relevant to coordinate consistency within cross sections. We used backsight checks at individual stations to assess position error for points within the same cross section. A backsight check records the change in horizontal angle datum over the time a station is occupied. To estimate the average displacement due to the angle difference, we multiplied the angle difference from each backsight check by the average distance measured from the station.

A final component of position error for the field surveys was the precision of the total station used. The same operators and instrument were used for both surveys, and instrument precision is usually very small relative to the other errors (Downward, 1995). Therefore, we did not factor the precision of the instrument[3] into our analysis.

Position error was more relevant to our ability to survey the same locations for cross sections in both 2007 and 2008 for the downstream reaches than the upstream reach. Few of the cross section markers from 2007 were present in 2008 for the downstream reach. Cross section re-location was achieved for the downstream reaches using the edge of water coordinates from 2007. For cross sections in the upstream reach, many of the cross section markers from 2007 were present in 2008. To relocate cross sections without markers for the upstream reach, the 2007 longitudinal distances between the edges of water of cross sections were used.

For aerial photos, the position error was a combination of the error in the inputs, and the error in the orthorectification process. Orthorectification was used to assign coordinates and create a consistent scale across each photo (Hughes et al., 2006). There were three inputs for the orthorectification process we used: (1) exterior camera orientation, (2) interior camera orientation, and (3) a digital elevation model (DEM). The exterior camera orientation was established using ground control points (GCPs). We used building corners visible on the photos as GCPs. We obtained coordinates for these GCPs with a Topcon HiPer® Lite + GPS base station and corrected using OPUS-RS or

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[3] Nikon DTM 352 has a dual-axis ± 3’ tilt compensator, and a precision of ± (10 + 5 parts per million x distance) mm in normal mode (Tripod Data Systems, 2008).

Topcon Tools (National Geodetic Survey, 2008; Topcon Positioning Systems, 2007). Interior camera orientation parameters (camera type, focal length, principal point location, and fiducial mark locations) were obtained from USGS camera calibration reports for the specific cameras used for the photos. We made a mosaic of USGS 10 m DEMs from 2001 for quadrangles in the Calapooia Basin, and used the combined DEMs for the elevation underlying the aerial photos. The overall position error for each photo was assessed as the Root Mean Square Error (RMSE) of the ground control points used for the orthorectification, plus the error in the coordinates of the GCPs. For the photos processed by 3Di West (1996 and spring 2000), Oregon Geospatial Enterprise Office (summer 2000), or Mapcon Mapping (2005), the GCPs used for the error analysis were the two GCPs closest to the river.

3.4.2 Identification Errors

For the field surveys, errors in identification of the wetted boundary by the rod operator were estimated by repeated surveys. For the repeated surveys, the same rod operator surveyed the top cross section for each channel unit twice in both the 2007 and 2008 surveys. The identification error for the wetted width at a cross section was calculated as the difference in wetted widths for each repeat cross section for both years. The identification error for the bar width and wetted width midpoint at a cross section was assumed to be the same as the identification error for the wetted width at a cross section. The identification errors from each repeat cross section were averaged for each reach, and the average of each reach was applied to all the cross sections within each reach.

Errors in identifying features from the aerial photos were due to indistinct feature (e.g. channel, bar) boundaries for the feature itself, shadows, the cell size of the digital version of the photo, and the warping and pixel resampling of features during the processing of the photos. The error associated with identifying feature boundaries was estimated by repeatedly, 20 times, digitizing one channel unit for each reach in the 2006 photo, representing the photo with the least distinct boundaries (Downward, 1995; Downward et al., 1994; Van Steeter and Pitlick, 1998). The channel units selected for redigitizing were representative worst case scenarios, in terms of shadows and boundary clarity, and because of the presence of mid channel bars and/or lateral bars. The channel unit repeat digitized for US did not have mid channel bars because no mid-channel bars were visible for US for any of the aerial photos. From each iteration for each channel unit, we measured the wetted widths, bar widths, and wetted width midpoints at the 4 cross sections within the channel unit. The identification error was estimated as the RMSE of the wetted widths, bar widths, and the wetted width midpoints at the 4 cross sections from the digitizing iterations relative to the wetted widths, bar widths, and the wetted width midpoints at the 4 cross sections calculated from the original digitizing of the channel unit. The identification error from the four cross sections in each channel unit were averaged for each channel unit, and applied to all the cross sections within the same reach.

3.4.3 Wetted Boundary Datum Errors

All three response metrics (wetted width, bar width, and wetted width midpoint) were analyzed relative to the wetted boundary at the time of measurement. Average daily discharge was the common datum to ensure an equitable comparison of the measurements between years. Therefore, there were two components to the wetted boundary datum error calculation: estimation of average daily discharge for each aerial photo or field survey measurement, and estimation of the change in metrics associated with different discharges for consecutive measurements (Figure 1).

There was error inherent in the predictions of average daily discharge due to: 1) error in the discharge values used to create the linear models; 2) error in the discharge values used in the linear models to predict new discharge values; 3) error in using linear regression to predict new values; 4) error in using predictions upstream of the study area; and 5) error in using predictions based upon a model created with data from at least 7 to 21 years before the date of interest. USGS average daily discharges used to create the regression models and make predictions were assumed to have at least an accuracy of ± 15 % based upon the accuracy of the average daily discharges for the South Santiam gage from 2002-2008 (Herrett et al., 2005; U.S. Geological Survey, 2008b; U.S. Geological

Survey, 2008c). Additional linear models were created from error adjusted discharges, ± 15 % of the original value, for the Calapooia, South Santiam, and Mohawk Rivers from 1963-1988. The resulting model terms were compared to the original model terms to calculate the uncertainty (as a percent) in predicted discharges. Similarly, additional predictions for the average daily discharge on photo days and survey days were calculated with error adjusted discharges, ± 15 % of the original value, for the South Santiam and Mohawk Rivers from 1994-2008. The resulting error adjusted predictions were compared to the original predictions to calculate the uncertainty (as a percent) in the predicted discharges.

The error in predicting values of average daily flows using linear regression was assessed by comparing data from the USGS gage on the Calapooia River at Holley from 1988-1990 to values predicted using the linear models and South Santiam and Mohawk River USGS discharge data (see Section 3.3). The RMSE from the 1988-1990 comparison of measured and predicted discharges, as well as the uncertainty from the variability in the USGS measurements, was added to the difference in discharge calculated for each pair of photos or field surveys to estimate the largest difference in flow. The maximum flow difference between photos or field surveys was used to calculate the wetted boundary datum error. The comparison of measured and predicted discharges from the 2008 water year was used (a) to qualitatively assess the current relationship between the rivers, and (b) to scale discharge with distance. Any errors associated with our discharge gaging or provisional USGS data from the 2008 water year were not quantitatively assessed.

The second component of the wetted boundary datum error calculation consisted of relating changes in discharge to changes in the wetted width using the 2007 field data. We used WinXSPro (Stream Systems Technology Center, 2005) to calculate the wetted width and discharge for the 2007 field survey data for each cross section at 0.03 m increments of stage over the range of discharge values predicted for the field surveys and aerial photos. We divided the change in width by change in discharge for the calculated values from each consecutive 0.03 m stage increment, and averaged the results for each cross section and over each reach. To estimate the difference in wetted width over the difference in discharge estimated for each aerial photo or field survey comparison, we multiplied the predicted maximum difference in discharge (estimated difference in discharge plus error in discharge estimates) by the calculated average change in width per change in discharge for each reach.

For the field surveys, the wetted boundary datum error was calculated and applied for each cross section comparison. Cross sections were surveyed over multiple days both years, and did not have consistent differences in average daily discharge at the time of measurement. The wetted boundary datum error was calculated for each photo comparison for each reach. We assumed (a) a linear relationship between wetted width and discharge at a cross section over the range of flows observed for the aerial photos and field surveys, and (b) comparability across time and space for the change in wetted width to change in discharge ratio. In addition, the estimate of wetted boundary datum error for the changes in wetted width for each photo or field survey comparison was used to adjust measured changes in bar width and wetted width midpoint.

The wetted boundary datum error calculated from the 2007 field survey was validated using two aerial photos taken in 2000. One photo was taken at low flow during the summer, when most of the photos were taken, and one photo was taken at a higher flow during spring, when the 1996 photo was taken. There was assumed to be no substantial channel change between the two 2000 photos: the three storms between the two photos each produced an estimated peak flow at Holley of less than 40 cms. The position and identification errors were added to the measured changes in bar width, wetted width, and wetted width midpoint at cross sections between the spring 2000 and summer 2000 photos. The errors plus the difference between the measurements were assumed to represent the maximum change in width due to discharge between the two photos. The maximum change in width at a cross section, the measured width plus position and identification errors, between the 2000 photos was averaged over each reach. By calculating the specific wetted boundary datum error for the comparison of the spring and summer 2000 photos using two methods, one from the 2000 aerial photos and one from the 2007 field survey, we were able to assess the validity and comparability of the two methods for calculating wetted boundary datum error.

3.4.4 Combination of Errors

Errors were not assumed to be independent, and the errors from each measurement in a comparison were assumed to occur in opposite directions to assess the maximum possible error (Downward, 1995; Mount and Louis, 2005). For each aerial photo, the total position error for each response metric was double the calculated position error to account for error in the position of both the left and right boundaries. The identification error for each response metric for each aerial photo was assessed from one photo for the combined left and right boundaries, so the total identification error for the comparison of aerial photos was double the calculated identification error to account for the error in each photo. For each response metric for each aerial photo comparison, the overall error was the sum of each year's position error and identification errors, plus the wetted boundary datum error calculated for the comparison (Equation 1).

$$e_{comp:aerial} = (e_{xy,year1} + e_{xy,year2}) + 2*(e_{id}) + e_{bd,year1-2} \qquad \text{Equation 1}$$

where $e_{comp.aerial}$ is the total error for a response metric for an aerial photo comparison, e_{xy} is the total position error for an aerial photo, e_{id} is the total identification error for a response metric for an aerial photo, and e_{bd} is the total wetted boundary datum error for the comparison.

For the field surveys, total position error was calculated differently for cross sections in the downstream reaches and cross sections in the upstream reach due to the use of separate controls. The total position error for each response metric for the field survey comparison of the downstream reaches was the sum of the errors calculated from backsight checks for each year, and the error calculated from the station re-occupations. The position error associated with the GPS coordinates for the base station control in the downstream reaches is relevant to field survey changes relative to aerial photo changes, but not between the field surveys since the same location and coordinates were used for both 2007 and 2008. The total error for each response metric of the field survey comparison of the downstream reaches was the sum of the position error for the comparison, the identification error for each survey, and the wetted boundary datum comparison for the comparison (Equation 2).

$$e_{comp:DS.field} = e_{xy} + 2*(e_{id}) + e_{bd,year1-2} \qquad \text{Equation 2}$$

where $e_{comp:DS.field}$ is the total error for a response metric for the field survey comparison, e_{xy} is the total position error for the field surveys, e_{id} is the total identification error for a response metric for a field survey, and e_{bd} is the total wetted boundary datum error for the comparison.

