Journal of Environmental Management xxx (2008) 1–12

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals

Denine Schmitz [a,*], Matt Blank [b], Selita Ammondt [c], Duncan T. Patten [a]

[a] *Land Resources and Environmental Sciences, Montana State University, Bozeman, MT 59717, USA*
[b] *Western Transportation Institute, Montana State University, Bozeman, MT 59717, USA*
[c] *Earth Sciences, Montana State University, Bozeman, MT 59717, USA*

A R T I C L E I N F O

Article history:
Received 29 February 2008
Received in revised form 29 June 2008
Accepted 30 July 2008
Available online xxx

Keywords:
Dam removal
Dam failure
Dam breach
Paleoflood hydrology
Ecological response
Riparian vegetation
Hydrologic modeling
Montana

A B S T R A C T

The restorative potential of dam removal on ecosystem function depends on the reversibility of dam effects and its operations. While dam removal is an established engineering practice, the need for an understanding of the ecological response remains. We used paleoflood hydrology, hydrologic modeling, and aerial photo interpretation to investigate the long-term ecologic responses to dam failure and breach. We investigated downstream geomorphic and vegetation responses to a dam failure (Pattengail Dam in 1927) and a controlled dam breach, which used natural sediment removal (Mystic Lake Dam in 1985). Our data showed vegetation responses indicative of channel and floodplain evolution at Pattengail. The size of the flood following the Pattengail dam failure initiated a series of channel adjustments and reworked over 19 ha of floodplain downstream of the dam. In Mystic, we observed few flood stage indicators and a slight response in floodplain vegetation. We made several findings. (1) Dam removal effects on channel evolution and floodplain development depend on reach types and their responsiveness to flow regime change. (2) Ecologic response to dam removal depends on the sizes and timing of high flow events during and following removal. (3) Paleohydrology can be used to assess historic floods (>20 years). We see the utility of assessing the ecological responsiveness of a system to previous fluvial events or changes in flow regime. Informed about the character of a system based on its history, dam removal scientists can use these tools to set realistic restoration goals for removing a dam.

1. Introduction

At a 2004 dam removal conference in Missoula, Montana, the nation's leading dam removal scientists expressed a recurring and resounding theme; they need knowledge of the long-term ecological effects of small dam removal in order to develop dam removal as a restoration tool. Despite this gap, dam removal as an approach to restoring riparian and aquatic ecosystems is gaining popularity worldwide (Iversen et al., 1993; Arnould, 1997; Pohl, 2002). Yet, Hart et al. (2002) report the rarity of ecological monitoring incorporated in dam removal projects. Consequently, we lack long-term knowledge of reach and watershed scale ecological responses to dam removal and need to address this issue with interdisciplinary approaches. In a perfect world, one would design a study to compare ecological function before and after a dam removal. However, these opportunities are rare, costly, and often wrapped in layers of sociopolitical agendas.

Alternatively, we can gain some insight into the ecological effects of two dam removals using a retrospective approach. Because floodplains retain relicts (*e.g.* flood deposits, old channels, vegetation patterns) from decades of floods, base lowering events, and flow regime alteration, we can examine a floodplain's history in its landforms. In addition to landscape relicts, we often have access to a recorded, albeit broken, history for a watershed through aerial photography archives. Paleohydrology is the study of the history and indicators of hydrologic events (Stedinger and Cohn, 1986). Using a combination of aerial photography interpretation and paleohydrology, we can attribute changes in floodplain geomorphology and riparian vegetation distribution to specific events (*i.e.* floods, dam construction, failure, or removal). Thus, researchers and practitioners have the opportunity to assess channel and riparian vegetation responses to past dam removals.

Floodplains retain relicts (*e.g.* flood deposits, old channels, vegetation patterns) from centuries of floods and base lowering events followed by decades of human flow regime alteration. In addition to landscape relicts, we often have access to a recorded, albeit broken, history for a watershed through aerial photography archives. Using a combination of aerial photography interpretation

---

[*] Corresponding author. Tel.: +1 541 523 1353; fax: +1 541 523 1965.
E-mail addresses: denine_schmitz@blm.gov (D. Schmitz), mblank@coe.montana.edu (M. Blank), dtpatten@montana.edu (D.T. Patten).

0301-4797/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jenvman.2008.07.028

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

and paleohydrology (which focus on the history and indicators of floods), for documenting landscape relicts, we can attribute changes in floodplain geomorphology and riparian vegetation distribution to specific events (*i.e.* floods, dam construction, failure, or removal). Although new as restoration tool, dam removal has a history as long that of dam building. Thus, worldwide, we have opportunities to ascertain the effects of dam removal for a given ecological setting.

In addition, dam removal scientists can apply these retrospective techniques to assess the responsiveness of a stream system to past changes in flow regime. Restorationists can use historical assessments that incorporate aerial photography and paleohydrology to design dam removals as channel and floodplain restoration tools. With a long-term understanding of the character of a river system, dam removal decision makers and restoration scientists can set attainable restoration goals for dam removals. We examine two geomorphically different stream systems for evidence of ecological responses to dam removal using paleoflood hydrology and aerial photo interpretation.

1.1. *Background*

Dams are removed for many reasons: environmental (aquatic connectivity and river restoration), economic (dam maintenance and improvement) and social (private water rights and dam ownership). The current state of the science of dam removal in the United States is mostly based on experiences in Midwestern and Northeastern states under highly controlled environments. Western states (*i.e.* California, Oregon and Washington) are increasingly removing dams, adding to the variety of dam removal settings. Internationally, Nilsson et al. (2005) showed that over half of the world's large river systems are altered by dams, and that number is increasing to serve growing populations in developing countries. Thus, as existing dams age, their downstream populations grow, and the ecological cost of their effects outweighs their utility, ecologists worldwide will eventually be faced with the issue of dam removal.

1.1.1. *Restoration potential*

The restorative potential of dam removal on ecosystem function depends on the reversibility of the ecological effects of the dam. The initial effect of dam removal is the reestablishment of the natural flow regime, sediment dynamics, and longitudinal connectivity between up-and downstream reaches (Bednarek, 2001). In a restored natural flow regime, vegetation recruitment, species diversity, and successional processes within riparian areas will increase with time. Restored sediment dynamics can increase channel and floodplain development, in addition to water quality and nutrient cycling, all of which ecologists can detect in riparian plant communities (Shafroth et al., 2003) and biogeochemistry (Stanley and Doyle, 2002). Thus, by removing a dam, managers can restore the vertical, lateral, and longitudinal gradients that drive ecological processes along a stream.

The ranges of channel and floodplain environmental gradients, as they affect riparian vegetation, are wider under natural versus regulated flow regimes. Vertical gradients directly affect plant composition through changes in water table elevations (Stromberg et al., 1996), but indirectly through changes in water depth during floods (Bendix, 1994). Lateral gradients incorporate several environmental conditions, such as soil moisture and other properties (Nilsson, 1987), depth to water table (Stromberg et al., 1996), flow hydraulics (Simon and Rinaldi, 2006), as well as floodplain and valley geomorphology (Piegay et al., 2000; Steiger and Gurnell, 2003). Along longitudinal gradients, flow hydraulics vary with valley and reach geomorphology (Grant and Swanson, 1995) and, therefore, influence plant community composition.

Additionally, when restorationists restore natural sediment dynamics by removing a dam, they will incur short-term losses. The effect of releasing sediment stored in reservoirs is channel incision; adding sediment to sediment starved downstream channels and floodplains results in burial of fish and riparian habitat. The aquatic and riparian communities will be negatively impacted by the abrupt change in flow and sediment dynamics. However, most sediment responses to dam removals and failures are short-term, and on the order of days to weeks to a few years (Winter, 1990; Department of Urban and Regional Planning (DURP), 1996), and vary with discharge (Pizzuto, 1994). By the same token, many aquatic and riparian species are adapted to, at times require, sediment pulses (Junk et al., 1986). Over a short time, fish spawning habitat, macroinvertebrate habitat, and water quality will likely improve (Iversen et al., 1993; Bushaw-Newton et al., 2002; Stanley et al., 2007). In addition to these benefits, by removing dams, we run the risk of permanently losing species that have adapted to lentic, cold water, and low sediment environments (Catalano et al., 2001). Importantly, in order to realize the restoration potential of dam removal on a system, managers need to document the ecological functions and traits lost due to the dam and its operations as well as the ability of the system to respond to the removal, as intended.

1.1.2. *Sediment management*

The sediment management method used in dam removal has great influence over the short- and long-term geomorphic, chemical, and ecological effects (Bednarek, 2001; Pizzuto, 2002; Burroughs, 2007). Sediment in the empty reservoir can be removed naturally, removed mechanically, or stabilized in place. Natural sediment removal allows the natural processes of erosion, deposition, floodplain development and channel evolution to distribute reservoir sediments with subsequent flood events. These processes occur as a result of base level lowering (Schumm et al., 1984) and depend on dam, reservoir, river, substrate, and watershed characteristics. Mechanical sediment removal entails dredging the reservoir sediments (once drained) and using them elsewhere, such as in road bases, filling of open pits and construction foundation materials (Shuman, 1995). Stabilizing sediments occurs through capping with concrete (or equivalent) or vegetation. Both mechanical removal and stabilization reduce short-term effects on up and downstream reaches and inhibit invasive plant establishment on newly eroded or deposited surfaces (Winter, 1990). While we recognize that the sediment removal method is highly influential on the outcome of a dam removal effort, a full discussion of the topic is beyond the scope of this work. See Doyle et al. (2003a) and Grant et al. (2003) for further discussion on the topic.

