Available online at www.sciencedirect.com

SCIENCE DIRECT®

Geomorphology 71 (2005) 48–60

GEOMORPHOLOGY

www.elsevier.com/locate/geomorph

The geomorphic influences of beaver dams and failures of beaver dams

David R. Butler[a,*], George P. Malanson[b]

[a]*Department of Geography, Texas State University-San Marcos, San Marcos, TX 78666-4616, United States*
[b]*Department of Geography, University of Iowa, Iowa City, IA 52242, United States*

Received 29 July 2003; received in revised form 23 August 2004; accepted 24 August 2004
Available online 20 April 2005

Abstract

Uncounted millions of beaver ponds and dams existed in North America prior to European contact and colonization. These ponds acted as sediment traps that contained tens to hundreds of billions of cubic meters of sediment that would otherwise have passed through the fluvial system. Removal of beavers by overtrapping in the 16th–19th centuries severely reduced their number and the number of ponds and dams. Dam removal altered the fluvial landscape of North America, inducing sediment evacuation and entrenchment in concert with widespread reduction in the wetlands environments. Partial recovery of beaver populations in the 20th century has allowed reoccupation of the entirety of the pre-contact range, but at densities of only one-tenth the numbers. Nevertheless, modern beaver ponds also trap large volumes of sediment in the high hundred millions to low billions of cubic meters range.

Failure of beaver dams is a more common phenomenon than often assumed in the literature. During the past 20 years, numerous cases of dam failure have been documented that resulted in outburst floods. These floods have been responsible for 13 deaths and numerous injuries, including significant impacts on railway lines.

Keywords: Beavers; Beaver dam; Beaver-dam failure; Sedimentation; Zoogeomorphology

1. Introduction

In his landmark paper on American dams, Graf (1999) posed three questions about the influence of human-constructed dams. These same three questions can be applied, with only slight revision, to the influence of beaver dams in North America:

- How many beaver dams exist?
- What is the geographical distribution of beaver dams with respect to natural and human contexts?
- What are the magnitude and distribution of likely impacts of beaver dams on the surface water component of the hydrologic cycle?

* Corresponding author. Tel.: +1 512 245 7977; fax: +1 512 245 8353.
E-mail addresses: db25@txstate.edu (D.R. Butler), george-malanson@uiowa.edu (G.P. Malanson).

0169-555X/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2004.08.016

To these three questions a fourth must be added in the context of beaver dams:

- How would these questions have been answered in the period prior to European colonization of North America?

Several review papers have examined the distribution and ecological role of the beaver, *Castor canadensis* (Novak, 1987; Naiman et al., 1988; Hammerson, 1994; Snodgrass, 1997; Collen and Gibson, 2001; Wright et al., 2002). Prior to European colonization of North America, beavers were found in every American state except Hawaii, every Canadian province, and the northern border regions of Mexico. Estimates of the population of North American beavers prior to European contact range from ca. 60 to 400 million (Naiman et al., 1988; Butler, 1995). Current population estimates range from 6 to 12 million beavers (Naiman et al., 1988). In the early 21st century, beavers have re-occupied the entirety of that range, but at only roughly 10% of the pre-European-contact density.

The primary geomorphological significance of beavers is the propensity to build dams to impound water and create ponds in which they live (in lodges constructed of wood and mud, typically placed near the center of a pond; and in bank burrows around the periphery of the pond). Individual beaver dams can function successfully for decades, acting as successful long-term sediment sinks (cf. Butler, 1995). In this paper we examine the zoogeomorphological influences of the construction of beaver dams, removal of dams, and failure of dams. We restrict our discussion to North America and the species *C. canadensis*, but refer readers here to several research projects that have examined the ecological role of the European beaver, *Castor fiber* (e.g. Żurowski, 1992; Hartman, 1996; Harthun, 2000; Krylov, 2002).

2. Background

2.1. The geomorphic effects of beavers and beaver dams

The geomorphic role of beavers and beaver dams has been reviewed in several publications (e.g., Butler, 1991, 1995; Butler and Malanson, 1994, 1995; Marston, 1994; Gurnell, 1998; Meentemeyer et al., 1998). Beaver ponds trap and accumulate sediment, reduce stream velocities, and reconfigure the landscape from a strictly fluvial to a wetlands environment. Naiman et al. (1988) noted that historically (i.e. prior to European contact and beaver removal by trapping), streams throughout North America had different features than at present. In first- to fourth-order streams, "numerous reaches (had) open canopy, large accumulations of detritus and nutrients, expanded wetted areas (including riparian zones), and substantial shifts to anerobic biogeochemical cycles" (Naiman et al., 1988, p. 760). On higher order streams, Naiman et al. (1988, pp. 760–761) described the pre-contact role of the beaver in the following fashion.

"In middle-order streams (i.e., orders 5–8), beaver-cut wood from upstream and the immediate riparian zone augmented local allochthonous inputs. Debris accumulations resulted in massive storage of sediment and detritus in the main channel, often forming small islands. In large rivers (i.e., orders greater than 9) beaver utilized floodplains and backwaters, where they constructed dams and canals and cut large amounts of wood...centuries of sediment deposition behind beaver dams may have reduced floodplain complexity.... The effects of this activity, which can still be seen in the terrestrial vegetation of meadowlands centuries after the extirpation of beaver...is testimony to their widescale influence on the landscape of North America." Naiman et al. (1988) also noted that streams with beaver ponds are probably more resistant to disturbance than are modern streams without beavers, and that beavers aid in returning streams to predisturbance conditions as they rebuild dams that accumulate water and sediment.