The only difference between the downstream reaches total error and the upstream reach total error was the position error. For the upstream reach, the position error for the comparison of the field surveys was the sum of the error in the control point positions for each year, the error calculated from the backsight checks for each year, and the error calculated from the downstream reaches station re-occupations. Since the difference in discharge varied by cross section, due to surveying over multiple days, the total error for each response metric for the field survey comparison was calculated and applied for each cross section.

4. Results

4.1 Error Analysis

We found that the largest component of error for the field surveys was the wetted boundary datum error, while the dominant error for the aerial photos varied by photo pair and metric (Figure 4, Table 4). The total position and identification errors for all metrics were larger for the aerial photo comparisons than the field survey comparison (Figure 4, Table 4). The average total error, 3.6 m, for the wetted width and wetted width midpoint at a cross section, for the field survey comparison was less than a third of the smallest average total error for an aerial photo comparison. We found 13 m to be the smallest of the average total errors for a metric (change in wetted width midpoint) for an aerial photo comparison (1994-1995).

Figure 4. Average total errors by metric for the aerial photos (1994-2006) and field surveys (2007-2008).
The summer (7/2000) 2000 to spring (4/2000) 2000 photo comparison was used solely for wetted boundary datum error validation.

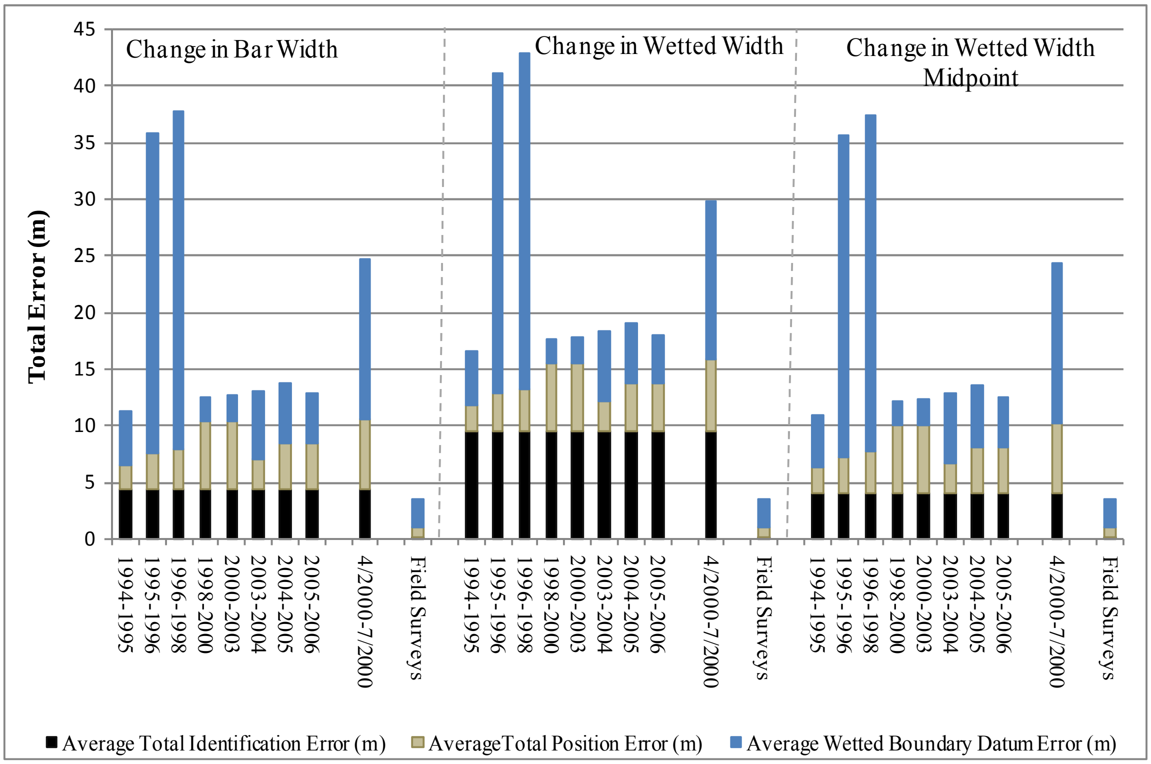


Table 4. Average total errors for aerial photos and field surveys.
The comparison between the spring 2000 and summer 2000 photos was used solely to validate the boundary datum error (see Section 4.1.3). Total errors are the combined error for each photo or field survey in the listed comparison. Averaged errors indicate an average of the total error for the three reaches (DS1, DS2, and US).

Years compared	Difference in average daily discharge at time of measurement (cms)	Average Wetted Boundary Datum Error (m)	Average Total Position Error (m)	Average Total Identification Error (m)		
		All metrics	All metrics	Δ bar width	Δ wetted width	Δ wetted width midpoint
1995-1994	-0.5 ± 3.7	4.7	2.2	4.4	9.6	4.1
1996-1995	12.4 ± 12.9	28.3	3.2	4.4	9.6	4.1
1998-1996	-14.5 ± 12.0	29.7	3.6	4.4	9.6	4.1
Sum. 2000 - 1998	0.3 ± 1.6	2.1	6.0	4.4	9.6	4.1
2003- Sum. 2000	0.2 ± 1.8	2.3	6.0	4.4	9.6	4.1
2004-2003	2.4 ± 3.0	6.1	2.6	4.4	9.6	4.1
2005-2004	-1.1 ± 3.6	5.3	4.1	4.4	9.6	4.1
2006-2005	0.5 ± 3.3	4.3	4.1	4.4	9.6	4.1
Sum. 2000 – Spr. 2000 (Validation)	-5.2 ± 7.4	14.1	6.2	4.4	9.6	4.1
2008-2007 (Field surveys)	0.4 ± 1.7	2.4	0.9	0.2	0.2	0.2

The large range in values for the different types of error associated with the aerial photos, especially the wetted boundary datum error, was a function of the different sources, and associated processing, of the photos, and the different times of year at which they were taken, summer versus spring. Since the magnitude and importance of different types of error were different between the aerial photo and the field survey comparisons, accounting for error was important in making equitable comparisons between changes observed between aerial photos and changes observed between field surveys.

4.1.1 Position Errors

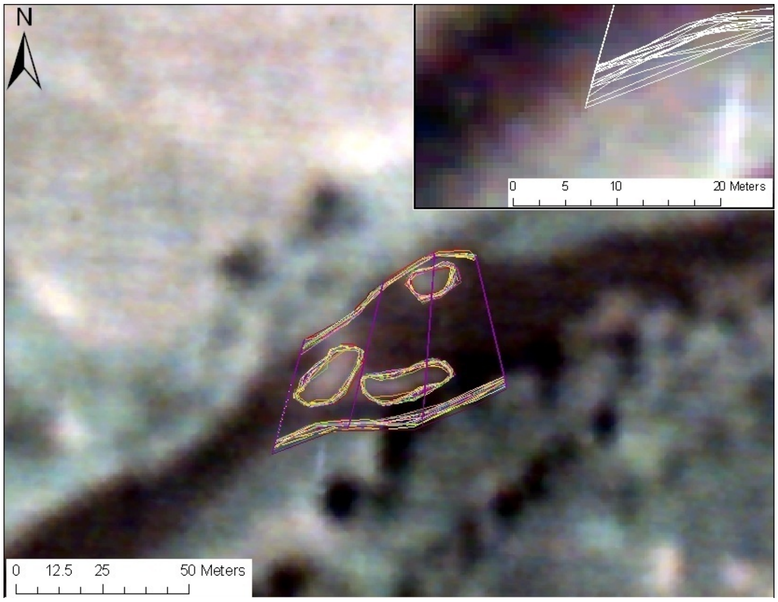
The second largest error for the field surveys was the position error. The dominant proportion of the position error for both the upstream reach and downstream reaches was attributed to the combined error from the GPS coordinates for the initial horizontal angle datum, the control backsight, and instrument operation. The position error for the downstream reaches increased linearly with distance from the GPS control points at the dam and was at a maximum, 1.6 m, at the cross section the farthest away from the controls (1327 m downstream from the control point at the dam). This linear relationship, 0.0014 meters error per meter from control, started 155 meters from the control, and was used to calculate the error at each cross section. For the downstream reaches, the further from the control point at the dam, the greater the error in relocating the cross-section using the Total Station coordinates. The position error for the upstream reach was assumed to increase linearly as well, and had a maximum of 1.9 m at the cross section the farthest away, 650 m, from the initial controls. Since cross sections were re-located in 2008 for the upstream reach using distances instead of coordinates for the few un-monumented cross sections, the error in re-locating cross sections did not increase with distance from the control. The position error within cross sections was negligible, as established by backsight checks at individual stations throughout the reaches.

In contrast to the field surveys, position error was the smallest of the errors for the aerial photos (Table 4). The highest position errors were for those photos not specifically processed for this study: 1996, summer and spring 2000, and 2005. The position error standards for individual photos were dependent on the source and intended purpose of the photos. For example, our objective of digitizing and comparing channel boundaries required different photo processing for greater position accuracy than for the objectives of Linn County (e.g., assessing property values, S. Barnett, personal communication, 2008).

4.1.2 Identification Errors

Of the three types of error, only the identification error for the aerial photos was assessed individually at a cross section for the change in bar width, wetted width, and wetted width midpoint. Due to shadows, riparian vegetation overhanging the channel, and poor image quality, the identification of the wetted boundary could be variable, and therefore make a large contribution to the error in measurements from an individual photo (Table 4, Figure 5). This is reflected in a doubling of the identification error in assessing the change in wetted width as opposed to errors in identifying bar width or wetted width midpoint at cross section with aerial photos. For bar widths and the wetted width midpoint, the identification error at each cross section was only a function of two boundaries. However, for cross sections with mid-channel bars, the identification error for the wetted width was a function of four or more boundaries: two for the left and right extremes of the wetted channel, and two for each mid-channel bar. Therefore, the identification error used for the change in wetted width at a cross section was appropriate for cross sections with mid-channel bars, and likely larger than necessary for cross sections without mid-channel bars.