1.1.3. *Dam removal versus dam failure*

Engineered removals are done at base flow (including breach to bed level, partial removal, or full removal), and the structure is either completely or partially dismantled down to the original channel bed level and transported offsite. In the Lake Mills drawdown experiment (Glines Canyon Dam, Port Angeles, WA), a notched method allowed controlled drainage of the large reservoir (Grant, 2004). If natural sediment removal is chosen, a small to moderate amount of the reservoir sediment is transported with drainage (Winter, 1990; Department of Urban and Regional Planning (DURP), 1996). Then, during subsequent floods, varying amounts of sediment are removed depending on flood size and sediment composition (Winter, 1990; Department of Urban and Regional Planning (DURP), 1996; Doyle et al., 2003b). Short-term data show that channel adjustments will likely mimic base level lowering (Schumm et al., 1984; Doyle et al., 2003b) and vary with dam, river, and watershed attributes. Additionally, vegetation responses may tend toward weedy species due to the timing of the

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

disturbance (Dukes and Mooney, 1999). These weedy species may have a founder's effect and inhibit native species establishment (Middleton, 1999).

Conversely, dam failures (natural or human dams) generally occur at peak flow. The large flows have the capacity to transport more volume and larger-sized sediments. While some failures are explosive, resulting in flash floods, many failures occur slowly due to piping, overtopping, or partial rupture, causing slow drainage over a period of days to weeks (Costa and Schuster, 1988; Cenderelli and Wohl, 2001, 2003; Butler and Malanson, 2005). Differences in flood peaks from natural dam failures are controlled by dam characteristics and failure mechanisms (Costa and Schuster, 1988) similar to human dam removals. Ecologically, draining reservoirs (natural or human) at peak flow has the highest potential to benefit up- and downstream riparian and aquatic plant communities. In the western United States, cottonwood, alder, and willow species release seed at about the time of peak flow, increasing their probability of landing on moist, wet sediment, germinating, and surviving to reproductive age (Mahoney and Rood, 1998). Further, some wetland species have adapted to reproducing during anaerobic conditions at specific times during the growing season (Middleton, 1999; Mitsch and Gosselink, 2000). Also, some aquatic communities have adapted to sediment pulses during peak flows (Catalano et al., 2001), and once established, these natives have a higher chance of resisting non-native invasions. Thus, an analysis of the natural flow regime of a potential dam removal setting and the adaptations of native species to that regime can inform restoration goals.

1.1.4. Paleohydrology

Paleohydrology is the study of past or ancient floods where paleoflood stage indicators are used to estimate peak flows (Baker, 1987). Where dams have failed or been removed with natural sediment removal, subsequent flood events transport sediment downstream, creating fluvial deposits of sediment and wood, as well as scour zones and vegetation scars on the floodplain. While paleohydrology is generally applied to Holocene floods (100–10 000 years), Jarrett (1990) estimated the peak discharge from the 1976 Big Thompson flood near Loveland, Colorado using a combination of paleohydrology and regional flood frequency estimates. Wohl (1995) applied these techniques in ungaged streams in Nepal where hydrologic data are sparse, or untraceable. We can use this technique to estimate peak flows and their paths following dam removal. In addition, where we need to understand the ecological responsiveness of a stream system prior to setting restoration goals, we can apply paleohydrology to estimate peak flows and assess the ecological response.

2. Materials and methods

We chose two existing dam sites that varied in environmental setting and removal method—Pattengail Dam and Mystic Lake Dam. The relatively large reservoir and drainage area of Pattengail combined with high water dam failure and glacial alluvial valley made it a good site for testing our method in a geomorphically responsive, high energy environment. Conversely, the small reservoir size and drainage area of Mystic combined with a controlled dam removal in a constrained, stream cut valley made it a good site to investigate dam removal effects in a geomorphically unresponsive, low energy setting.

2.1. Site description

Pattengail Dam is located in the Pioneer Mountains 40 miles southwest of Butte, Montana, on Pattengail Creek (Fig. 1). The dam is 1.5 km upstream of the Pattengail Creek-Wise River confluence. Pattengail Dam was built in 1903 and failed during a rain on snow event in 1927. The estimated flow from the failure was intense enough to incise the channel up to 2 m from its pre-failure elevation and to deposit car-sized boulders.

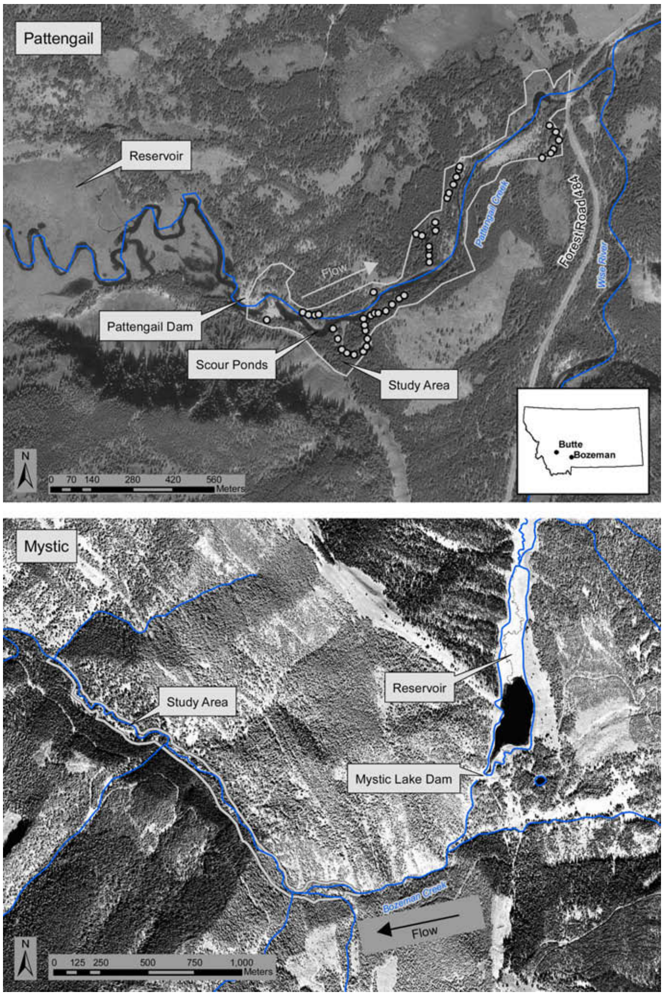

Fig. 1. The Pattengail study reach was 1.5 km long with plane-bed and riffle-pool channel types (1995 aerial). The Mystic study reach was 2 km long with cascade and plane-bed channel types (2001 aerial). The two study areas occur in southwest Montana in the Pioneer and Gallatin Mountains, respectively.

The Pattengail Creek watershed is approximately 186 km^2. When the dam was in operation, the reservoir stored 14.8 million m^3 of water which created a reservoir over 3.2 km long. Much of the 12-m tall original structure exists today. There has been no channel restoration, removal of remaining dam structures, or treatment of reservoir sediments since the failure. Below the dam, the creek flows through a wide valley along an unconstrained reach in plane-bed and riffle-pool channel types. Based on relict channels detected during field reconnaissance, local interviews, and aerial photo interpretation, we found that there was a meandering channel prior to dam failure. The current channel has low sinuosity, and is in a state of high flux. Also, the channel evolves from a series of scour ponds near the dam break to glides, braids, and riffle/pool sequences about 2 km downstream (Fig. 1).

The geology of the Pattengail area is Precambrian meta-sandstone and meta-conglomerate bedrock overlaid with glacial and lake deposits. Upland land cover is predominantly *Pinus contorta* and *Populus tremuloides*. The creek meanders through the valley floor where several beaver ponds and *Salix–Carex* wetlands occur. We located our 2 km study reach immediately downstream of the Pattengail Dam and upstream of the bridge on Forest Road 484.

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

Mystic Lake Dam (Fig. 1) is located approximately 16 km south of Bozeman, Montana, on Bozeman Creek (Fig. 1). It was built in 1901 and removed in 1985. This 13-m tall dam augmented a lake formed naturally from an active landslide. Once dammed, the reservoir volume was approximately 1.5 million m^3. The drainage area at the dam is approximately 31 km^2. Due to many structural integrity issues and an increasing human population downstream, the dam was removed at low flow in April 1985, according to the City of Bozeman. The reservoir sediment was left untouched. US Forest Service and City of Bozeman restored approximately 100 m of stream channel and riparian area below the removed dam.