Recently, Meentemeyer and Butler (1999) and Bigler et al. (2001) provided quantitative data on the amount of sediment entrapped in beaver ponds in northwestern Montana, and illustrated that dam emplacement reduced stream velocities from as little as 2% to as much as 100%, i.e. in some cases no discernible outflow existed. Sediment depths and volumes varied dramatically, but with impressive amounts of sediment entrapped in all cases. Variability in sediment accumulation among ponds is probably related to watershed-scale influences such as stream order, surficial geology, and vegetation cover upstream. Bigler et al. (2001) illustrated that the distribution of particle sizes in beaver ponds did not follow expected down-pond or across-pond fining. In both studies, older dams were clearly shown to have accumulated more sediment behind them than younger dams, leading to the confirmation that infilling of beaver ponds and transformation to so-called "beaver meadows" (Ruedemann and Schoonmaker, 1938; Ives, 1942) can occur if dam integrity is sufficiently maintained for several years.

2.2. Beaver-dam removal and catastrophic failure of dams

Surprisingly little is known about the geomorphic effects of human-constructed dam removal (e.g., Stanley and Doyle, 2002; Doyle et al., 2003). Even less is specifically known about the effects of dam removal associated with the decline in beaver populations resulting from European over-trapping that nearly exterminated beavers throughout North America by the end of the 19th century (Naiman et al., 1988). Marston (1994, p. 11) noted that where beaver dams are removed, water tables drop, riparian vegetation undergoes a loss in diversity and productivity, and stored sediment and nutrients are released, causing a degradation in downstream water quality. He also noted that dam removal can lead to severe entrenchment downstream, resulting from an increase in stream power after removal of the energy-dissipating dam. In general, beaver trapping and population decimation led to dam deterioration, dam failures, and increased sediment yield on North American streams (Parker et al., 1985); and increases in beaver populations in recent decades has led to increases in sediment storage (Brayton, 1984; Apple, 1985). Fluctuations in beaver populations associated with European colonization of North America, therefore, present nonequilibrium conditions for fluvial geomorphology.

Similar to the limited information available on the effects of the removal of beaver dams as a result of decimation of the North American beaver population, very little is known about the geomorphic consequences of catastrophic failure of beaver dams. It has been suggested elsewhere that beaver-dam failures are rare, because of the "very limited literature on this subject" (Gurnell, 1998, p. 182). We agree that the geomorphic literature has given scant attention to this process, but we show that beaver-dam failure is a more widely occurring, and potentially hazardous, process than has been previously recognized.

Beaver dams may fail as the result of a variety of processes, including high-intensity precipitation, rapid snowmelt, animals burrowing through the dam, human destruction of portions of dams, and collapse of upstream dams (Rutherford, 1953; Reid et al., 1988; Butler, 1989, 1995; Kondolf et al., 1991; Stock and Schlosser, 1991; Marston, 1994; Gurnell, 1998; Hillman, 1998; Cenderelli, 2000). The results of dam failure on flooding, stream hydrographs, and stream biota have been the focus of most of the works cited above. Few works have focused attention on sediment movement from failure of beaver dams. Butler (1989) described a beaver-dam outburst flood that carried granite boulders over 1 m in diameter and washed a small truck over 100 m downstream. The washout of a beaver dam in the Sierra Nevada of California (Kondolf et al., 1991) lowered local base level and caused ca. 0.5–0.6 m of incision across the entire width of the channel. Gravels, formerly deposited against the upstream face of the beaver dam, were swept away. Washing of finer-grained sediments downstream from failed dams can be of sufficient amount and depth to smother benthic organisms and fish eggs (Rupp, 1955; Stock and Schlosser, 1991). Marston (1994) described how failure of one beaver dam can lead to a "domino-effect" on downstream dams impacted by water-sediment surges, resulting in rapid sediment transport from ponds and severe entrenchment in the channel below the dams.

3. Study area

Published sources on the number and nature of beavers and beaver dams in North America, and fieldwork on several beaver ponds in Glacier National Park (GNP), Montana, USA, provide the observations for this paper. GNP, chosen as a study site because of its robust beaver population that had been only minimally impacted by 19th-century trapping, is the U.S. portion of the Waterton–Glacier International Peace Park, a United Nations-designated World Heritage Site and International Biosphere Reserve.