Figure 5. Repeat digitizing of wetted channel and bars on the 2006 aerial photo to document identification errors.
Displayed below is the riffle channel unit in the near downstream reach with mid channel bars in DS1, 385 m downstream from the dam, that was repeat digitized. The photo is displayed using a n=2 standard deviation stretch based off of the current display extent, which was how photos were displayed during digitizing to emphasize contrast. The inset is at the scale used for digitizing.



The field survey identification error for the change in wetted width, bar width, and wetted width midpoint at a cross section was assessed from the wetted boundaries exclusive of mid-channel bars. The field survey identification error was the smallest field survey error as a result of our ability to identify and measure the coordinates of wetted boundary at close range with precision.

4.1.3 Wetted Boundary Datum Errors

There was a large range of values for the difference in average daily discharge at the time of measurement, and, therefore, the importance of the wetted boundary datum error was comparison dependent. The error for the comparisons of photos taken in the spring to those taken in the summer, 1995-1996, 1996-1998, and spring 2000 to summer 2000, was dominated by the wetted boundary datum error due to the relatively large differences in average daily discharges, amplified by predictor discharge uncertainty (Section 3.3). However, wetted boundary datum error was important for all comparisons as it was only the smallest error for comparisons where error was dominated by large position errors and when predicted discharge differences were small (e.g. 1998-2000 and 2000-2003).

The uncertainty in the discharge predictions greatly increased the calculated wetted boundary datum errors (Table 4). For all aerial photo and field survey comparisons except 1996-1998, the combined error for each pair of discharge predictions was greater than the difference in predicted discharge (Table 4). The largest proportion of the error in the discharge predictions was due to error in the USGS discharge measurements used to create the models and the discharges used to predict new values (Table 5). The spring discharge predictions had greater errors than the summer discharge predictions due to lesser fit of the linear regression equation, and the larger discharges used to predict (Table 5).

The error estimate for the regression model of the average daily discharge, based on the summer 2008 validation, was more than double the 1988-1990 validation error. The error estimate for the regression model of the average daily discharge for the recession limbs of spring storms from the 2008 validation was a little less than double the

1988-1990 validation error. We suspect that an incomplete stage-discharge relationship (18 discharge measurements at sub-bankfull discharges) and collection of discharge measurement by a number of different field personnel for the OSU gaging station is likely the source of the larger error in average daily discharge estimates used in the 2008 validation. In addition, the Brownsville gaging station is 20.6 km downstream from the Holley gage, where the average daily discharge was predicted, and inclusion of consumptive flow or drainage area scaling may not have accurately compensated for the difference in location. However, in light of the magnitude of error associated with the discharge predictions due to uncertainty in discharge inputs for model creation and prediction, the additional error suggested by the 2008 validation in extrapolating the discharge predictions into the future and downstream seems unremarkable.

Table 5. Discharge estimation error components.
Error values in cms quoted relative to uncertainty in percent from the USGS discharges are the specific range of values from the average daily discharge predictions for the aerial photo and field survey dates.

Location	Type of estimate	Model validation RMSE	USGS discharges for model creation	USGS discharges for predictions
Holley	Average daily flow, summer	± 0.3 cms	± 31% (± 0.2 to 1.2 cms)	± 14% (± 0.1 to 0.6 cms)
	Average daily flow, spring	± 3.1 cms	± 35% (± 5.4 cms)	± 17% (± 2.6 cms)
Brownsville	Average daily flow, summer	± 0.7 cms	± 31% (± 0.2 to 1.2 cms)	± 14 % (± 0.1 to 0.6 cms)
	Average daily flow, spring	± 5.6 cms	± 35% (± 5.4 cms)	± 17% (± 2.6 cms)

Calculating changes in width associated with changes in discharge was the second component of the calculation of the wetted boundary datum error. To assess our methodology, we compared measured changes in bar width, wetted width, and wetted width midpoint measured from the spring 2000 and summer 2000 photos to the wetted boundary datum error calculated from the general ratio from the 2007 field survey data (Table 6). The error estimate from the 2007 field survey ratio resulted in overestimates of changes ranging from almost 105 %, for the change in wetted width in DS2, to almost 500 %, for the change in wetted width midpoint in US. From both assessments, DS1 had the smallest wetted boundary datum error due to the relatively confined and unchanging channel with nearly vertical banks. The larger overestimate of the error for the upstream reach using the 2007 field survey ratio suggests that either the aerial photo measurements did not capture all the changes in wetted width and wetted width midpoint, or that the upstream reach bar and bank slopes changed between 2000 and 2007. For all three reaches, the change in wetted width midpoint was close to half of the change in wetted width, suggesting somewhat asymmetrical banks leading to 2/3 of the wetted width change on one side, and 1/3 on the other. Since the change in bar width was greater than the change in wetted width midpoint, the larger part of the wetted width change occurred on bars, as opposed to the banks.

Table 6. Validation of the wetted boundary datum error.
Position and identification errors were added to the 2000 changes to calculate the maximum possible difference and therefore greatest error. The boundary datum error from the 2000 aerial photo comparison is listed as an average for all metrics and for each individual metric for ease of comparison.

Reach	Average wetted boundary datum error from 2007 field survey ratio (m)	Average wetted boundary datum error from comparison of spring and summer 2000 aerial photos (m)			
	All metrics	All metrics average	Δ bar width	Δ wetted width	Δ wetted width midpoint
DS1	15.3	7.2	5.9	10.0	5.6
DS2	18.1	12.6	12.2	17.5	8.0
US	24.0	8.0	8.2	10.9	4.9

4.2 Analysis of Aerial Photos by Study Reach: Channel Changes Relative to Error

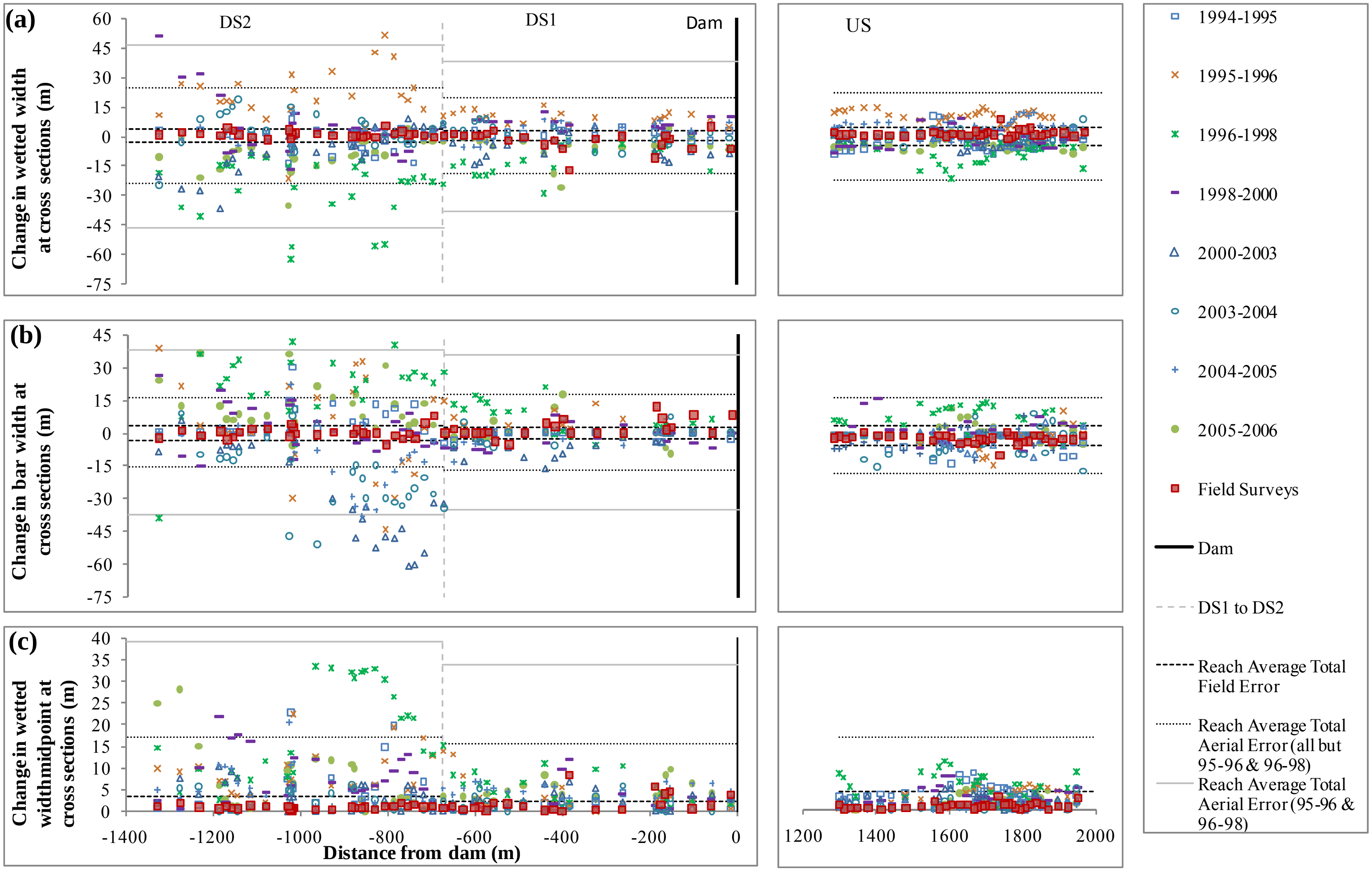
The analysis of aerial photos from 1994 to 2006 was used to establish the baseline variability prior to dam removal. For all the photos compared, changes in wetted width, bar width, and wetted width midpoint at cross sections were greater in DS2 than in DS1 or US (Figure 6). For cross sections in DS1 and US, most changes in wetted width, bar width, and wetted width midpoint as observed from the aerial photos were less than the total measurement error for each photo-year comparison.

The greatest magnitude and quantity of changes in all metrics were in cross sections in the far downstream reach, DS2. DS2 can be looked at as two separate regions split at a cross section approximately 1030 m downstream from the dam (Figure 6). For cross sections in the upstream part of DS2, above-error changes in bars (1 – 45 m) were observed for all aerial photo comparisons except 1998-2000. In the downstream part of DS2, one to four cross sections in every aerial photo comparison had above-error changes in bar width (1 - 24 m) except for 1994-1995, 2000-2003, and 2004-2005. In contrast, only photo comparisons for 1995-1996, 1996-1998, and 2005-2006 had above-error changes in wetted width (1 - 28 m) in the upstream part of DS2. More aerial photos comparisons, all but 1994-1995, 1995-1996, and 2004-2005, had above error changes in wetted width (1 – 88 m) in the downstream part of DS2. Three aerial photo comparisons had above-error lateral shifts in the wetted channel (2 – 13 m) in the upstream part of DS2, but only two aerial photo comparisons had above-error lateral shifts in the wetted channel (1 – 15 m) in the downstream part of DS2. The prevalence and range of above-error changes in bar width, wetted width, and wetted width midpoint throughout the time period of aerial photo analysis demonstrate the high variability of the second downstream reach.