The geology of the Mystic area is primarily Cambrian sedimentary with intrusions of gneiss. The dominant upland and valley bottom land cover is *Picea engelmannii–Symphoricarpos alba*. Directly downstream of Mystic Lake Dam is a narrow canyon with limited or no floodplain area. We located our 2 km study reach just downstream of this canyon where the valley widened and allowed floodplain development. This study reach was constrained in a narrow valley with cascade and plane-bed channel types (Montgomery and Buffington, 1997).

2.2. Aerial photo processing

We chose not to use reference reaches, that is, space for time, to avoid ascribing spatial differences potentially attributed to geomorphic, cover type, land use, or other environmental factors to temporal changes.

We assessed aerial photos showing the Mystic site from 1971, 1989, 1995, and 2001 (Table 1) and the Pattengail site from 1942, 1979, and 1995. We acquired the 1995 digital orthophoto quadrangles (DOQ) for both sites from the Montana NRIS web site and the Mystic 2001 (orthorectified, color infrared) images from the Gallatin Local Water Quality District. With a high resolution scanner, we digitized hard copies of Mystic photos from 1971 and 1989 and Pattengail images from 1942 and 1979 and computed photo scale (Table 1). Then, we georeferenced them to the 1995 photos using ArcView 9.1. Using 15 control points in each image, we produced georeferenced images with maximum root mean square (RMS) values of 3.5 and 2.6 for Mystic and Pattengail, respectively. RMS values are dimensionless measures of the difference between control points on the control photo (1995 digital orthoquad quadrangle) and the georeferenced image (scanned image). While we cannot assign a distance measure to RMS values, we can choose control points that minimize RMS values as an indication of best fit (ESRI, 2005). We interpreted all photos at a scale of 1:10 000.

2.3. Floodplain delineation

We identified floodplains for 2 km study reaches downstream of each dam. In addition to this, we delineated the Pattengail Creek floodplain using aerial photos and field reconnaissance. We used a 1995 digital elevation model to topographically distinguish the floodplain from the steep sides of the Bozeman Creek valley. Based on texture, color, shape, size, pattern, and association, we interpreted images and classified land cover into five types: coniferous, deciduous, herbaceous, bare ground, and water. We limited our interpretation to canopy vegetation because it was visible on all aerial photos and indicative of major changes to the riparian landscape. While understory vegetation is disturbance-dependent, its analysis was not possible using the historic aerial photos.

Table 1
The aerial photos used to assess historic vegetation distributions ranged from 4 to 78 years after dam removal.

Pattengail			Mystic		
Photo year	Photo scale	# Years post-removal	Photo year	Photo scale	# Years post-removal
1942	1:18 300	15	1971	1:19 400	Pre-removal
1979	1:18 200	52	1989	1:20 200	4
1995	1:40 000	68	1995	1:40 000	10
			2001	1:24 000	16
2005[a]	1:40 000	78	2005[a]	1:40 000	20

[a] Field observation.

Table 2
The regional estimate equations using active channel width were developed in Parrett and Johnson (2004).

	Equation	Flow estimate (m^3/s)	Standard error of prediction (%)
Pattengail Region	$Q100 = 41.8$ channel width$^{1.02}$	32.8	89.5
	$Q500 = 93.2$ channel width$^{0.875}$	45.9	112.4
Mystic Region	$Q2 = 2.44$ channel width$^{1.52}$	3.0	71.1
	$Q5 = 10.1$ channel width$^{1.29}$	4.3	67.4

2.4. Hydrologic characterization

We estimated historic peak flows using four independent approaches: (1) modeled flow using paleohydrology and step-backwater techniques (Cenderelli and Wohl, 2001), (2) empirically derived, regional estimates of peak annual discharge (Parrett and Johnson, 2004), (3) hydrograph records, and (4) reservoir drainage time. We applied the fourth approach only to Pattengail because the dam failed and the reservoir drained there; whereas, the dam at Mystic was removed in a controlled manner during low flow.

While paleohydrology is generally applied to Holocene floods (100–10 000 years) (Baker, 1987), it may also be used to estimate the peak discharge from an event if fluvial deposits can be identified and attributed to that event (Jarrett, 1990). Jarrett (1990) used these methods to determine the recurrence interval of a flood that occurred 20 years prior to analysis, and Wohl (1995) applied them to ungaged streams to determine discharges from events that occurred 40 years ago.

Flow model. We estimated peak discharge by combining paleoflood hydrologic techniques with a step-backwater model (Cenderelli and Wohl, 2001). By approaching flow estimation with two independent data sources, flood stage indicators (FSIs) and nonflooded surfaces, we arrived at the best possible estimate of the historic flood environment. We included fluvial sediment deposits, woody debris piles, and scour zones in the suite of FSIs, and undisturbed vegetation and changes in substrate as nonflooded surfaces. The step-backwater method uses gradually varied flow hydraulics to calculate the water surface for a discharge of interest. See Chow (1959) for a detailed discussion of gradually varied flow and the step-backwater method. We used HEC-RAS version 3.1.2 to calculate water surfaces with the assumptions that the gradually varied flow (in space) was steady (over time) and one-dimensional.

Peak stage determination is a critical component of our historic peak discharge estimate (Pruess et al., 1998). The accuracy of FSIs and nonflooded surfaces for estimating peak flows is susceptible to several uncertainties (Jarrett and Tomlinson, 2000): FSIs tend to underestimate peak discharge, and while high water marks tend to accurately indicate peak stage, they are ephemeral (Jarrett and Tomlinson, 2000). Lastly, using nonflooded surfaces as an indicator of peak stage tends to overestimate peak discharge.

In order to maximize the accuracy of the peak discharge estimate and to account for the uncertainties previously described, we estimated a range of flood stages by bracketing the upper and lower limits of the flood environment at each of several cross sections in the stream channels. The lower elevations of nonflooded surfaces

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

and high water marks served as the upper limits and the highest elevations of FSIs served as the lower limits. We predicted water surfaces bounded by nonflooded surfaces and FSIs. The "best match" was the discharge that minimized the average error, calculated as the average of the difference between the predicted water surface and the upper and lower limits at each cross section, across the entire modeled reach.

The step-backwater technique requires estimated boundary conditions to initiate the calculation of the water surface. We assumed the water surface at the downstream end of the model was equal to the critical depth and that the flow was subcritical during the flood events. Due to the constriction, a bridge at the downstream end of Pattengail may have caused critical flow, a potential assumption violation. For Mystic, we placed the farthest downstream cross section at a natural constriction in the river channel because flow during extreme flood events in these channels is primarily subcritical (Jarrett, 1984; Trieste and Jarrett, 1987). Sources of energy loss in the step-backwater method include channel and floodplain roughness elements, in addition to points of flow expansion and contraction. Also, significant energy loss occurs during extreme flood events due to turbulence and sediment/debris transport. We used Manning's *n* as an integrated flow resistance coefficient to account for the total energy loss.

An iterative process approximated discharge and energy losses while maintaining subcritical flow through the modeled reach. With each iteration, we varied the channel roughness coefficients at each cross section, starting with an initial value based on analysis of aerial photographs and field assessments. Typically, we increased the roughness coefficients to maintain subcritical flow at each cross section.

In general, we placed cross sections at locations with gradually varied flow characteristics and paid attention to points of floodplain constriction and expansion along the reach (Fig. 2). At each cross section, we surveyed breaks in slope, banks, channel margins, and thalwegs. For Pattengail, we used a Leica survey-grade GPS system with sub-centimeter vertical accuracy. For Mystic, we used an autolevel and stadia rod because the narrow valley and dense vegetation interfered with satellite signals. The equipment yielded sub-meter vertical accuracy. We made site-specific adjustments to maximize model performance. For example, we excluded the upper reach because flow during failure was likely rapidly varied, thus violating the assumptions behind the step-backwater method.

For the Mystic study, we predicted the discharge required for overbank flow based on surveyed bank elevations for two reasons. First, the dam breach was controlled, meaning there was no single large magnitude flow event (such as a dam failure) to create detectible FSIs. Second, we could not conclusively attribute the few detectible FSIs to post-dam breach flows. We chose a reach approximately 1.5 km downstream of the former dam site because the reach nearest the dam was largely a bedrock canyon, which made identification of overbank elevations difficult.

2.4.1. Regional estimates

As a second estimate method, we used empirically derived, regional estimates of peak discharge. Based on channel geometry, Parrett and Johnson (2004) developed regression models for hydrologic regions in Montana, Wyoming, Idaho, and Canada. Using the active channel width in these regional regression equations, we estimated peak discharges for 100-year and 500-year floods at Pattengail and for the 2-year and 5-year floods at Mystic, respectively (Table 2).

2.4.2. Hydrograph records

We analyzed hydrograph records as a third peak flow estimate. While the flow spike of the Pattengail Dam breach was detectible on the hydrograph (Big Hole River near Melrose, USGS 06025500, 80 km downstream), we could not conclusively separate it from other contributing sources. Therefore, we did not use this method for Pattengail. Hydrograph records for Mystic (Bozeman Creek, USGS 06047500, 4.8 km downstream) are discontinuous and represent only 1951–1953, 1967–1969, and 1975–1980, despite the fact that the drainage provides a significant volume of municipal water to over 35 000 people. The peak recorded discharge for this period was 11 m^3/s.