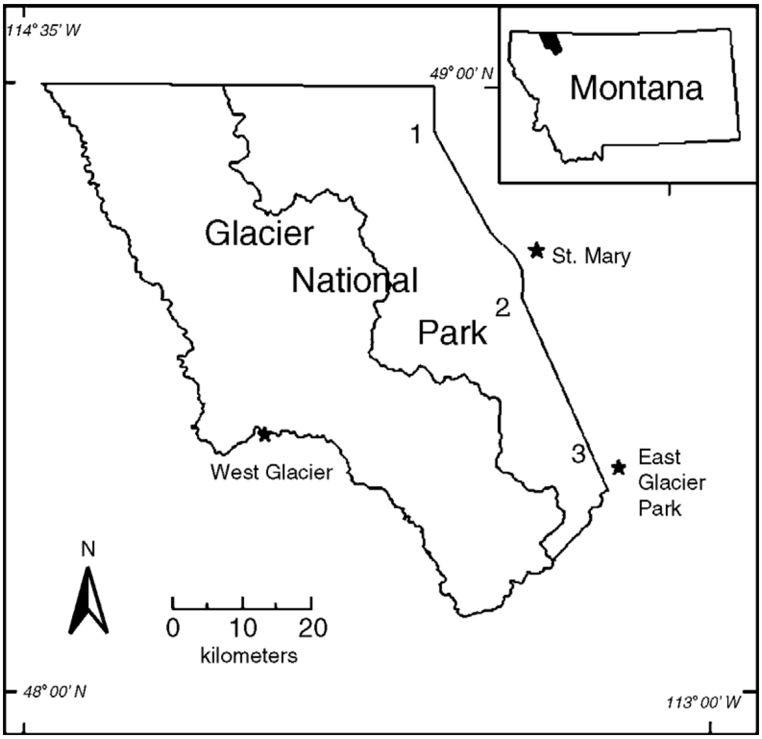


Fig. 1. Map of beaver-pond sites in Glacier National Park, Montana, USA, described in text. Numbers refer to sites as follows: 1, Otatso Creek ponds (see Figs. 5 and 6); 2, St. Mary drainage site (see Figs. 3 and 4); 3, Two Medicine infilled pond (see Fig. 2).

We examined beaver ponds in numerous valleys throughout the eastern half of GNP, ranging from the Otatso Creek watershed in the northeastern corner of the Park to the Two Medicine drainage in the southeastern corner (Fig. 1). Fieldwork described in this paper was undertaken between 1991 and 2002, with some beaver ponds examined annually, whereas others were re-visited about every 3–4 years. All ponds occupy gently sloping valley floors within U-shaped glacial valleys.

4. Methods

4.1. Field measurements of sediment depth and monitoring of beaver ponds

At sites in the Two Medicine area we have annually (in some years, as many as three separate times during the year) monitored the nature of succession around, and infilling of, beaver pond sites since 1991. We have taken repeat photographs at these locations from a standard, fixed spot overlooking the ponds. One unnamed pond has undergone complete infilling during the 1991–2002 time span (Fig. 2). In 2002 we probed the depth of sediment in this infilled pond at 10 locations, using a standard soil probe. We probed through the soft pond sediments until firm resistance from a more resistant gravel layer underneath, representing a former stream channel, was encountered. From these data we calculated the mean sediment depth of the pond and the annual sedimentation rate.

A pond in the St. Mary drainage along the Red Eagle trail was first observed and photographed in the field in 1992. We revisited this site in 2002, and rephotographed the dam and pond, which had become almost completely infilled with sediment during the intervening years (Fig. 3). We discovered a dam breach at the base of the primary dam and photographed and took notes on the nature of the dam failure (Fig. 4). We probed sediment depth at five

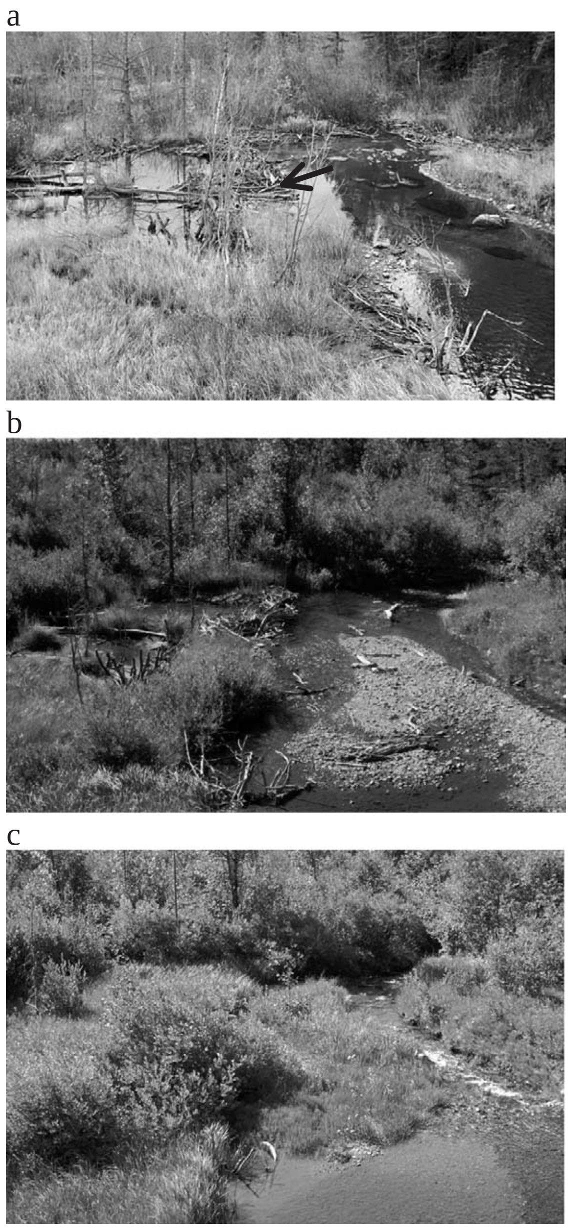


Fig. 2. Small beaver pond in the Two Medicine drainage (site 3, Fig. 1), formed in 1991. a) The pond and associated dam as it appeared in October 1993. b) The pond in July 1996. Gravel deposition in the adjacent stream (right) occurred during the floods of June 1995. c) The pond in July, 2002 completely infilled with sediment.