In contrast to DS2, the majority of the changes in bar width and wetted width for cross sections in the near downstream reach, DS1, and the upstream reach, US, for aerial photos were less than the average total error. None of the aerial photo comparisons had above-error changes in wetted width midpoint for DS1 or US. In DS1, three cross sections, two from the 2005-2006 comparison and one from the 1996-1998 comparison had above-error changes in wetted width (1 – 10 m). Only one cross section for one comparison, 2005-2006, had an above-error change in bar width (4 m). For the upstream reach, the only above-error changes (1 – 4 m) were for bar width at seven cross sections within three aerial photo comparisons: 1994-1995, 1998-2000, and 2003-2004. For both DS1 and US, most of the changes in bar width, wetted width, and wetted width midpoint were small and beyond our ability to quantify above measurement errors due to the quality of aerial photos compared and uncertainty in discharge measurements.

Figure 6. Plots of changes in (a) wetted width, (b) bar width, and (c) wetted width midpoint at each cross section relative to distance from the dam.
The average total aerial error for each reach is displayed as two different quantities for the downstream reaches: summer comparisons (1994-1995, 1998-2000, 2000-2003, 2003-2004, 2004-2005, 2005-2006), or summer-spring comparisons (1995-1996, 1996-1998). The reach average total error for the summer-spring comparisons is approximately double that for the summer comparisons, and is not displayed for the upstream reach due to scale.

Figure 6.


(a)
DS2
DS1
Dam
US
Change in wetted width at cross sections (m)
60
45
30
15
0
-15
-30
-45
-60
-75
(b)
Change in bar width at cross sections (m)
45
30
15
0
-15
-30
-45
-60
-75
(c)
Change in wetted widthmidpoint at cross sections (m)
40
35
30
25
20
15
10
5
0
-1400
-1200
-1000
-800
-600
-400
-200
0
Distance from dam (m)
1200
1400
1600
1800
2000
1994-1995
1995-1996
1996-1998
1998-2000
2000-2003
2003-2004
2004-2005
2005-2006
Field Surveys
Dam
DS1 to DS2
Reach Average Total Field Error
Reach Average Total Aerial Error (all but 95-96 & 96-98)
Reach Average Total Aerial Error (95-96 & 96-98)

4.3 Analysis of Field Surveys by Study Reach: Channel Changes Relative to Error

For the field surveys, DS1 was the reach with the most cross sections with above-error changes in bar width (1 – 10 m), wetted width (1 – 15 m), and wetted width midpoint (2 – 6 m). More than half of the 21 cross sections in DS1, predominantly within the first 560 m downstream from the dam, had above-error changes in bar width, wetted width, or wetted width midpoint. The larger magnitude changes observed across all reaches in all three metrics were also at cross sections in DS1. Most of the bars widened, while most of the wetted channel narrowed between the field surveys at cross sections in the DS1 reach. This suggests that the bars expanded in response to the pulse of gravel supplied by the dam removal, constraining the flow into a narrower channel. Due to the much smaller measurement error associated with the field surveys, we were able to detect the small changes that were potentially associated with the dam removal.

The concentration of the changes in bar width, wetted width, and wetted width midpoint at cross sections near the dam was easier to detect because there were fewer changes in these metrics at cross sections in DS2 and US. At cross sections in DS2 for the field survey comparison, above-error changes in bar width (1 – 5 m) and wetted width (2 m) were small and scattered in contrast to the above-error changes in bar width (1 – 10 m) and wetted width (1 – 15 m) at cross sections in DS1 for the field surveys, and in DS2 for the aerial photo comparisons (1 – 45 m for bar width, 1 – 28 m for wetted width). In DS2 of the field survey comparison, only 3 of the 28 cross sections in the reach had above-error bar width changes, and there was only one cross section with a change above-error in wetted width and none with a change above-error in wetted width midpoint. The largest bar width changes in DS2 were the result of (a) a bar surveyed in 2008 which was not present in the 2007 survey because of a more restrictive definition of bars, and (b) a cross section that crossed the downstream end of a bar, which had a boundary fragmented by water in 2008 but not in 2007 and resulted in the largest wetted width change for DS2 as well. We thus believe that both of the largest bar width changes at cross sections, and the largest wetted width change at a cross section, in DS2 are more indicative of the challenges in consistently identifying and delineating bars between survey years than changes in the feature itself.

Similar to DS2, changes in bar width, wetted width, and wetted width midpoint in the upstream reach were minimal in extent and magnitude with respect to total measurement error. Only 1 of the 34 cross sections in the upstream reach had above-error changes (4 m) in bar width or wetted width, and no cross sections had above-error changes in wetted width midpoint. At this cross-section the bar split between the two surveys, which was reflected by a similar magnitude increase in wetted width and decrease in bar width. A larger total error was observed for the upstream reach (4.3 m) than the downstream reaches (2.5 m for DS1 and 3.6 for DS2) due to the lack of a consistent physical monument for control, and greater estimated width changes with discharge. However, most of the under-error changes observed in the upstream reach were also below the smaller total error of the downstream reaches.

4.4 Estimated Peak Discharge and Channel Change

Characterizing the peak flow between measurements was important for understanding the extent of channel change between compared years within the aerial photos and between the aerial photos and the field surveys. For the median above-error change in wetted width at a cross section, there is some evidence of an increasing linear relationship with the estimated peak discharge between measurements (Figure 7). In contrast, above-error changes in wetted width midpoint were among the smallest for the three aerial photo comparisons with the greatest estimated peak flows between the photos. For above-error changes in bar width, many of the aerial photo comparisons had similar ranges, but both widening and narrowing occurred for the four comparisons with the highest peak flows between measurements.

One of the common issues with aerial photo analysis is uneven time intervals between photos. For this study, we assessed the annual peak discharges for the comparisons with more than one year between the photos to evaluate possible differences due to change over different time periods. As a surrogate for the bankfull, or channel forming flow (Doyle et al., 2007), the 1.5 return year interval (RYI) flow at Holley (130 cms) was compared to the estimated peak discharge between measurements (Table 7). The aerial photo comparisons with more than one year between them included mostly lower flow years: the estimated peak annual flow for the 1998, 2001, 2002, and 2007 water years was below the 1.5 RYI flow, and the estimated annual peak flow for 1999 was the only comparison year above it at 198 cms. Therefore, two of the multi-year comparisons, 1996-1998 and 2000-2003, should be comparable to the annual comparisons in the amount of channel changing flows experienced. However, a single estimated peak flow may not be representative of the flows that caused channel change between 1998 and 2000, especially because the third highest estimated peak flow during the aerial photo analysis occurred between the 1998 and 2000 photos (Table 7). For the downstream reaches for all three metrics, the median and range of changes for the 1998-2000 comparison was more similar to the median and range of the 1995-1996 comparison than the 1996-1998 comparison (Figure 7).

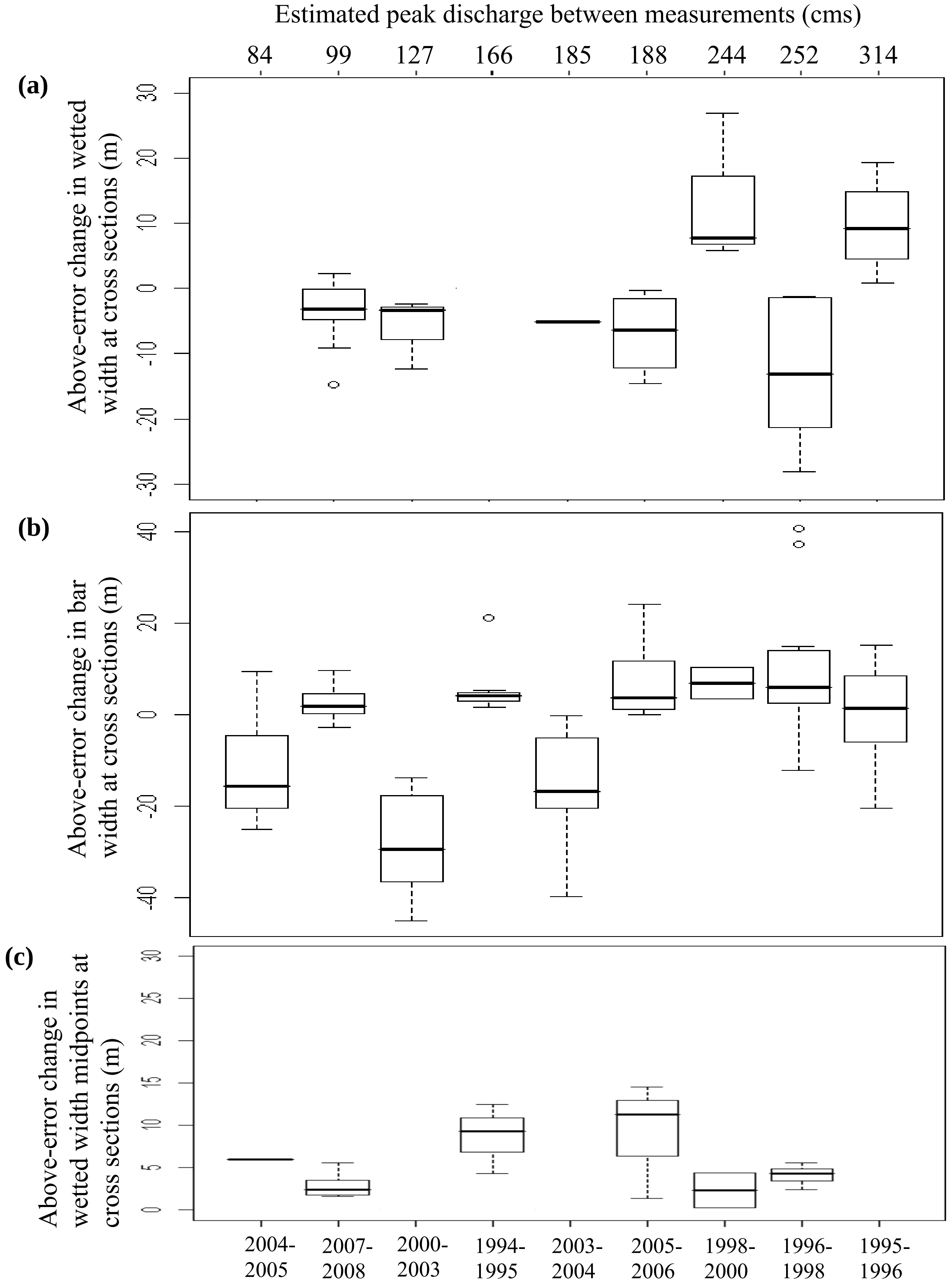
Table 7.
Estimated peak discharge between measurements at the former USGS gage for the Calapooia River at Holley.
1.5 RYI flow at Holley is 130 cms. Error estimates for the estimated peak discharge are from the 1988-1990 validation.