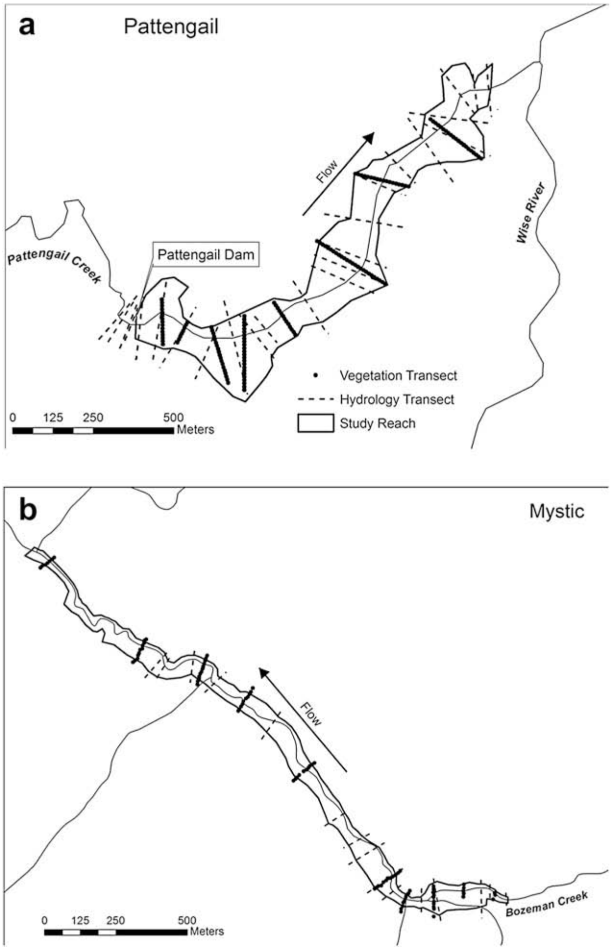

Fig. 2. Pattengail and Mystic vegetation and hydrology transects used to characterize historic land cover and estimate peak flows.

2.4.3. Reservoir drainage time

Our fourth flow estimate was reservoir drainage time; the time required to drain the reservoir volume. For Pattengail, we estimated the time required for the reservoir volume (14.8 million m^3) to drain over 48 and 72 h. These times were based on the flood spike duration detected at the gage. It is important to point out that this method is extremely coarse and the assumptions behind it, such as steady flow during the breach are not very realistic. However, it does provide another peak flow estimate for comparison. We did not apply reservoir drainage time to Mystic because dam managers removed the dam at low water.

2.5. Vegetation response

2.5.1. Data collection

We ascertained historic land cover data through aerial photo interpretation. We combined these data with field observations in 2005 to complete the time series 1942–2005 for Pattengail and 1971–2005 for Mystic, and we analyzed these series to determine

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

long-term vegetation changes due to dam failure and removal, respectively.

The field crew assessed vegetation transect points on the ground in Summer 2005 and mapped them using a Trimble GeoXT Global Positioning System (GPS) receiver. Pattengail transects ranged from 167 to 389 m with total 111 points; Mystic transects ranged from 57 to 169 m with 79 total points. To test the effect of downstream distance, we identified eight valley-wide transects perpendicular to floodplains. We spaced eight valley-wide transects 100 m apart for the first 500 m downstream from the dams, and 500 m apart for the remainder of the 2 km study reaches (Fig. 2). We tested for the effect of lateral distance from the thalweg by dividing each transect into points 10 m apart and interpreted land cover at each point for each photo year. For each year and land cover type, we entered the data in a binary format.

2.5.2. Analysis

We used logistic Generalized Linear Models (GLMs) to analyze the land cover response for each photo year to three variables indicative of vertical, lateral, and longitudinal environmental gradients. See Austin et al. (1990) for a detailed discussion of using GLMs to test the importance of environmental variables (continuous and categorical). As indicators of vertical, lateral, and longitudinal processes, we tested the influence of mean sea level (MSL), distance from the thalweg (DisTH), and distance from the dam (DisDam), respectively, on land cover data for each year. Because we did not collect vegetation data during the topographic surveys, we acquired MSL data from GPS data. While MSL is known to influence riparian vegetation on a watershed scale, we make the assumption that the study area stream reaches do not cross these thresholds. Also, we found that the channel slopes introduce less vertical error than the GPS data. We intend MSL to coarsely indicate environmental gradients associated with elevation changes across valley bottoms.

We tested simple linear and modal (quadratic) univariate models as well as multivariate models for significant relationships between land cover distribution and environmental gradients. We chose the best models based on the statistical significance of predictors in the model, maximum deviance explained, and highest prediction accuracy. We identified functional models as those with predictors with an alpha level of 0.1 or less. We assessed model performance using maximum deviance explained for the least number of degrees of freedom used. We compared the predicted "present" values with a probability greater than 0.5 with the observed values to calculate a percent accuracy.

3. Results

3.1. Pattengail flood hydrology

3.1.1. Flow model

We estimated a flood flow of 80 m^3/s based on the step-backwater technique in combination with paleohydrology. This model provided the minimum error and the "best fit" to the FSIs. Using the critical depth control at the downstream end of the modeled reach, we estimated the water surface relative to the FSIs and the non-flooded surface (Fig. 3). The extent of the modeled flood waters is shown in Fig. 4. We increased the channel roughness coefficients up to 100% from their initial values to maintain subcritical flow through the modeled reach (Table 3).

3.1.2. Other flood estimates

The other methods yielded varying estimates of flood flow. The regional estimates for the 100- and 500-year events at Pattengail, based on active channel widths (Parrett and Johnson, 2004), were 33 m^3/s and 45 m^3/s, respectively (Table 2). The estimates based on reservoir drainage time in 48 h and 72 h were 85 m^3/s and 43 m^3/s, respectively. The flood spike from the dam failure contributed to the 345 m^3/s measured at the Big Hole River gage near Melrose.

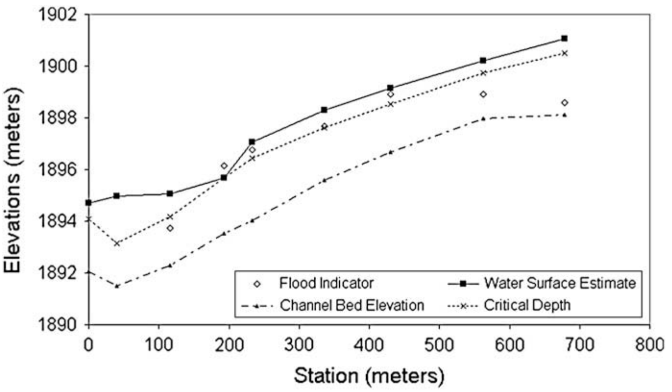

Fig. 3. The figure shows a longitudinal profile of the "best fit" water surface relative to the FSI elevations, channel bed elevations and critical depth elevations for Pattengail Creek.

3.2. Mystic flood hydrology

3.2.1. Modeled flow using paleohydrology

The modeled discharge required for overbank flow ranged between 2 m^3/s and 6 m^3/s. The "best fit" estimate for overbank flow was 3.5 m^3/s (Fig. 5). We increased the channel roughness coefficients by up to 87% from their initial values to maintain subcritical flow through the modeled reach (Table 3). The flow was constrained within the overbanks. Therefore, we did not adjust the floodplain roughness coefficients.

3.2.2. Other flood estimate methods

We estimated a 2-year flood of 3.2 m^3/s using the empirically derived regional estimate based on active channel width (Parrett and Johnson, 2004). This compared well with modeled estimates of overbank flow. We omitted 100-year flood estimates due to the lack of flood stage indicators along the Mystic study reach. The hydrograph records for Mystic showed the largest discharge on record, 11 m^3/s in June 1975, prior to dam breach in 1985. Overbank flows occurred in three of the nine years of record, based on the step-backwater estimated discharge required for overbank flow and the hydrograph record.

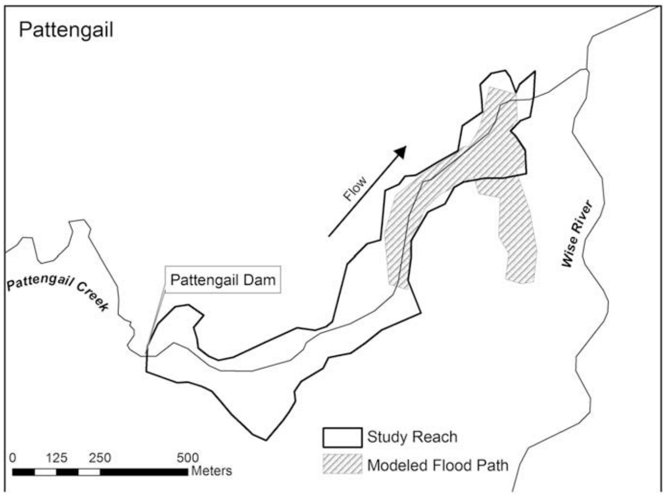

Fig. 4. Modeled flow path for Pattengail Creek following 1927 failure.