separate locations, all of which exceeded the 1-m length of our soil probe. Because a longer probe was not available, we recorded sediment depth at these sites as “>1 m”. We also re-examined and rephotographed two nearby small beaver ponds.

In the Otatso Creek drainage, previous work (Butler and Malanson, 1995) revealed that beaver ponds constructed in an upvalley sequence in 1990 and 1991, and from which sediment depths were collected in 1994, had undergone dam failure in June of 1995 because of an intense thunderstorm over the area. In July of 1995 and 2002 we revisited and rephotographed these two ponds, the dams and the points of failure, and the amount of sediment preserved behind the failed dams (Figs. 5 and 6). We sought to discern if the dams had been repaired after the 1995 outbursts, and if not, how much sediment had been removed by subsequent erosion.

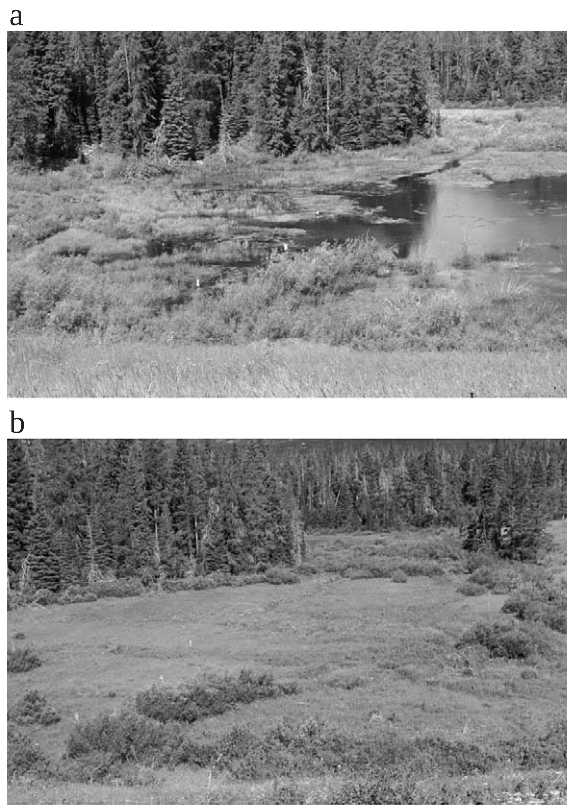


Fig. 3. Beaver pond in the St. Mary drainage (site 2, Fig. 1), over a 10-year time span. a) The pond in July 1992. Beaver canals and abundant open water are visible. b) The remnants of the pond in July 2002. The dam was breached (Fig. 4) on an unknown date between the 1992 and 2002 visits.

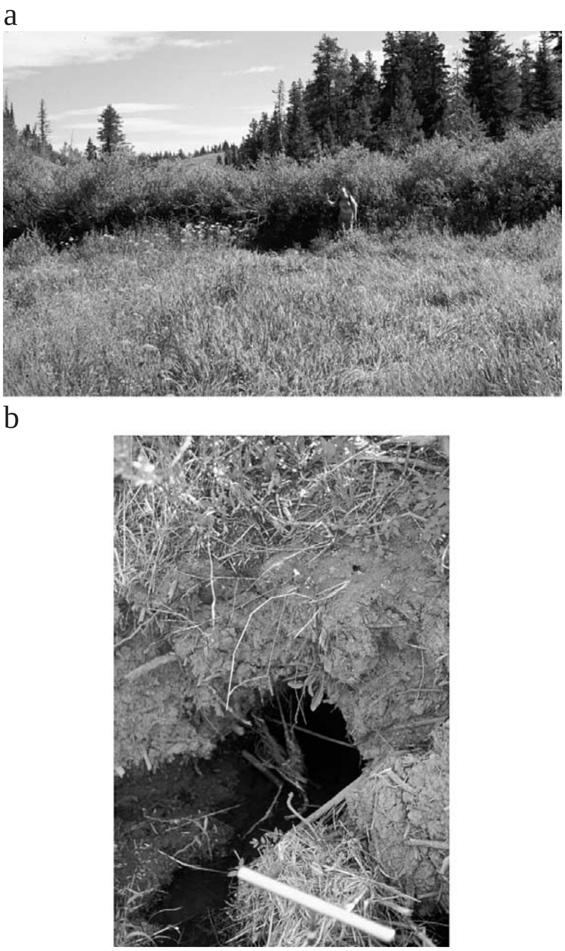


Fig. 4. Views of the beaver dam that impounded the pond shown in Fig. 3. a) A general view of the breached dam (person for scale). The widespread willow shrubs across the crest of the dam indicate that the dam had been in place for a reasonably long period of time, perhaps as much as 20–30 years. The person is standing adjacent to the breach in the dam (located in the dark area on person's right). b) A view of the breach in the dam. This breach did not extend to the surface of the dam, but was instead a large hole through the base of the dam. The handle of a standard soil probe is visible in lower right, for scale.