Years compared	Date of Peak Discharge	Estimated Peak Discharge (cms)	RYI
1995-1994	1/13/1995	166 ± 7	2.3
1996-1995	2/7/1996	314 ± 7	25
1998-1996	11/19/1996	252 ± 7	6.5
2000-1998	11/25/1999	244 ± 7	6
2003-2000	1/30/2003	127 ± 7	1.5
2004-2003	12/13/2003	185 ± 7	3
2005-2004	3/27/2005	84 ± 7	1.1
2006-2005	12/31/2005	188 ± 7	3
2008-2007	12/24/2007	99 ± 7	1.3

Figure 7. Box and whisker plot of estimated peak discharge (cms) vs. above-error change in (a) wetted width, (b) bar width, or (c) wetted width midpoint at a cross section (m) for the downstream reaches for all comparisons.

Notice that the discharges on the x-axis are evenly spaced, not scaled by quantity. The location of changes (DS1 vs. DS2) is not represented on these plots. All values displayed for changes in wetted width, bar width or wetted width midpoint are measurements minus error. Only cross sections with non-zero error-adjusted values were included. Peak discharge between measurements was estimated at Holley using multiple linear regression with data from the South Santiam and Mohawk River USGS gages. The bold line represents the median of the data. The box represents the middle 50 % of the data: the interquartile range (IQR), while each whisker is at the largest magnitude value that is at most 1.5 times the IQR away from the box (Ramsey and Schafer, 2002). The dots are values more than 1.5 IQRs away from the box (Ramsey and Schafer, 2002).

Figure 7.


Estimated peak discharge between measurements (cms)
84
99
127
166
185
188
244
252
314
(a)
Above-error change in wetted width at cross sections (m)
30
20
10
0
-10
-20
-30
(b)
Above-error change in bar width at cross sections (m)
40
20
0
-20
-40
(c)
Above-error change in wetted width midpoints at cross sections (m)
30
25
20
15
10
5
0
2004-2005
2007-2008
2000-2003
1994-1995
2003-2004
2005-2006
1998-2000
1996-1998
1995-1996

The estimated peak discharge between the field surveys, 99 cms, was a 1.3 RYI event (Table 7) and lies between the estimated peak discharges for two of the aerial photo comparisons: 2000 to 2003, and 2004 to 2005. If the changes in bar width, wetted width, and wetted width midpoint were solely a function of peak discharge between measurements, we would expect the field survey changes in bar width, wetted width, and wetted width midpoint to be similar to the changes in bar width, wetted width, and wetted width midpoint for 2000-2003 and 2004-2005.

The majority of field survey data for the downstream reaches, as represented by the box and whiskers, is more tightly clustered for all three metrics than most of the aerial photo comparisons (Figure 7). The median and range of the above-error changes in wetted width for the field surveys was similar to the 2000-2003 aerial photo comparison. However, most of the other aerial photo comparisons with lower estimated peak flows between measurements, 84 – 188 cms, had few or no above-error changes in wetted width. For the above-error changes in bar width, the field survey changes were more similar to those for the 1998-2000 photo comparison than those for photo comparison with lower estimated peak flows between measurements (e.g. 2004-2005 and 2000-2003). There were few to no above-error changes in wetted width midpoint for either the field surveys or the aerial photo comparisons, but the field survey comparison had a small range and median more similar to the higher peak annual flow aerial photo comparisons (1998-2000 and 1996-1998).

The estimated peak discharge between measurements is not sufficient to describe the downstream trends in the median changes in wetted width, bar width, and wetted width midpoint at a cross section for the aerial photo comparisons relative to the field survey comparison. This could suggest some effect of the dam removal, relative to historical variability of the channel. Looking at both downstream reaches, above-error changes in bar width at cross sections were lower in magnitude for the field survey comparison than in most aerial photo comparisons. Above-error changes in wetted width and wetted width midpoint for both downstream reaches were smaller for the field survey comparison than most of the aerial photo comparisons with above-error changes, but three to four of the aerial photo comparisons had few to no above-error changes in wetted width or wetted width midpoint. This may be a reflection of using conservative error estimates to minimize inclusion of unrealistic changes. However, given the substantial natural variability of DS2 (Section 4.2) and its distance from the dam, the separate analysis of the two downstream reaches seems more appropriate (Section 4.3). From the comparison of error-adjusted changes of DS1 field surveys and aerial photos, we found that the field survey comparison had higher or equal changes in bar width, wetted width, and wetted width midpoint at cross sections in DS1 than all aerial photo comparisons, despite the relatively low peak flow between the two years, when the different total errors for the two methods are considered (Figure 6).

5. Discussion

5.1 Observed Responses to Dam Removal

Consistent with other studies of downstream channel change following dam removal (Doyle et al., 2005; Stewart, 2006), most of the above-error changes in bar width, wetted width, and wetted width midpoint at cross sections following the removal of Brownsville Dam occurred in the channel immediately below the dam (Figure 6, Section 4.3). Most of the cross sections within the first 600 m downstream from the dam indicated narrowing of the wetted channel and widening of the bars after the removal, reflecting the importance of bars as deposition features. The concentration of larger magnitude effects near the former dam site is a reflection of the dominance of dispersion (Lisle et al., 2001). As a result, the sediment from the reservoir will likely have a delayed and minimal effect farther downstream while the region directly below the dam will continue to be demonstrably affected, and unstable, until all the erodible reservoir sediment has been released (Pizzuto, 2002).

From our aerial photo analyses, we established the range of above-error changes in bar, width, wetted width, and wetted width midpoint that have occurred recently relative to estimated annual peak flows between 84 and 314 cms (Sections 4.2 and 4.4). For both lower and higher annual peak flows, the far downstream reach, DS2, had above-error changes in bar width of at least 20 m, above-error changes in wetted width of at least 10 m, and above error changes in wetted width midpoint of at least 6 m (Figure 6). The other two reaches in our study, DS1 and US, both had few, lower magnitude changes that were above-error: 4 m change in bar width in both DS1 and US, and 1-10 m change in wetted width in DS1. Therefore, without an effect of the dam removal, we would expect the majority of larger magnitude changes to be in DS2, and the number and magnitude of changes in DS1 and US to be similar to each other and less than in DS2.

From our field surveys, we found a difference, in terms of magnitude and quantity, in the above-error changes one year after the dam removal for DS1 relative to both DS2 and US. Despite the higher variability observed previously in DS2 with aerial photos, there were few, low (less than 5 m) above-error changes observed with field surveys in DS2 (Section 4.3). With an estimated annual peak flow of 99 cms between the field surveys, we expected the magnitude of the changes unrelated to the dam removal observed from the field surveys to be low in magnitude relative to the aerial photos analysis. Unlike the aerial photo comparisons and discharge related expectations, above-error changes in DS1 (up to 10 m for bar width and up to 15 m for wetted width) were much greater and more numerous than those in DS2 for the field surveys (Section 4.3, 4.4). We inferred that the changes observed in DS1 were a result of the dam removal as they were greater and more numerous than those previously observed in DS1, and than those simultaneous observed in the typically more dynamic reach, DS2. In addition, the upstream reach had minimal above-error changes, as expected from the aerial photo comparisons, and therefore highlighted the departure of DS1 from similar expectations.

5.2 Issues in and Best Practices for Minimizing Errors

Dam removal is plagued by lack of pre-removal data and yet, this information is key to understanding the significance of and processes driving channel changes with dam removal. Aerial photos are one option to establish baseline variability, but the issues and errors need to be considered. In as many ways as possible, we attempted to minimize the differences between measurements and calculations from aerial photos versus field surveys. The largest components to making the measurements comparable were the selection of channel metrics, estimation of errors, and the integration of different observational techniques.

5.2.1 Selection of Channel Metrics

Our measurement techniques, aerial photos and field surveys, dictated which changes we were able to observe. Aerial photo analysis of rivers is typically restricted to planform changes as techniques for determining water depth are still being developed (Gilvear et al., 1998). However, the changes observed and reported associated with dam removals are typically related to sediment depth (Doyle et al., 2005). Our analysis was restricted to indirect measures of aggradation and degradation within the bankfull channel, width changes in bars and the wetted channel, due to our use of aerial photos and the small amount of change we expected. These metrics were sufficient relative to observation error to establish baseline variability using the aerial photos, and map the extent and relative magnitude of changes associated with the dam removal (Sections 4.2-4.4).

5.2.2 Estimating Observation Error in Field Surveys

We considered error in our analysis in order to improve the comparability of the results from different kinds of measurements and from different locations. For the field survey comparisons, the position error was the second largest source of error. The majority of the field survey position error, on average 0.9 m, was due to inconsistent controls between the two surveys. Establishment and maintenance of permanent survey monuments are a challenge for any actively-used river under predominantly private ownership. We were able to estimate the effects of the inconsistent controls, however, as well as instrument operation, on both the downstream reaches and the upstream reach, and consequently found a linear increase in error with distance from the control. The identification was very small, 0.2 m, relative to the position error for the field survey comparison. We suggest that efforts in future studies should be spent identifying willing landowners to establish a large number of survey monuments as controls to minimize position error.

5.2.3 Estimating Observation Error in Aerial Photo Analysis

Position error was one of the smaller errors for most of the aerial photo comparisons, 2.2-4.1 m, except for the 1998-2000 and 2000-2003 comparisons which included the photo with the greatest position error (summer 2000). Since we only processed one photo frame per year, we were able to use GPS to acquire ground control points instead of relying on a digital ortho quad for positions. Thus, we were able to orthorectify photos to the same, if not better, position error standard as photos processed by other entities. As was shown by our analyses, attention to processing of photos can be an important component of reducing position errors in analysis of aerial photos, and best practices for orthorectification or geocorrection of aerial photos are well-described in the literature (Hughes et al., 2006; Leys and Werritty, 1999; Zanoni et al., 2008).