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

Table 3
We altered initial channel roughness coefficients as much as 100% for Pattengail and 87% for Mystic in order to find the best model of peak flow since dam failure or removal.

Cross section	River station (m)	Initial values	Final values
Pattengail			
1	0.00	0.075	0.075
2	40.26	0.075	0.075
3	116.11	0.075	0.050
4	192.64	0.075	0.150
5	232.74	0.075	0.100
6	335.66	0.075	0.100
7	429.94	0.075	0.100
8	562.46	0.075	0.050
9	678.64	0.075	0.050
Mystic			
1	1717.43	0.04	0.060
2	1636.15	0.04	0.050
3	1608.26	0.04	0.075
4	1387.39	0.04	0.050
5	1091.44	0.04	0.060
6	1002.80	0.04	0.050

3.3. Pattengail land cover changes

In order for our techniques to detect the ecological response of the Pattengail plant communities, the communities had to either survive the 1927 flood or develop since the event. Therefore, our results are biased toward active processes that occurred adjacent to or along the margins of the flood path such as subirrigation, deposition of fine sediment, and water table recession. In addition, those processes active within the channel since June 1927, such as channel migration, deposition, erosion, and low magnitude floods potentially influenced land cover within the study reach. Also, our techniques will necessarily include plant communities that occurred along the margins of the flood wave, which include a substantial amount of upland plant communities. Thus, because of the shear magnitude of the 1927 flood, our results will include an unusual amount of upland plant communities for a riparian study.

3.3.1. Temporal distribution

In Pattengail, we observed a steady decline in bare ground and deciduous cover and comparable increase in coniferous cover between the 15 and 78 years since dam failure (Fig. 6). Herbaceous cover and channel area showed no detectible changes over the study period.

Bare ground markedly declined from 36% to 10% between 1942 and 1995 (Fig. 7). Then it declined further from 10% to 5% in 2005. This second decline could be due to overbank flows recorded in the region in 2005. Of this 36%, 10% was colonized by coniferous species, 11% by deciduous species, and 3% by herbaceous species (Table 4). Two percent of the bare ground was overtaken by the channel and the remaining 11% remained unchanged between 15 and 52 years since dam failure.

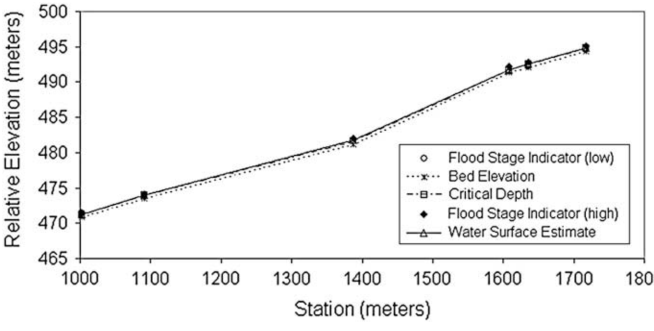

Fig. 5. The figure shows a longitudinal profile of the "best fit" water surface relative to the FSI elevations, channel bed elevations and critical depth elevations for Mystic model.

Deciduous cover gradually decreased from 37% to 12% since Pattengail Dam failed (Fig. 7). We attributed the net loss of deciduous cover to coniferous species encroachment (Table 4). However, there were simultaneous gains in deciduous cover due to bare ground colonization by deciduous species (11%) and channel migration (4%).

Coniferous cover steadily increased from 12% to 61% from 1942 to 2005 (Fig. 7). We attributed the net increase to substantial and steady declines in deciduous cover and bare ground since the 1927 dam failure (Table 4). We observed small losses of coniferous cover due to increases in deciduous (4%), herbaceous (2%), and channel migration (2%).

3.3.2. Environmental relationships

Although not discernable through descriptive statistics, we detected several relationships between Pattengail land cover types and the environmental gradient variables MSL, DisTH, and DisDam using a multivariate approach. We focused our multivariate analysis on coniferous, deciduous, and bare ground cover types because they encompassed the majority of the data set. We found significant GLMs at the $\alpha = 0.1$ level for all but the 1942 deciduous cover type (Table 5). We found all three environmental variables made contributions to more than one model. While coefficients were all very low (10^{-1} to 10^{-6}), they were statistically different from zero. The best models explained between 12% and 74% of the deviance and accurately predicted 68–98% of the data (Table 5).

In the 1942 coniferous model, we found that increasing MSL and DisTH were related to higher probabilities of coniferous cover (Table 5). Further, we interpreted model output to show an increasing elevation effect with increasing distance from the thalweg. We saw a significant improvement in model performance with the addition of DisTH (88–93%). In the 1979 model, MSL, DisTH, and modal DisDam terms corresponded with higher probabilities of coniferous cover. We found that MSL exerted the strongest effect on coniferous cover 52 years after the dam failed (Table 5). In the 1995 and 2005 coniferous models, we discovered modal forms of DisTH and DisDam were related to optimal coniferous cover probabilities. Table 5 shows that DisTH carries the most weight in both models. In 1995 and 2005, 68 and 78 years since dam failure, we found that the probability of coniferous cover reached a maximum at 60 m from the thalweg (Fig. 8). Further, DisDam showed its greatest effect on this relationship between 500 and 1000 m downstream from the dam (Fig. 8).

The Pattengail deciduous models were variable between years. None of our 1942 deciduous models were statistically significant at $\alpha = 0.1$. For 1979 deciduous cover, we detected a linear model that showed increased probabilities of deciduous cover as MSL increased (Table 5). The 1995 model included DisTH and a modal MSL term. With this model, we found higher probabilities of deciduous cover at optimal MSL values and decreased DisTH. Although MSL carried the most weight, we saw an increase in deviance explained (10–23%) and no benefit in prediction accuracy with one less degree of freedom by adding DisTH to the model. Further, we detected minimal interaction between MSL and DisTH meters from the thalweg. Thus, interaction was greatest on the tails of the distribution. In the 2005 GLM, we found that modal forms of DisTH and DisDam produced a model that best fit the deciduous data. We detected an increase in probability of deciduous cover at optimal levels of DisTH and DisDam. Interestingly, we observed the maximal effect of DisDam on this relationship occurred at 60 m from the thalweg.

We found that all GLMs of bare ground distribution along Pattengail Creek included modal forms of DisTH or DisDam or both (Table 5). Using a modal form of DisTH, we saw higher probabilities of 1942 bare ground at an optimal DisTH of 55 m. The 1979 bare ground model included modal DisTH and MSL terms. We found the highest probability of bare ground at optimal MSL and DisTH

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

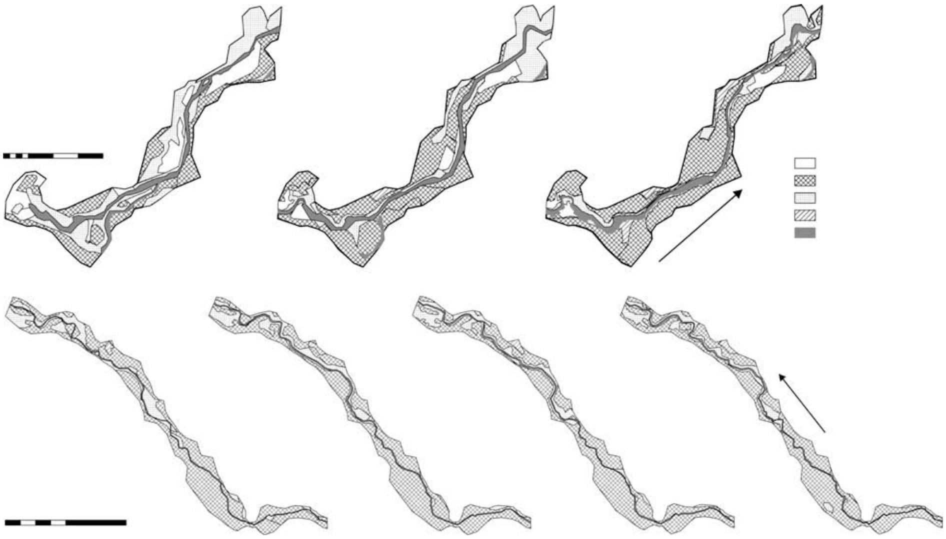

Fig. 6. Vegetation changes in Pattengail and Mystic show varying degrees of change.

values. Although we detected MSL as the dominant driver in the relationship, we found that DisTH increased the deviance explained from 13% to 23%, decreased the prediction accuracy from 87% to 68%, and reduced the degrees of freedom used by two. In the 1995 and 2005 GLMs, we found modal forms of DisTH and DisDam yielded the best results for bare ground cover. Of note, the effect of DisDam on DisTH peaked between 50 and 60 m from the thalweg. Conversely, the modal effect of DisTH on DisDam reached a *minimum* between 600 and 1000 m from the dam. The 1995 and 2005 models respectively accounted for 34% and 74% of the deviance and accurately predicted 94% and 98% of bare ground data. Thus, we found the 1995 and 2005 bare ground GLMs to perform the best of all the land cover models we tested (Table 5).