4.2. Compilation of beaver-dam failures

As mentioned in Section 2.2, little attention has been paid in the geomorphic literature to the number, distribution, or nature of beaver-dam failures. To supplement the limited number of observations of failed beaver dams that we have seen, we searched the geomorphic and ecological literature as well as

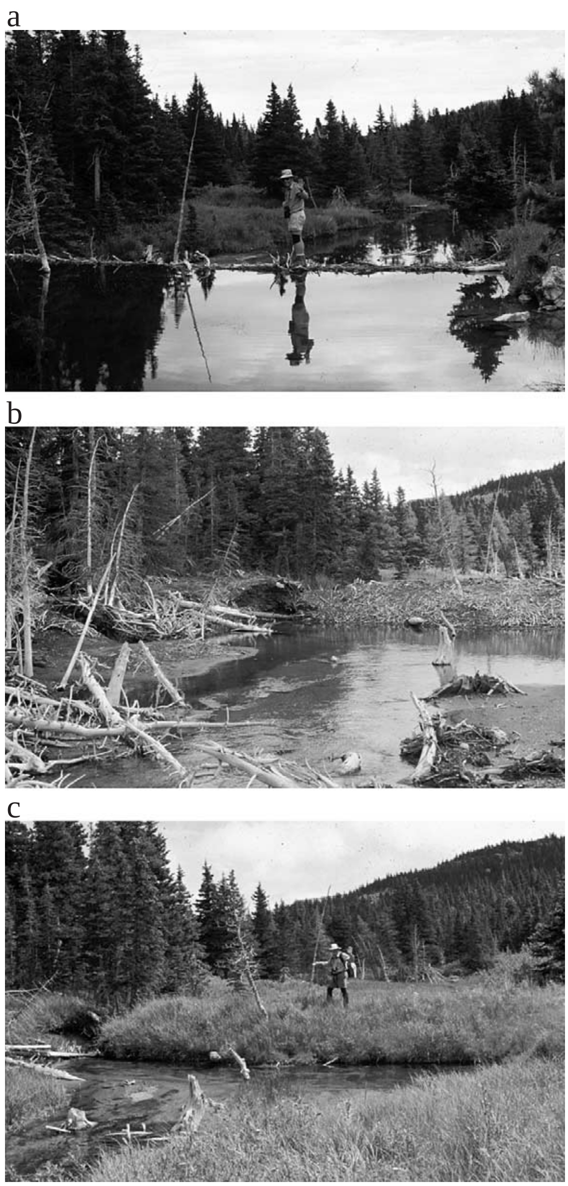


Fig. 5. Beaver dam in Otatso Creek drainage (site 1, Fig. 1), the location of sediment data acquisition described in Butler and Malanson (1995). Co-author GPM provides scale in views a and c. a) The dam in July 1994, viewed from upstream with pond. b) The dam in July 1995, after breaching (note notched breach on left of dam) in June of the same year. Widespread sediment exposed on floor of drained beaver pond is visible. c) The dam in July 2002. The dam has undergone rapid vegetative colonization on the upstream side, where mud was used by beavers to seal the dam and where sediment was deposited at base of dam. Widespread vegetative colonization on the floor of the pond has stabilized sediment there. No visible erosional scouring or sediment removal from the floor of the pond appeared to have occurred since 1995.

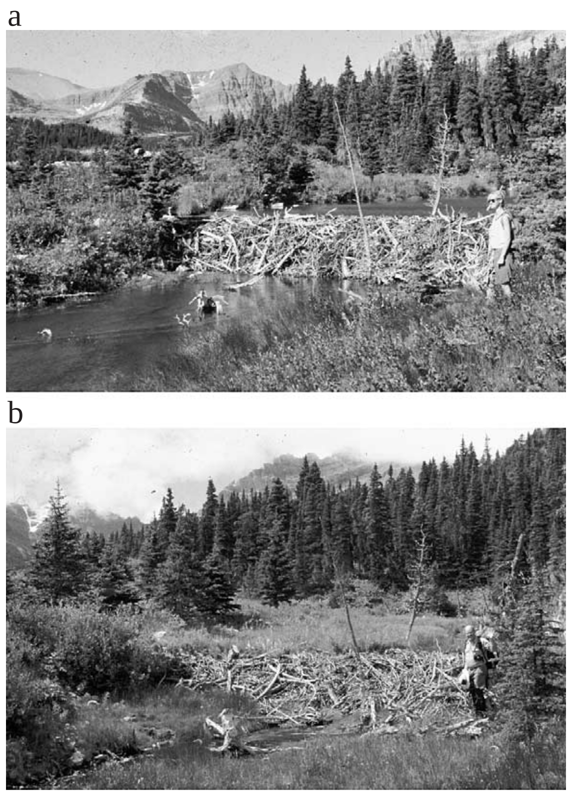


Fig. 6. Upstream view of the same dam as in Fig. 5, with pond above the dam. Lower pond adjacent to person was even more widespread than the upper pond. Both dams failed and were similarly breached with notches in 1995. a) Dam impounding upper pond in July 1991. b) Dam in July 2002. Observe the widespread stabilizing vegetation, in effect preserving beaver meadows, above and below the dam. The downstream side of the dam has not been colonized by vegetation, because dams on the downstream sides are typically not plastered with mud by beavers for stability, thus providing little in the way of a stable sediment medium for plants to take root.

popular literature, newspapers, and the Internet for any references to beaver-dam failures, and recorded the information contained therein. These references have been compiled into a table and are presented here as a general survey of the effects and hazards of beaver-dam failure (Table 1).