The two largest errors in the aerial photo comparisons for our study, identification and wetted boundary datum, were a function of the photos used. Issues associated with these two errors types include the discharge at the time photos were taken, discharge uncertainty, the scale at which photos were flown, shadows in the photo, and scanning contact prints using a flatbed scanner. In this study, identification error for the aerial photos was approximated from only one photo and applied to all the photos due to the time and effort required for re-digitizing. We chose the aerial photo and channel units for which we expected the greatest identification errors in order to be conservative in our assessment of changes. We estimated average identification errors at 4.4 m for the change in bar width at a cross section, 9.6 m for the change in wetted width at a cross section, and 4.1 m for the change in wetted width midpoint at a cross section. There was likely a range of values for identification error due to differences in the scale, quality of scan, and cell size for each of the photos.

Since the identification error was one of the larger errors for aerial photo comparisons, we believe documentation of this error is critical, and recommend that future studies analyze each photo individually to establish upper and lower bounds for the identification error. In this study, we digitized each channel unit 20 times, but we likely could have digitized fewer times with similar results. In addition, there was an unquantified but noticeable difference in clarity for aerial photos scanned from film using photogrammetric scanners (1995, 1996, spring 2000, and 2005), and photos scanned from contact prints using a flatbed scanner (1994, 1998, 2003, 2004, 2006). Thus we recommend that aerial photos be professionally scanned from film for detailed analyses of channel change.

Wetted boundary datum error is frequently ignored in wetted channel and bar analyses of aerial photos because wetted boundary datum error can be small relative to other errors for comparisons with small, similar discharges, (Table 4) (Van Steeter and

Pitlick, 1998). Wetted boundary datum error is also difficult to accurately quantify without field data taken at different discharges. With the greater frequency and availability of aerial photos taken today, researchers analyzing bars or the wetted channel can choose to exclude comparisons between photos with large differences in flows at the times of the photos. However, historic photos are limited, and a particular photo may document the results of an important event, such as the 1996 photo for this study, so exclusion may not be desirable. As well, uncertainty in discharge measurements may increase error associated with using the wetted boundary for any difference in discharge.

The wetted boundary datum error estimate required the most assumptions of the three types of error calculated because it was not directly measureable for each comparison. We were only able to calculate the wetted boundary datum error using two different years of data, 2000 and 2007, with two different techniques: estimation from field survey cross section data using software to simulate the flows associated with different wetted widths, and comparison of two aerial photos between which we were able to reasonably assume no channel changes. From a comparison of the estimates for the 2000 photos to the measurements from the 2000 photos, we found that wetted boundary datum error varied greatly with metric, and that the estimation from the 2007 field survey data was an overgeneralization over space, and a gross overestimation for the upstream reach.

From the magnitude of the differences between metrics and within reaches, in the future we would expend more time and effort to calculate separate estimates of wetted boundary datum error for each metric and for similar cross sections. We would assess the similarities of cross sections based upon: region of the river, presence/absence and location (left versus right) of lateral bars, and presence/absence of mid channel bars, for example. With more time, and fewer cross sections, calculating and applying wetted boundary datum error estimates based upon smaller scale groupings would be possible and desirable, but we did not assess the relative benefits in this study.

5.2.4 Establishing Discharge in Ungaged Basins

While overgeneralization was one issue with our calculation of wetted boundary datum error, the primary shortcoming resulting in overestimation of values was uncertainty in our discharge predictions. For many of the comparisons, the uncertainty associated with a difference in discharge was almost equal to or 9 times greater than the difference in discharge, e.g. 0.2 ± 1.8 cms for 2000-2003. Our overestimates of wetted boundary datum error for the upstream reach are likely what prevented us from observing more than a few above-error changes for either the field survey or the aerial photo comparisons, and limited our ability to evaluate the previous and current relationship between the upstream and downstream reaches. Without accurate discharge measurements, we had difficulty detecting small changes relative to the wetted boundary without error.

Since relatively few of the rivers in the United States are currently or have historically been gaged for discharge, many discharge dependent analyses will have to resolve the issue of discharge uncertainty. In this study, we were able to extrapolate from historic discharge records, and we may have been able to reduce uncertainty associated with our regression by using a more robust method such as Maintenance of Variance Extension (MOVE) (Hirsch, 1982). However, for completely ungaged rivers, options for predicting discharge with constrained uncertainty are more limited (e.g. rainfall-runoff models). Researchers may choose qualitative comparisons of discharge dependent features instead, regardless of discharge record availability (O'Connor et al., 2003).

5.2.5 *Integration of Different Observation Techniques and Errors*

Designing this study, we were aware of possible difficulties in comparing results from different observation techniques. Aerial photos and field surveys measure features at different scales using instruments with different precisions and accuracies. We were not able to directly compare measurements and changes between aerial photos and field surveys because no aerial photos were taken in 2007, and aerial photos taken in 2008 were not available at the time of this study.

As it is common to lack aerial photos for the same year and season as field studies, the results from this study indicate that with awareness and calculation of errors, the comparison of field studies and aerial photos is still viable. We were feel confident about our comparison of results from aerial photos and field surveys because we chose to compare changes in measurements relative to error. Using changes, instead of measurements, we made more equitable comparisons between mixed methods because biases associated with the methods themselves, such as indistinct banks due to shadows in aerial photos, were common to both measurements used to calculate each change. By including error, we were able to avoid differing overestimates of change due to differences in the accuracy and precision of the two techniques.

We were able to meet our objective of evaluating the possible effects of the dam removal with respect to the natural variability for the downstream reaches through our aerial photo analysis, and with respect to our upstream control reach. By assessing measurement errors, we were able to minimize differences as a result of using different measurement techniques. The changes we observed relative to the dam removal were not outside natural variability, but the locations of the larger changes for the comparison were in the first downstream reach and not in the second downstream reach, as was typical for the aerial photos.

6. Conclusions

Our study site, as a small dam removal, represents a worst case scenario with respect to being able to detect effects. With little sediment stored behind the dam, we anticipated small effects on the downstream channel relative to natural variability. This scenario made detection of important differences more difficult than would be expected at a larger and more geomorphically-dramatic dam removal. Therefore, this small dam removal provides an important opportunity to investigate issues and techniques in detecting low-level effects on the downstream channel. These issues and techniques translate to the study of greater magnitude and more obvious effects. Larger dam removal studies, where changes are more dramatic, will benefit from this work as a baseline for improving the documentation of errors and variability, and thus confidence in observations.

The three response metrics and methodologies presented indicate differences between the downstream reaches for the field surveys versus the aerial photos, and between the downstream reaches and upstream reach for the field surveys. These differences suggest that the dam removal had an effect on the downstream channel. Evaluation of effects using the low flow channel and bars was necessary and helpful for comparability between measurement techniques and the small magnitude of effects, but these metrics also provided a challenge due to discharge uncertainty. In these assessments, documenting and including measurement errors in the analysis of change provided greater confidence that the differences were not due to observational error.

Dam removal studies are rarely grounded on extensive data to characterize baseline variability of the system and consequently of any changes post-removal. Aerial photos can provide some context for changes following removal. However, caution should be used when analyzing aerial photos to characterize temporal dynamics due to observation errors. Further, comparison of aerial photo data and field survey data is subject to some constraints, such as restriction to planform changes and greater identification errors for aerial photos, but they can provide a reasonable control in dam removal and other river restoration and management studies where pre-implementation data is not available. However, with care, errors in aerial photo analysis can be minimized by non-photogrammetrists by choosing photos taken at similar discharges, scanning from film for better quality images, and geocorrecting photos. Such best practices can be used to minimize and document errors, and when used appropriately, can be important to place responses to dam removal in the context of natural geomorphic variability. As researchers and scientists work toward a more practical and specific understanding of the downstream effects of small dam removals, assessments of measurement errors and rigorous controls should play a larger role in providing context for channel changes.

Bibliography

Ahearn, D.S. and Dahlgren, R.A., 2005. Sediment and nutrient dynamics following a low-head dam removal at Murphy Creek, California. Limnology and Oceanography, 50(6): 1752-1762.

Brasington, J., Rumsby, B.T. and McVey, R.A., 2000. Monitoring and modelling morphological change in a braided gravel-bed river using high resolution GPS-based survey. Earth Surface Processes and Landforms, 25(9): 973-990.

Bushaw-Newton, K.L., Hart, D.D., Pizzuto, J.E., Thomson, J.R., Egan, J., Ashley, J.T., Johnson, T.E., Horwitz, R.J., Keeley, M., Lawrence, J., Charles, D., Gatenby, C., Kreeger, D.A., Nightengale, T., Thomas, R.L., and Velinsky, D.J., 2002. An integrative approach towards understanding ecological responses to dam removal: the Manatawny Creek Study. Journal of the American Water Resources Association, 38(6): 1581-1599.

Cantelli, A., Paola, C. and Parker, G., 2004. Experiments on upstream-migrating erosional narrowing and widening of an incisional channel caused by dam removal. Water Resources Research, 40(W03304): 12.

Downward, S.R., 1995. Information from topographic survey. In: A.M. Gurnell and G.E. Petts (Editors), Changing river channels. Wiley, New York, pp. 303-323.

Downward, S.R., Gurnell, A.M. and Brookes, A., 1994. A methodology for quantifying river channel planform change using GIS. In: L.J. Olive, R.J. Loughran and J.A. Kesby (Editors), Variability in stream erosion and sediment transport. IAHS Press, Wallingford, Oxfordshire, UK, pp. 449-456.

Doyle, M.W., Shields, D., Boyd, K.F., Skidmore, P.B. and Dominick, D., 2007. Channel-forming discharge selection in river restoration design. Journal of Hydraulic Engineering, 133(7): 831-837.

Doyle, M.W., Stanley, E.H. and Harbor, J.M., 2002. Geomorphic analogies for assessing probably channel response to dam removal. Journal of the American Water Resources Association, 38(6): 1567-1579.

Doyle, M.W., Stanley, E.H., Harbor, J.M. and Grant, G.S., 2003. Dam removal in the United States: Emerging needs for science and policy, EOS. American Geophysical Union, pp. 29, 32-33.

Doyle, M.W., Stanley, E.H., Orr, C.H., Selle, A.R., Sethi, S.A., and Harbor, J.M., 2005. Stream ecosystem response to small dam removal: Lessons from the Heartland. Geomorphology, 71(1-2): 227-244.

ESRI, 1999-2006. ArcMap, Redlands, CA.

Evans, J.E., 2007. Sediment impacts of the 1994 failure of IVEX dam (Chagrin River, NE Ohio): A test of channel evolution models. Journal of Great Lakes Research, 33(sp2): 90-102.

Evans, J.E., Mackey, S.D., Gottgens, J.F. and Gill, W.M., 2000. Lessons from a dam failure. Ohio Journal of Science, 100(5): 121-131.