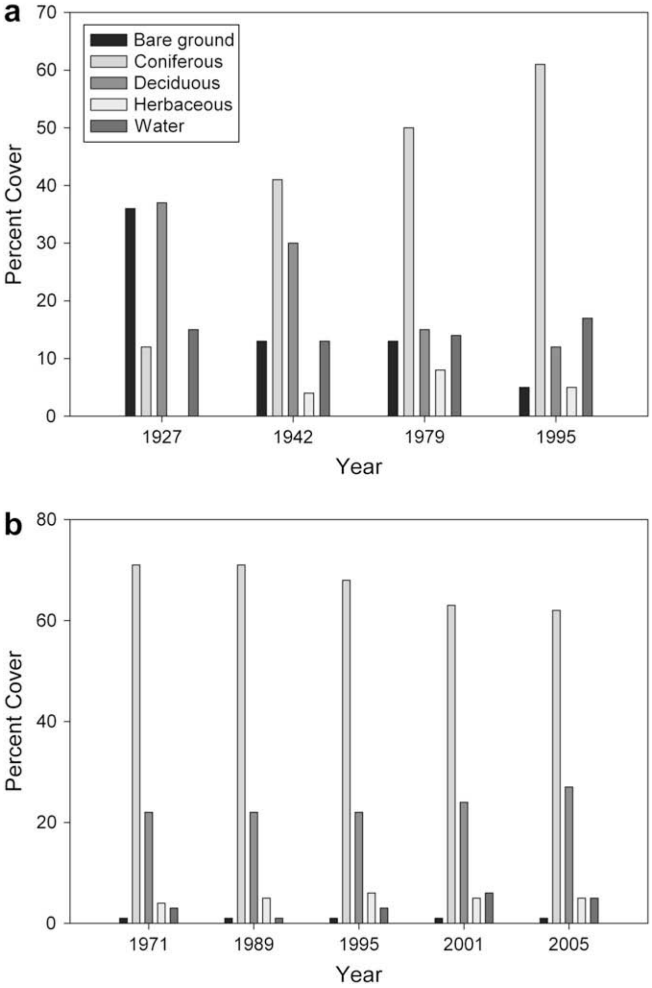

Fig. 7. Vegetation cover type changes following the 1927 Pattengail Dam failure indicate bare ground colonization, coniferous species expansion, and deciduous species constriction. Mystic land cover remained stable in response to dam removal.

3.4. Mystic land cover changes

At Mystic, we observed 62–71% of the observed points were coniferous and 21–27% were deciduous (Fig. 7). In the remaining 2–

Table 4
Land cover changes for Pattengail show the largest changes occurred due to coniferous species establishment. Mystic land cover changes for 79 points in each photo period were minimal. Land cover changes not observed were excluded from the table.

Pattengail	Photo Period			
	1942–1979	1979–1995	1995–2005	1942–2005
Land cover change (%)				
Deciduous–coniferous	16	7	1	13
Bare ground–coniferous	4	1	1	8
Deciduous–water	1	2	2	3
Bare ground–deciduous	7	0	1	3
Deciduous–herbaceous	1	1	1	2
Water–deciduous	2	2	2	2
Coniferous–deciduous	4	0	1	1
Coniferous–bare ground	0	0	1	1
Water–coniferous	2	1	1	1
Bare ground–water	1	0	0	1
Bare ground–herbaceous	0	0	0	1
No change	62	86	89	64

Mystic	Photo period				
	1971–1989	1989–1995	1995–2001	2001–2005	1971–2005
Land cover change (%)					
Coniferous–deciduous	6	0	5	1	11
Deciduous–coniferous	6	0	0	1	6
Coniferous–water	0	1	0	3	3
Coniferous –herbaceous	3	1	0	0	3
Herbaceous –coniferous	1	0	0	1	1
No change	81	97	91	90	76

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

Table 5
Summary of the best logistic GLMs for each land cover type, year, and site.

Year	Cover type	Predictors	Coefficient	Deviance explained	Prediction accuracy	Df (res/null)
Pattengail						
1942	Coniferous	MSL	0.138800	26%	93%	108/110
	+	DisTH	0.035720			
1979	Coniferous	MSL	0.259200	27%	77%	106/110
	+	DisTH	0.017580			
	+	DisDam	0.006807			
	+	DisDam^2	−0.000004			
1995	Coniferous	DisTH	0.133000	39%	84%	106/110
	+	DisTH^2	−0.000724			
	+	DisDam	0.009349			
	+	DisDam^2	−0.000007			
2005	Coniferous	DisTH	0.148000	34%	70%	106/110
	+	DisTH^2	−0.000981			
	+	DisDam	0.009520			
	+	DisDam^2	−0.000005			
1942	Deciduous	NS		NA	NA	NA
1979	Deciduous	MSL	−0.226370	12%	75%	109/110
1995	Deciduous	MSL	169.900000	23%	84%	107/110
	+	MSL^2	−0.044340			
	+	DisTH	−0.040410			
2005	Deciduous	DisTH	−0.024820	14%	88%	107/110
	+	DisDam	−0.007677			
	+	DisDam^2	0.000005			
1942	Bare ground	DisTH	0.106984	15%	68%	108/110
	+	DisTH^2	−0.000970			
1979	Bare ground	DisTH	0.118300	23%	87%	106/110
	+	DisTH^2	−0.001167			
	+	MSL	516.500000			
	+	MSL^2	−0.134600			
1995	Bare ground	DisTH	0.197300	34%	94%	106/110
	+	DisTH^2	−0.001916			
	+	DisDam	−0.011060			
	+	DisDam^2	0.000007			
2005	Bare ground	DisTH	0.650183	74%	98%	107/110
	+	DisTH^2	−0.005131			
	+	DisDam	−0.019561			
Mystic						
1971	Coniferous	DisDam	−0.000826	6%	76%	77/78
1989	Coniferous	MSL	1.314000	9%	76%	77/78
		MSL^2	−0.003552			
2005	Coniferous	MSL	0.061650	11%	77%	77/78
1971	Deciduous	MSL	−0.063070	10%	78%	77/78
1989	Deciduous	MSL	−0.102110	21%	80%	77/78
2005	Deciduous	MSL	−0.102110	21%	80%	77/78

17% of points we saw a combination of herbaceous, bare ground, and water cover types. Because the vast majority of land cover of observed points was coniferous or deciduous, we limited our multivariate approach to these two cover types. Through descriptive analyses, we found that herbaceous cover types remained between 1835 and 1850 m elevation, and decreased in cover with distance from the channel and the dam over the 34-year study period. We observed up to 10 m of channel migration.

All GLM models performed poorly. With the exception of one model, the best coniferous and deciduous models for all four years were simple models of MSL and cover type. We detected linear relationships between decreased MSL and increased probabilities of coniferous and deciduous cover. They explained 9–21% of the deviances and had 76–80% prediction accuracies (Table 5). In contrast, we found DisDam yielded the best results for the 1971 coniferous cover. We saw decreased probabilities of coniferous cover as DisDam decreased.

4. Discussion

4.1. Pattengail

The dam failure of 1927 on Pattengail Creek (built in 1901) yielded catastrophic stream flows, produced marked channel change, and evoked substantial floodplain vegetation response. The modeled flood path (80 m^3/s) covered approximately 110 m of the valley floor with highly energetic flow. Regional regression equations estimated a $>$500-year event of 45 m^3/s, which was only 56% of the estimated flood produced by the dam break, and further underscores the immensity of this historic flood. Such flows greatly exceeded the creek banks and reworked 19 ha of floodplain compared to 4 ha occupied by the current active floodplain. The vegetation response indicated the maximum probability of coniferous cover beyond 60 m from the thalweg and deciduous cover within that distance. Because in the system, the coniferous species are indicative of upland plant communities, and the deciduous of riparian, the boundary between them suggests that of the flood path. Thus, the flood path created with paleohydrology model aligns with that indicated by the vegetation distributions.