4.3. Continent-wide calculations of sedimentation rates and sediment volume in beaver ponds

To calculate volumes of sediment entrapped in beaver ponds, questions arise as to "average" sizes of ponds, and amounts and rates of sediment captured per pond. Each of these issues had to be addressed in our attempts to characterize the continent-wide geomorphic role of beavers prior to, and after, European colonization.

4.3.1. Annual rates of sedimentation

Calculation of annual rates of sedimentation is dependent on knowledge of the age of a beaver pond. Annual rate is simply determined by dividing total depth of sediment (typically an average value of several depth measurements into the bottom of a pond) by number of years of existence. We surveyed the literature to determine if a realistic, average rate of sedimentation could be identified. Published values range from lows of <1 cm yr^{-1} for ponds in Ontario and Colorado (Devito and Dillon, 1993 and Ives, 1942, respectively) to nearly 40 cm yr^{-1} in northwestern Montana (Meentemeyer and Butler, 1999). Very few published values exist, however, making generalizations about the rates of sedimentation of questionable value; rather, these rates seem to be site-specific and should be calculated accordingly for each study site. Even within our study area the rate of sedimentation may vary by a factor of 10 (cf. Butler and Malanson, 1995). Because of these issues, we deemed it inappropriate to calculate average rates of sedimentation over the extraordinarily extensive area of North America.

4.3.2. Total volume per pond

As with rates of sedimentation, we were unable to derive an average size of a pond that would be useful for calculating average volume of sediment per pond (where total volume of sediment = pond area × mean thickness of sediment). No "average" beaver pond exists in terms of the area of surface water impounded. Pond size is clearly dependent on the physiography of an area as well as the size and stream order of the rivers and streams (Butler and Malanson, 1995). In GNP, Butler and Malanson (1995) and Meentemeyer and Butler (1999) collectively examined 15 beaver ponds that averaged only 483 m^2 in area. On the coastal plain of eastern North Carolina, USA, Townsend and Butler (1996) mapped 56 beaver ponds that averaged 1.84 ha in size, a size similar to beaver ponds in the

Table 1
Recorded beaver-dam failures and associated effects

Source	Notable aspects and effects of beaver-dam failure
Rutherford, 1953	Flood removed 7 beaver dams and 2 lodges, Cache la Poudre River, Colorado, USA.
Anonymous, 1984	Outwashed beaver dams released water that damaged drainage culvert and railroad embankment, causing Amtrak passenger train derailment near Williston, Vermont, USA, killing five persons and injuring 149.
Butler, 1989	Several beaver dams failures described in US states of Georgia and South Carolina. One dam failure produced outburst flood in Oglethorpe County, Georgia, that killed four people, floated a truck, and deposited two survivors 3–4 m up in trees.
Stock and Schlosser, 1991	A July 1987 dam collapse on a stream in northern Minnesota, USA, produced a flash flood that dramatically decreased downstream benthic insect density, and also altered downstream fish community structure.
TSB Canada, 1994	A Canadian National freight train derailed near Nokina, Ontario, Canada because of track bed failure caused by a sudden drawdown of water resulting from a failed beaver dam. Two crew members were killed and a third received serious injuries.
Hillman, 1998	Describes a June 1994 outburst flood in central Alberta, Canada, which produced a flood wave 3.5 times the maximum discharge recorded for that creek over 23 years. Five hydrometric stations downstream were destroyed.
Vt ANR, 1999	The outburst of a large beaver pond in Fairfield, Vermont, USA, killed two people in an unspecified fashion.
Anonymous, 2003	A freight train in central Michigan, USA, derailed after a beaver dam collapsed and washed out a culvert underneath the railway. Two railway employees suffered minor injuries.

taiga of northern Manitoba, Canada (1.8 g ha/pond) (Wheatley, 1997).

Because of the absence of a "typical" beaver pond in terms of area or rates of sedimentation, we searched the literature for published data on volume of sediment per beaver pond. Naiman et al. (1986) described a very broad range of volumetric data, ranging from 35 to 6500 m^3 of sediment per beaver pond in their study area in Quebec, Canada. For the aforementioned 15 ponds in GNP (Butler and Malanson, 1995; Meentemeyer and Butler, 1999), along with those for which we collected data on depth of sediment in 2002, average volume of sediment was about 225 m^3 per pond, ranging from less than 100 to about 5000 m^3 with most values falling between 10 and 500 m^3.