Gilvear, D.J., Waters, T.M. and Milner, A.M., 1998. Image analysis of aerial photography to quantify the effect of gold placer mining on channel morphology, Interior Alaska. In: S.N. Lane, K.S. Richards and J.H. Chandler (Editors), Landform Monitoring, Modelling and Analysis. John Wiley & Sons, Ltd, Chichester, pp. 195-216.

Ham, D.G. and Church, M., 2000. Bed-material transport estimated from channel morphodynamics: Chilliwack River, British Columbia. Earth Surface Processes and Landforms, 25(10): 1123-1142.

Heinz Center, 2002. Dam removal: Science and decision making. Heinz Center for Science, Economics, and the Environment, Washington, DC.

Herrett, T.A., Hess, G.W., Stewart, M.A., Ruppert, G.P. and Courts, M.-L., 2005. Water resources data for Oregon, water year 2005, U. S. Geological Survey.

Hirsch, R.M., 1982. A comparison of four streamflow record extension techniques. Water Resources Research, 18(4): 1081-1088.

Hughes, M.L., McDowell, P.F. and Marcus, W.A., 2006. Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. Geomorphology, 74(1-4): 1-16.

Kershner, J.L., Roper, B.B., Bouwes, N., Henderson, R. and Archer, E., 2004. An analysis of stream habitat conditions in reference and managed watersheds on some federal lands within the Columbia River Basin. North American Journal of Fisheries Management, 24(4): 1363-1375.

Leica Geosystems Geospatial Imaging, 2007. Image Analysis for ArcGIS 9.2, Norcross, GA.

Leys, K.F. and Werritty, A., 1999. River channel planform change: software for historical analysis. Geomorphology, 29: 13.

Lisle, T.E., Cui, Y., Parker, G., Pizzuto, J.E. and Dodd, A.M., 2001. The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers. Earth Surface Processes and Landforms, 26(13): 1409-1420.

MacBroom, J.G., 2005. Evolution of channels upstream of dam removal sites. In: G.E. Moglen (Editor), Managing Watersheds for Human and Natural Impacts. ASCE, Williamsburg, Virginia, USA, pp. 26.

Martin, J.D., 2007. Brownsville Dam removal report, Cascade Earth Sciences, Albany, OR.

McCowan, K., 2007. Dam's end washes away a bit of history, The Register Guard, Eugene, OR, 28 August: A.1.

Mount, N. and Louis, J., 2005. Estimation and propagation of error in measurements of river channel movement from aerial imagery. Earth Surface Processes and Landforms, 30(5): 635-643.

National Geodetic Survey, 2008. Online Positioning User Service. NOAA. http://www.ngs.noaa.gov/OPUS/.

Nielsen, L.A. and Johnson, D.L., 1983. Fisheries techniques. American Fisheries Society, Bathesda, Maryland, U.S.A, 468 pp.

O'Connor, J., Major, J. and Grant, G., 2008. The dams come down: Unchaining U.S. rivers. Geotimes, 53(3): 22-27.

O'Connor, J.E., Jones, M.A. and Haluska, T.L., 2003. Flood plain and channel dynamics of the Quinault and Queets Rivers, Washington, USA. Geomorphology, 51(1-3): 31-59.

Pizzuto, J., 2002. Effects of dam removal on river form and process. BioScience, 52(8): 683-691.

Ramsey, F.L. and Schafer, D.W., 2002. The statistical sleuth: A course in methods of data analysis. Thomson Learning, Pacific Grove, CA, 742 pp.

Randle, T.J. and Daraio, J.A., 2003. Sediment and geomorphic assessment for the potential removal of Chiloquin Dam, Sprague River, Oregon, U. S. Bureau of Reclamation, Denver, CO.

Rantz, S.E. and others, 1982. Measurement and computation of streamflow: Volume 1. Measurement of stage and discharge, U.S. Geological Survey Water-Supply Paper, vol. 2175. U.S. Government Printing Office, Washington, DC.

Rappe, C.F. and Abbe, T.B., 2003. A framework for delineating channel migration zones. 03-06-027, Washington State Department of Ecology.

Rosgen, D.L., 1996. Applied River Morphology. Wildland Hydrology Books, Pagosa Springs, 385 pp.

Runyon, J., Andrus, C. and Schwindt, R., 2004. Calapooia River watershed assessment, Calapooia Watershed Council, Brownsville, OR.

Sherrod, D.R. and Smith, J.G., 2000. Geologic map of upper Eocene to Holocene volcanic and related rocks of the Cascade Range, Oregon, U. S. Geological Survey Geological Investigations Series I-2569. United States Geological Survey.

Stanley, E.H., Luebke, M.A., Doyle, M.W. and Marshall, D.W., 2002. Short-term changes in channel form and macroinvertebrate communities following low-head dam removal. Journal of the North American Benthological Society, 21(1): 172-187.

Stewart, G. and Grant, G., 2005. What can we learn from the removal of little dinky dams? In: G.E. Moglen (Editor), Managing Watersheds for Human and Natural Impacts. ASCE, Williamsburg, Virginia, USA, pp. 18.

S Stewart, G.B., 2006. Patterns and processes of sediment transport following sediment-filled dam removal in gravel bed rivers. PhD dissertation, Oregon State University, Corvallis, 100 pp.

Stream Systems Technology Center, 2005. WinXSPro, USDA Forest Service, Fort Collins, CO.

Sutherland, D.G., Hansler Ball, M., Hilton, S.J. and Lisle, T.E., 2002. Evolution of a landslide-induced sediment wave in the Navarro River, California. Geological Society of America Bulletin, 114(8): 1036-1048.

Tague, C. and Grant, G.E., 2004. A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. Water Resources Research, 40(4): 9.

Tippett, R.S., 1990. Description of gaging station: 14-1720.00 Calapooia River at Holley, Oreg., U.S. Department of the Interior: Geological Survey: Water Resources Division.

Topcon Positioning Systems, 2007. Topcon Tools, version 6.11.01, Livermore, CA.

Tripod Data Systems, 2008. Tripod Data Systems: Nikon 302 Series Total Station: Compare Specifications. http://www.tdsway.com/products/nikon_tstations/302_series/compare_specs?1=1&ID=85.

U.S. Geological Survey, 2008a. USGS real-time water data for USGS 14165000 Mohawk River near Springfield, OR. http://waterdata.usgs.gov/or/nwis/uv/?site_no=14165000&.

U.S. Geological Survey, 2008b. Water-data report 2008: 14185000 South Santiam River below Cascadia, OR, U.S. Department of the Interior. http://wdr.water.usgs.gov/wy2008/pdfs/14185000.2008.pdf.

U.S. Geological Survey, 2008c. Water resources in the United States - 2008 annual water data report - Documentation. U.S. Department of the Interior, http://wdr.water.usgs.gov/wy2008/documentation.html#stage.

Van Steeter, M.M. and Pitlick, J., 1998. Geomorphology and endangered fish habitats of the upper Colorado River 1. Historic changes in streamflow, sediment load, and channel morphology. Water Resources Research, 34(2): 287-302.

Zanoni, L., Gurnell, A., Drake, N. and Surian, N., 2008. Island dynamics in a braided river from analysis of historical maps and air photographs. River Research and Applications, 24(8): 1141-1159.

Appendix

A.1 Estimation of Reservoir Sediment Volume and Particle Sizes

The volume of sediment in the reservoir prior to removal was estimated by comparing the estimated pre-dam reservoir channel bottom to the reservoir channel bottom surveyed in 2007 as grids using tools from 3D Analyst and Spatial Analyst in ArcMap™ (Brasington et al., 2000; ESRI, 1999-2006). The pre-dam channel bottom for the reservoir was estimated from trapezoidal cross sections created using the average side slope of reservoir cross sections and average slope of the thalweg from the top of the reservoir to 1.4 km downstream from the 2008 field survey (Randle and Daraio, 2003). Bulk sediment samples were collected and wet sieved at 2 bars and 2 riffles for all reaches except the reservoir reach, which only had sampling at bars, during the summer of 2007 (Rosgen, 1996).

Figure A.1. Rating curve for Calapooia River at Brownsville for 2008 water year. The lowest and highest discharge measurements used for the rating curves are listed in the figure.

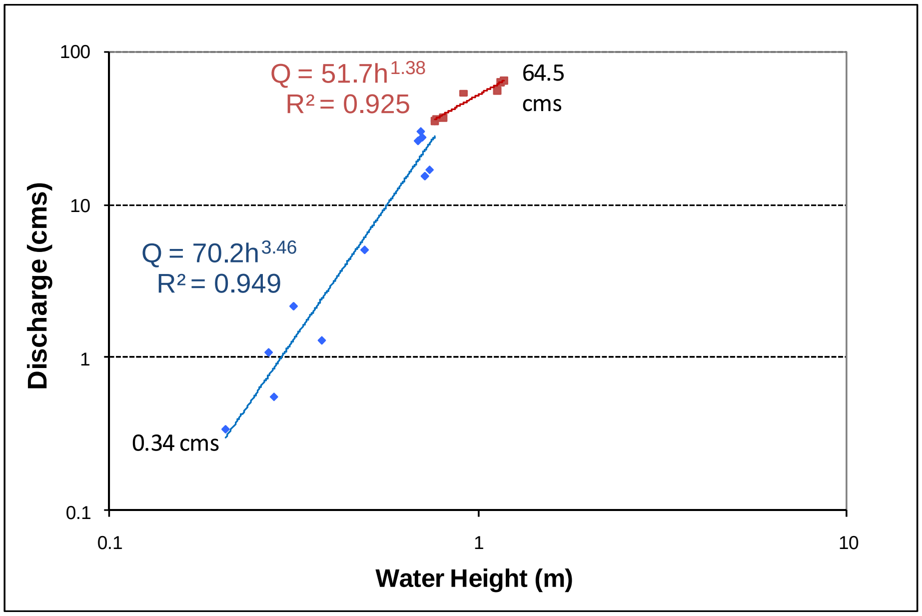


Figure A.2. Snapshots of each aerial photo adjacent to the dam in the first downstream reach (DS1).