Starting with aerial photos from 1942, we detected vegetation responses to flood-related vertical, lateral, and longitudinal gradients 15–78 years following dam failure. We found that coniferous, deciduous, and bare ground cover types responded to vertical gradients 15, 52, and 68 years after the 1927 flood (Table 5). Observed points higher above the thalweg potentially avoided the destructive forces of the flood. The coniferous points are generally higher above the active floodplain and may have been inundated or subjected to slow moving water, relative to other parts of the flood

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

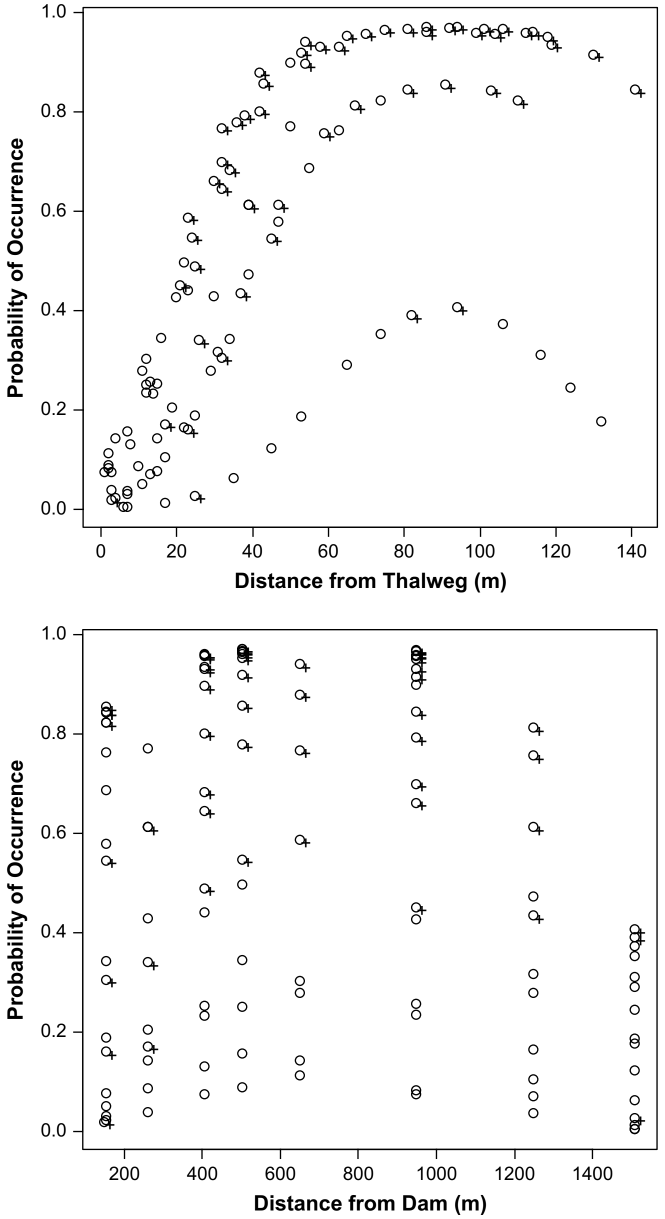

Fig. 8. The model output for the 1995 coniferous cover distribution with modal (quadratic) forms of distance from thalweg and distance from dam illustrates the interaction between the two variables. The "+" indicates observed values. The "○" indicates modeled values.

wave. Nakamura et al. (1997) found a similar relationship on the Tokachi River in northern Japan. The deciduous points may have escaped the high energy part of the flood due to the sinuous character of the pre flood channel. Grant and Swanson (1995) found that valley geometry strongly controls the pattern of erosion, deposition, and riparian vegetation disturbance during large floods. Wider valleys tend to channel flows with lower shear stresses than narrow valleys, and therefore, become depositional environments for fine sediment and evade erosion. However, the 1927 spate flowed straight down valley, carved a new channel bed, and reset the valley base level. While the high energy flows may have bypassed the vegetated meanders, they hydrologically stranded the vegetation by dropping the water table.

In Pattengail, we observed vegetation responses to lateral gradients were indicative of floodplain evolution and varied longitudinally (Fig. 8). The upper 1000 m of the study site is essentially a straight, incised channel with a series of scour pools in a wide alluvial valley. According to our model, flow in the upper reach was turbulent and highly energetic. The replacement of 1942 deciduous vegetation with coniferous vegetation in later years suggests that this part of the floodplain was converted to an upland plant community through base lowering (Fig. 6). Further, due to the depth of the scour ponds, flows through the upper 1000 m produce depositional environments. Doyle et al. (2003a) describe the process of channel evolution in a reservoir following dam removal as a progression through the following stages: 1) degradation, 2) degradation and widening, 3) aggradation and widening, and 4) quasi equilibrium. While this segment is not a drained reservoir, we infer that this reach will follow a similar progression. However, we expect the process will be elongated because the sediments of the valley alluvium are more consolidated than those found in reservoirs, and therefore, less erodible. Thus, we predict that the flood-carved pools will require several large floods (10–50-year recurrence interval) for aggradation to occur to the point where the channel will migrate and potentially provide conditions for deciduous riparian species establishment. Conversely, in the lower 1000 m, the floodplain shows evidence of secondary channels that are active during spring runoff. Thus, the channel began to laterally rework the floodplain by 1942, if not sooner. We observed deciduous species establishment in this segment in 1979, 1995, and 2005. However, the changes were not statistically significant until 2005 (Table 5). Thus, longitudinal and lateral gradients synergistically influenced the vegetation response to the Pattengail dam failure.

4.2. *Mystic*

The Mystic dam breach substantially differed from that of Pattengail in both hydrology and ecology. The historic flood path of Mystic (based on a modeled flow of 4–6 m^3/s) did not exceed its banks. Even the highest flow estimate (11 m^3/s from 1976 gage records) did not provide energy for deposition or erosion of sediments beyond 10 m from the channel. Therefore, there was little vegetation change laterally across the floodplain or longitudinally downstream (Fig. 6). The Mystic valley floor width averaged >100 m with coniferous vegetation (*P. engelmannii*) as the dominant land cover. The floodplain vegetation, free of disturbance, continued along a successional trajectory toward an upland community. Our land cover results showed an overwhelming dominance of *P. engelmannii*, a typical upland species of the Rocky Mountains. The lack of floodplain land cover change in combination with the modeled flows suggested that post-dam removal flows have had little influence on riparian vegetation.

According to city records, Mystic Lake Dam was inoperable much of the time due to a poor spillway design, instability, and a partial failure in 1978. The constrained narrow valley with cascade and plane-bed channel types are known to be unresponsive to all but the most catastrophic flows (Montgomery and Buffington, 1997). The channel and valley characteristics combined with dam operations strongly suggest that the dam had little effect on downstream riparian vegetation. Using three estimates of peak flow (paleohydrology model, hydrograph records, and regional estimates) and vegetation assessments, we saw no indication of overbank flows. Therefore, paleohydrologic methods combined with aerial photography accurately showed no change in the downstream system following the removal of Mystic Lake Dam in 1985.

4.3. *Conclusion*

We made several findings in the Pattengail and Mystic investigations. (1) Dam removal effects on channel evolution and

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028

floodplain development depend on reach types and their responsiveness to flow regime change (>20 years). (2) Ecologic response to dam removal depends on the sizes and timing of high flow events during and following removal. (3) Paleohydrology and aerial photo interpretation can be used to assess the ecological responsiveness of a riverine system.

Our data show that the valley and reach geomorphologies are first-order controls on a system's ecological response to dam removal. The Pattengail study reach was set in a geomorphically responsive valley type. The reach showed ongoing vegetation response after 78 years. The Mystic study reach showed that there was little effect of the dam operations on the study reach and, consequently, little response to the dam removal. Thus, the expectations for ecological response must be considered over a time period appropriate for the valley and reach geomorphologies, as well as their ability to respond to changes in flow regime. Downstream floodplain reaches that are riffle-pool and plane-bed types (Pattengail) will be more responsive than cascade reaches (Mystic) over many decades (Montgomery and Buffington, 1993).

Using paleohydrology and aerial photo interpretation, we were able to assess the ecological response of Pattengail and Mystic to dam failure and dam removal. In Pattengail, we saw vegetation changes indicative of a floodplain responding to a flood wave and a base lowering event. In Mystic, we saw minimal ecological response to a dam that rarely operated and a low flow dam removal. Thus, we found the methods yielded realistic and informative results. Used prior to a dam removal, we see the utility of paleohydrology and aerial photo interpretation when assessing the ecological responsiveness of a system to previous fluvial events or changes in flow regime. Informed about the character of a system based on its history, dam removal scientists can use these tools to set realistic restoration goals for removing a dam.

5. Implications

As the world's dams age and its communities hold environmental quality in higher regard, results from ecological studies of dam removal will become increasingly necessary. Regardless of the reason for dam removal (hazard reduction, restoration, migration), restorationists need to sufficiently assess available information to support the initial decision and method. Our results demonstrate the utility of paleohydrology and aerial photography in determining the ecological responsiveness of a system. Within a relatively small geographic area, we applied these methods to two geomorphically different systems. While the processes that drive riverine systems are the same, their magnitudes vary from place to place. For this reason, we encourage restorationists to use retrospective approaches to identify the first-order controls on a riverine system, as well as the responsiveness of the system to those controls prior to setting restoration goals for dam removal.

Acknowledgements

This research was supported by the USGS 104b Water Resources Research Program administered by the Montana Water Center. The City of Bozeman, NRCS in Dillon and Bozeman, Gallatin and Beaverhead-Deer Lodge National Forests and Gallatin Local Water Quality District provided access to aerial photos, hydrograph data, and access to study sites. Private land owners in the Wise River area provided anecdotal information and permission to access study sites. Wise River Merchantile provided equipment support. Steve Custer and Joel Cahoon provided technical assistance during the planning phase of the project. Selby's ESSCO of Bozeman provided assistance with GPS equipment.

References

Arnould, M., 1997. Loire dams to be dismantled for salmon. World Rivers Review 12 (4), 10.