Given the equally wide range of sediment volumes found per pond in the two disparate areas of Quebec and Montana, we settled upon using a conservative range of sediment volume (200–500 m^3) per beaver pond. Multiplying this value times the number of ponds in North America, prior to European colonization and at present, yields a crude continent-wide estimate of the amount of sediment entrapped in beaver ponds.

4.4. Calculation of number of beaver ponds in pre- and post-European North America

The number of beaver-dammed ponds in North America is unknown, although Novak (1987) stated that such dams and ponds number in "the millions". Calculation of the number of beaver ponds in existence, before European contact ("pre-European") and at present ("post-European") is complicated because not every beaver lives in a pond, but may excavate a bank burrow (e.g. Meentemeyer et al., 1998); and that a given beaver family may build numerous ponds in its range.

We therefore calculated an estimate of the number of beaver ponds in pre- and post-European-contact North America by following these steps:

1) We accepted the estimates of 60–400 million for pre-European, and 6–12 million for post-European beaver populations (see Section 1).
2) We conservatively assumed that 75% of the beaver population lives in ponds, with 6 beavers per pond (family sizes typically range from 4 to 8 members per pond; Novak, 1987).

3) We multiplied the pre- and post-European population low and high estimates by 0.75, to determine a probably conservative estimate of the number of beavers living in ponds.
4) We divided the number of beavers living in ponds by 6 (the mean of a beaver family size) to develop a minimum number of beaver ponds.
5) Our field experience and the literature suggest, however, that one beaver family may build 2–5 ponds, so we subsequently multiplied the minimum number of ponds by factors of 2 and 5 to arrive at a reasonable range of ponds, in both pre- and post-European times.

For subsequent calculations of sediment volume, we used the range of ponds for pre-European times, but only the maximum range for post-European times because of the unrealistically low values provided by the post-European minimum range.

4.5. Calculation of sediment volume in pre- and post-European beaver ponds in North America

We multiplied sediment volume times the range of pond numbers. These calculations provide a continent-wide picture of the total amount of sediment entrapped in beaver ponds at the time of European contact, and early in the 21st century.

5. Results

5.1. Number of beaver ponds in pre- and post-European North America

The number of potential beaver ponds in pre- and post-European North America, calculated as described in Section 4.4, is:

pre-European beaver ponds, minimum range of 15–100 million ponds;
pre-European beaver ponds, maximum range of 37.5 and 250 million ponds;
post-European beaver ponds, minimum range of 1.5–3 million ponds (and unrealistically low, given the "millions" of ponds seen on the landscape); and
post-European beaver ponds, maximum range of 3.75–7.7 million ponds.

5.2. Sedimentation and rates of infilling in beaver ponds

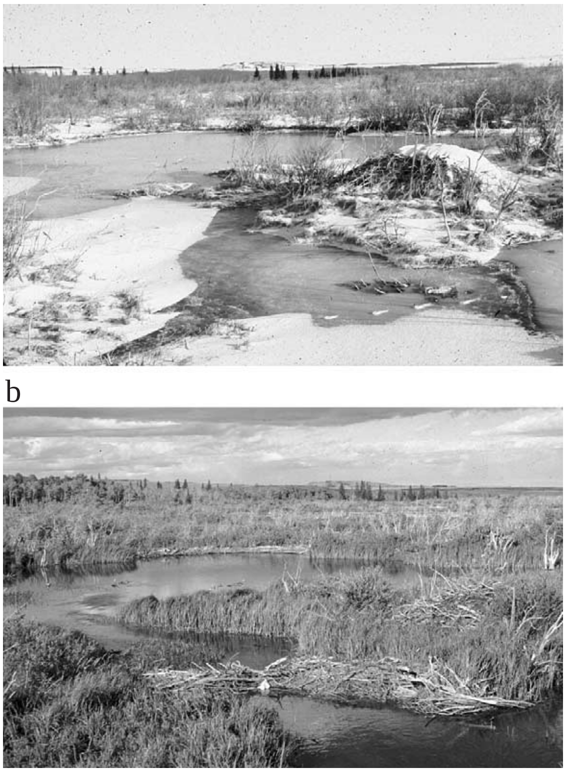
We previously reported (Butler and Malanson, 1995) that ca. 2–28 cm yr^{-1} of sediment accumulated in several beaver ponds in Glacier National Park. For six different ponds in GNP, Meentemeyer and Butler (1999) illustrated roughly similar rates of ca. 4–39 cm yr^{-1}. For the additional ponds for which we gathered data in ponds of known age in 2002, rates of sedimentation of ca. 3–6.5 cm yr^{-1} were calculated. These lower-range values probably result from the lower-energy (limited flow and visually slower velocity) streams upon which the dams had been constructed. The pond in the Two Medicine drainage was constructed in 1991. By 2002, the pond had disappeared and a marshy meadow completely occupied the former pond surface behind the dam (Fig. 2), illustrating that in some small ponds emplaced on low-energy streams, the entire life-cycle from creation to cessation of function as a pond can occur in only about a decade. Other, usually larger, ponds such as that illustrated in Fig. 7, which contrasts the appearance of the pond in the winter of 1993 and the summer of 2002, can exist with unimpeded function for well over a decade as long as maintenance of the dam continues.