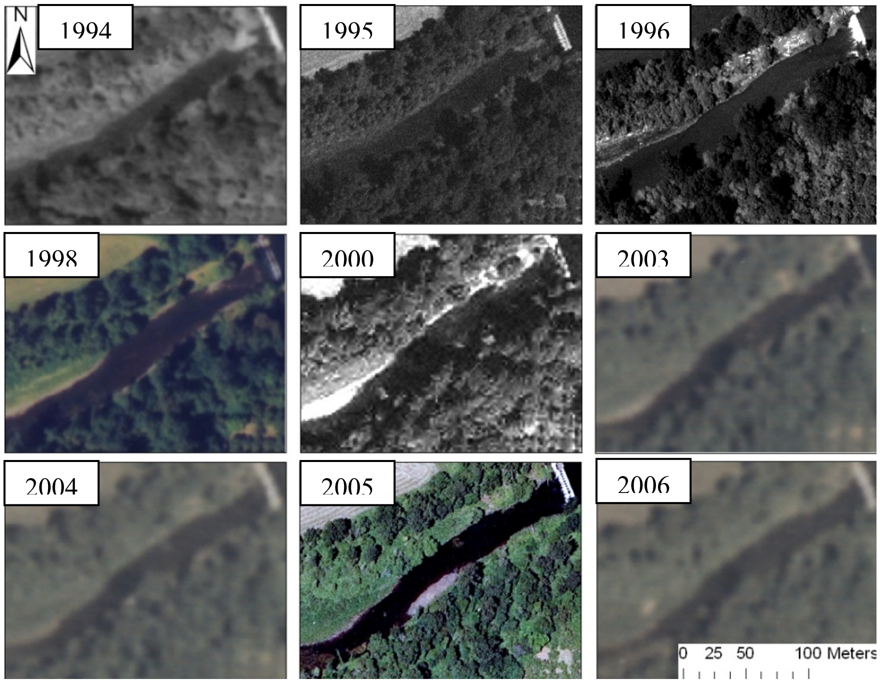


Figure A.3. Snapshots of each of the aerial photos in the upstream half of the second downstream reach (DS2).

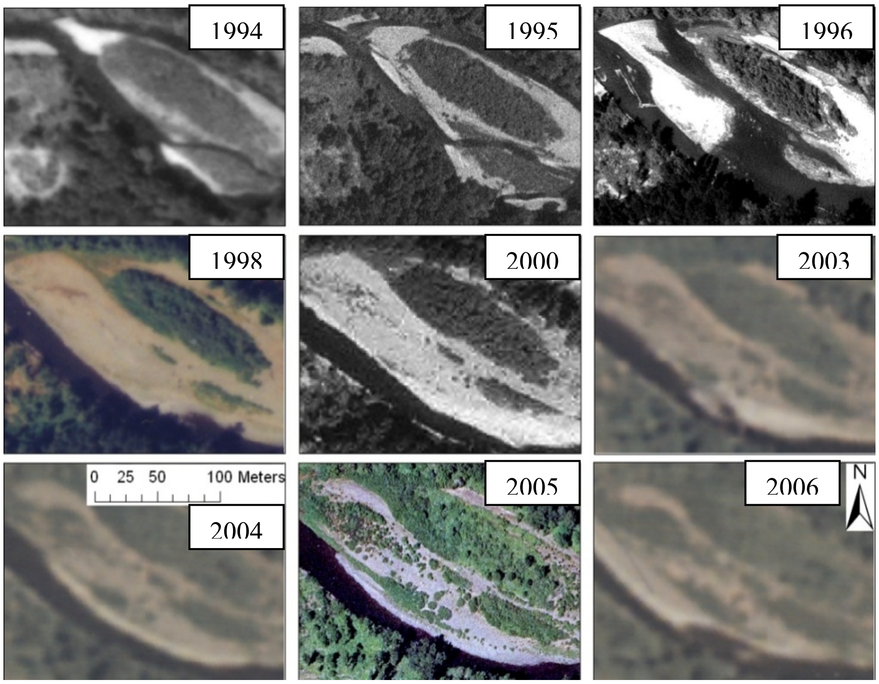


Figure A.4. Snapshots of each of the aerial photos in the downstream half of the second downstream reach (DS2).

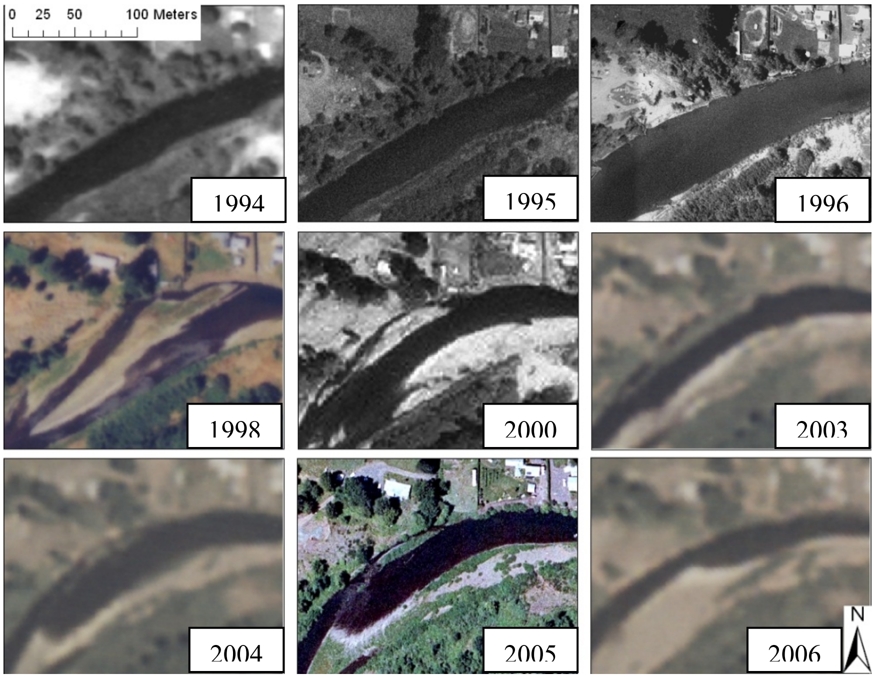


Figure A.5. Snapshots of each of the aerial photos in downstream half of the upstream reach (US).

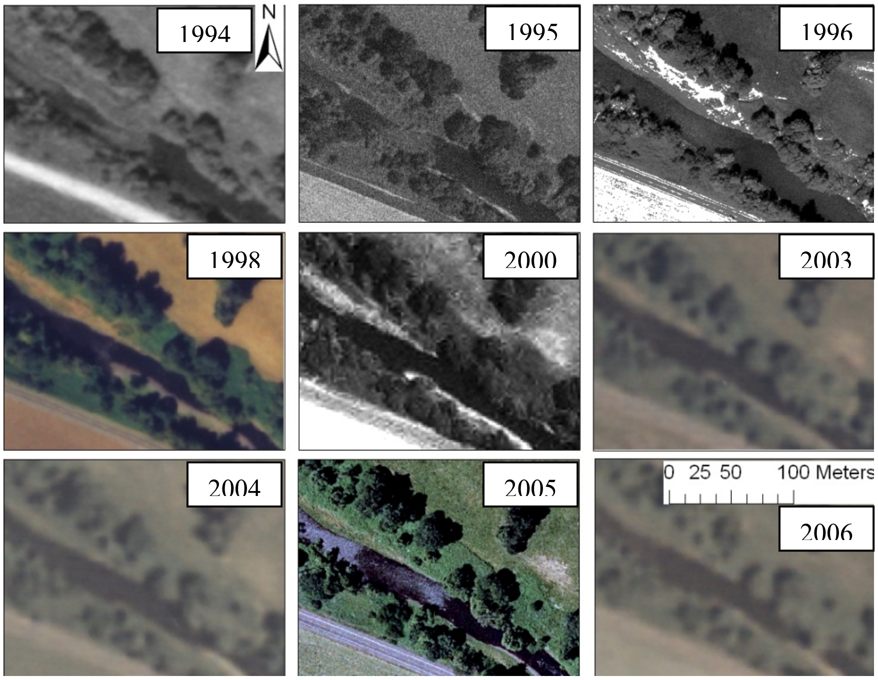


Table A.1.
Discharge regression models for the Calapooia River at Holley
Validation RMSE values are maximums as a result of including USGS discharge error

Model	Mohawk coefficient	South Santiam coefficient	Intercept	R^2
Annual Peak[a]	0.45	0.39	0.66	0.92
Average Daily Spring[a]	0.53	0.44	-0.21	0.96
Average Daily Summer[b]	N/A	0.81	0.12	0.92

[a]: $\ln(\hat{Q}_H / DA_H) = b_1 \ln(Q_M / DA_M) + b_2 \ln(Q_{SS} / DA_{SS}) + a$

[b]: $\ln(\hat{Q}_H) = b_1 \ln(Q_{SS}) + a$

Table A.2.
Consumptive use water rights by reach on the Calapooia River

Location	Consumptive use water rights (cms)
Above Holley USGS gage	0.06
Above US reach	0.34
Within US reach	0.35
Above DS1 reach	0.42
Within DS1 reach	0.42
Within DS2 reach	0.44
Above Brownsville Bridge	0.49

Source: Oregon Water Resources Department: Willamette Basin Water Right shapefile: http://www.wrd.state.or.us/OWRD/MAPS/index.shtml#Water_Right_Data_GIS_Themes

Table A.3.
Estimated average daily discharge at Holley during field surveys

Date	Average Daily Discharge (cms)	Reach	Error (cms)
8/16/07	0.7	US	0.6
8/17/07	0.7	US	0.6
8/18/07	0.7	US	0.6
8/21/07	1.4	DS1	0.9
8/22/07	1.0	DS1	0.8
8/23/07	0.9	DS1, DS2	0.7
8/24/07	0.8	DS2	0.7
8/25/07	0.8	DS2	0.6
8/28/07	0.7	DS2	0.6
9/27/07	0.6	US, DS2	0.6
7/30/08	1.4	DS1	0.9
7/31/08	1.4	DS1	0.9
8/5/08	1.2	DS1	0.8
8/6/08	1.1	DS1	0.8
8/7/08	1.1	DS1, DS2	0.8
8/11/08	1.0	DS2	0.8
8/12/08	1.0	US	0.8
8/13/08	1.0	US	0.7
8/14/08	1.0	US	0.7
8/19/08	0.9	DS 2	0.7
8/20/08	1.4	DS 2	0.9
8/21/08	2.4	DS 2	1.4
8/25/08	1.2	US	0.8
8/26/08	1.2	US	0.8
8/29/08	1.0	DS1, DS2	0.8

Table A.3.
Estimated average daily discharge at Holley during aerial photos

Date	Average Daily Discharge (cms)	Error (cms)
5/24/1994	3.7	1.9
6/29/1995	3.2	1.7
4/30/1996	15.6	11.2
8/10/1998	1.0	0.8
7/24/2000	1.3	0.9
6/26/2003	1.5	1.0
6/20/2004	3.9	2.0
7/3/2005	2.8	1.6
6/23/2006	3.3	1.8

4/1/2000	6.5	6.5