Austin, M.P., Nicholls, A.O., Margules, C.R., 1990. Measurement of the realized qualitative niche: environmental niches of five *Eucalyptus* species. Ecological Monographs 60 (2), 161–177.

Baker, V.R., 1987. Paleoflood hydrology and extraordinary flood events. Journal of Hydrology 96 (1–4), 79–99.

Bednarek, A.T., 2001. Undamming rivers: a review of the ecological impacts of dam removal. Environmental Management 27 (6), 803–814.

Bendix, J., 1994. Scale, direction, and pattern in riparian vegetation–environment relationships. Annals of the Association of American Geographers 84 (4), 652–665.

Burroughs, B.A., 2007. Rehabilitation Potential of Dam Removal: Temporal Perspective from Michigan's Past Dam Removals. PhD thesis, Department of Fisheries and Wildlife, Michigan State University, East Lansing, p. 27.

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., 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.

Butler, D.R., Malanson, G.P., 2005. The geomorphic influences of beaver dams and failures of beaver dams. Geomorphology 71 (1–2), 48–60.

Catalano, M.J., Bozek, M.A., Pellet, T.D., 2001. Fish–habitat relations and initial response of the Baraboo River fish community to dam removal. Bulletin of the North American Benthological Society 18, 177.

Cenderelli, D.A., Wohl, E.E., 2001. Peak discharge estimates of glacial-lake outburst floods and 'normal' climatic floods in the Mount Everest region, Nepal. Geomorphology 40 (1–2), 57–90.

Cenderelli, D.A., Wohl, E.E., 2003. Flow hydraulics and geomorphic effects of glacial-lake outburst floods in the Mount Everest region, Nepal. Earth Surface Processes and Landforms 28 (4), 385–407.

Chow, V.T., 1959. Open-Channel Hydraulics. McGraw-Hill, New York.

Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. Geologic Society of America Bulletin 100, 1054–1068.

Department of Urban and Regional Planning (DURP), 1996. The Removal of Small Dams: an Institutional Analysis of the Wisconsin Experience. University of Wisconsin-Madison/Extension, Madison, p. 52.

Doyle, M., Stanley, E., Harbor, J., 2003a. Channel adjustments following two dam removals in Wisconsin. Water Resources Research 39 (1), 1011, doi:10.1029/2002WR001714.

Doyle, M.W., Stanley, E.H., Harbor, J.M., 2003b. Channel adjustments following two dam removals in Wisconsin. Water Resources Research 39 (1), 1101, doi:10.1029/2002WR001714.

Dukes, J., Mooney, H., 1999. Does global change increase the success of biological invaders? Trends in Ecology and Evolution 14 (4), 135–139.

ESRI, 2005. ArcGIS 9.1 documentation.

Grant, G., 2004. The geomorphic response of rivers to dam removal. In: Assessing and Re-naturalizing Streams Impacted By Dams and Dam Removal, Missoula, Montana.

Grant, G.E., Schmidt, J.C., Lewis, S.L., 2003. A geological framework for interpreting downstream effects of dams on rivers. In: O'Connor, J.E., Grant, G.E. (Eds.), A Peculiar River, pp. 203–219.

Grant, G.E., Swanson, F.J., 1995. Morphology and processes of valley floors in mountain streams, western Cascades, Oregon. In: Costa, J.E., Miller, A.J., Potter, K.W., Wilcock, P.R. (Eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology. Geophysical Monograph, vol. 89. American Geophysical Union, Washington, DC, pp. 83–101.

Hart, D., Johnson, T., Bushaw-Newton, K., Horwitz, R., Bednarek, A., Charles, D., Kreeger, D., Velinsky, D., 2002. Dam removal: challenges and opportunities for ecological research and river restoration. Bioscience 52 (8), 669–681.

Iversen, T.M., Kronvang, B., Madsen, B.L., Markmann, P., Nielsen, M.B., 1993. Re-establishment of Danish streams: restoration and maintenance measures. Aquatic Conservation: Marine and Freshwater Ecosystems 3 (2), 73–92.

Jarrett, R.D., 1984. Hydraulics of high-gradient streams. Journal of Hydraulic Engineering 110 (11), 1519–1539.

Jarrett, R.D., 1990. Paleohydrologic techniques used to define the spatial occurrence of floods. Geomorphology 3 (2), 181–195.

Jarrett, R.D., Tomlinson, E.M., 2000. Regional interdisciplinary paleoflood approach to assess extreme flood potential. Water Resources Research 36 (10), 2957–2984.

Junk, W.J., Bayley, P.B., Sparks, R.E., 1986. The flood pulse concept in river–floodplain systems. In: Proceedings of the International Large River Symposium (LARS), Ontario, Canada. Canadian Special Publication of Fisheries and Aquatic Sciences.

Mahoney, J.M., Rood, S.B., 1998. Streamflow requirements for cottonwood seedling recruitment – an interactive model. Wetlands 18 (4), 634–645.

Middleton, B., 1999. Wetland Restoration: Flood Pulsing and Disturbance Dynamics. John Wiley & Sons, New York.

Mitsch, W.J., Gosselink, J.G., 2000. Wetlands. John Wiley & Sons, New York.

Montgomery, D.R., Buffington, J.M., 1993. Channel Classification, Prediction of Channel Response, and Assessment of Channel Condition. Washington State Department of Natural Resources, Olympia, p. 86.

Montgomery, D.R., Buffington, J.M., 1997. Channel-reach morphology in mountain drainage basins. Geological Society of America Bulletin 109 (5), 596–611.

Nakamura, F., Yajima, T., Kikuchi, S.-I., 1997. Structure and composition of riparian forests with special reference to geomorphic site conditions along the Tokachi River, northern Japan. Plant Ecology 133 (2), 209–219.

Nilsson, C., 1987. Distribution of stream-edge vegetation along a gradient of current velocity. Journal of Ecology 75 (2), 513–522.

Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. Science 308 (5720), 405–408.

Parrett, C., Johnson, D.R., 2004. Methods for Estimating Flood Frequency in Montana Based on Data Through Water Year 1998. U.S. Department of the Interior, U.S. Geological Survey, Reston, VA. Denver, CO: U.S. Geological Survey Information Services Distributor.

Piegay, H., Bornette, G., Citterio, A., Herouin, E., Moulin, B., Statiotis, C., 2000. Channel instability as a control on silting dynamics and vegetation patterns within perifluvial aquatic zones. Hydrological Processes 14 (16–17), 3011–3029.

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

Pizzuto, J.E., 1994. Channel adjustments to changing discharges, Powder River, Montana. Geologic Society of America Bulletin 106 (11), 1494–1501.

Pohl, M.M., 2002. Bringing down our dams: trends in American dam removal rationales. Journal of the American Water Resources Association 38 (6), 1511–1519.

Pruess, J., Wohl, E.E., Jarrett, R.D., 1998. Methodology and implications of maximum paleodischarge estimates for mountain channels, Upper Animas River basin, Colorado, USA. Arctic and Alpine Research 30 (1), 40–50.

Schumm, S.A., Harvey, M.D., Watson, C.C., 1984. Incised Channels: Morphology, Dynamics, and Control. Water Resources Publishing, Highlands Ranch, CO.

Shafroth, P.B., Friedman, J.M., Auble, G.T., Scott, M.L., Braatne, J.H., 2003. Potential responses of riparian vegetation to dam removal. Bioscience 52 (8), 703–712.

Shuman, J., 1995. Environmental considerations for assessing dam removal alternatives for river restoration. Regulated Rivers, Research and Management 11 (3–4), 249–261.

Simon, A., Rinaldi, M., 2006. Disturbance, stream incision, and channel evolution: the roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79 (3–4), 361–383.

Stanley, E.H., Catalano, M.J., Mercado-Silva, N., Orr, C.H., 2007. Effects of dam removal on brook trout in a Wisconsin stream. River Research and Applications 23 (7), 792–798.

Stanley, E.H., Doyle, M.W., 2002. A geomorphic perspective on nutrient retention following dam removal. Bioscience 52 (8), 693–701.

Stedinger, J.R., Cohn, T.A., 1986. Surface water hydrology: historical and paleoflood information. Reviews of Geophysics 25, 119–124.

Steiger, J., Gurnell, A.M., 2003. Spatial hydrogeomorphological influences on sediment and nutrient deposition in riparian zones: observations from the Garonne River, France. Geomorphology 49 (1–2), 1–23.

Stromberg, J.C., Tiller, R., Richter, B.D., 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. Ecological Applications 6 (1), 113–131.

Trieste, D.J., Jarrett, R.D., 1987. Roughness coefficients of large floods. In: Irrigation Systems for the 21st Century. Society of Civil Engineering, Portland, OR.

Winter, B.D., 1990. A Brief Review of Dam Removal Efforts in Washington, Oregon, Idaho and California. US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Seattle, p. 13.

Wohl, E.E., 1995. Estimating flood magnitude in ungauged mountain channels, Nepal. Mountain Research and Development 15 (1), 69–76.

Please cite this article in press as: Schmitz, D., et al., Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals, Journal of Environmental Management (2008), doi:10.1016/j.jenvman.2008.07.028