5.3. Sedimentation in pre-European North America

Following the procedures described in Section 4.4, the following minimum values represent pre-European sediment volumes entrapped in 15, 37.5, 100, or 250 million beaver ponds:

200 m^3 of sediment per pond × the minimum value of 15 million beaver ponds = 3 billion m^3 of sediment in pre-contact ponds; or
200 m^3 of sediment per pond × 37.5 million beaver ponds = 7.5 billion m^3 of sediment in pre-contact ponds; or
200 m^3 of sediment per pond × 100 million beaver ponds = 20 billion m^3 of sediment in pre-contact ponds; or
200 m^3 of sediment per pond × 250 million beaver ponds = 50 billion m^3 of sediment in pre-contact ponds. The pre-contact minimum range of sediment volumes, therefore, encompasses 3–50 billion

a



b

Fig. 7. A beaver pond and dam near St. Mary (Fig. 1), with adjacent beaver lodge, that illustrate long-term viability over the course of a decade. a) The frozen pond surface as seen in January 1993. Note the lodge and dam. b) The same site in July 2002, illustrating that a second dam, closer to the viewer, has been emplaced to supplement the original dam and expand open-water area. The downstream dam (farther from viewer) remains in excellent condition.

m^3 of sediment. These values are distinctly less than the pre-contact values calculated using the maximum value of sediment per pond. Substituting the higher value of 500 m^3 of sediment per pond, the following amounts are revealed:

500 m^3 of sediment per pond × 15 million beaver ponds = 7.5 billion m^3 of sediment in pre-contact ponds; or
500 m^3 of sediment per pond × 37.5 million beaver ponds = 18.75 billion m^3 of sediment in pre-contact ponds; or
500 m^3 of sediment per pond × 100 million beaver ponds = 50 billion m^3 of sediment in pre-contact ponds; or
500 m^3 of sediment per pond × 250 million beaver ponds = 125 billion m^3 of sediment in pre-contact ponds. The maximum range, based on 500 m^3 of sediment per pond, is thus 7.5–125 billion 500 m^3 of sediment. One can only imagine what values would be revealed if we had utilized maximum values of ca. 6500 m^3 of sediment per pond such as have accumulated in ponds in Quebec described by Naiman et al. (1986).

5.4. Sedimentation in post-European North America

Modern amounts of sediment do not begin to reach pre-contact values, but are nonetheless impressive. Using the same procedures, the following minimum values were calculated for modern-day ("post-European") sediment volumes entrapped in beaver ponds:

200 m^3 of sediment per pond × 3.75 million beaver ponds = 750,000,000 m^3 of sediment in modern ponds; or
200 m^3 of sediment per pond × 7.7 million beaver ponds = 1.54 billion m^3 of sediment in modern ponds.

Using the higher range of 500 m^3 of sediment per pond, the following amounts are revealed:

500 m^3 of sediment per pond × 3.75 million beaver ponds = 1.875 billion m^3 of sediment in modern ponds; or at the higher end,
500 m^3 of sediment per pond × 7.7 million beaver ponds = 3.85 billion m^3 of sediment in modern ponds.

5.5. Beaver-dam failure

Beaver-dam failures have been responsible for 13 deaths and numerous injuries since 1984 (Table 1). Dam failures typically occur after periods of intense and/or extended rainfall, or in association with high spring runoff from a melting snowpack (Rutherford, 1953; Townsend, 1953; Anonymous, 1984; Butler, 1989; Schipke and Butler, 1991; Stock and Schlosser, 1991; Hillman, 1998). The greatest hazard posed by outburst floods from drained beaver ponds seems to be to transportation corridors, especially railways (Anonymous, 1984; Butler, 1989; Transportation Safety Board of Canada, 1994; Vermont

Agency of Natural Resources, 1999; Anonymous, 2003).

5.6. Sediment removal and landscape recovery at sites of dam failure

At every location where we observed dam removal or failure (one case in Two Medicine by the National Park Service, where the impounded water threatened a Park road; the two dams in the Otatso Creek valley, and the dam in the St. Mary drainage), revegetation of the exposed sediment has been extremely rapid (Figs. 3, 5, and 6). In each case, the amount of sediment evacuated downstream beyond the breached dam appears to be small. Estimates of the amount of exposed sediment still in situ in 2002 (11 years after drainage in Two Medicine, and 7 years after drainage in Otatso; we do not know when the St. Mary area dam drained, only that it occurred between 1992 and 2002) are very high. In effect, we saw no removal of sediment from the area of exposed pond floors. Sediment removal obviously occurs during the period of dam breaching, as described by Butler (1989), Kondolf et al. (1991), Schipke and Butler (1991), Stock and Schlosser (1991), and Marston (1994), but subsequent to the failure event we see little evidence of additional sediment evacuation. Rather, the exposed sediment rapidly forms grass-and-shrub-covered beaver meadows even though the dam has been thoroughly breached.

6. Conclusions

Beaver dams have the ability to entrap very large amounts of sediment in beaver ponds. The role that beaver dams and ponds played in shaping the riparian environment in pre-European times cannot be understated. Under modern conditions of widespread but substantially reduced beaver populations, beavers are again transforming streams from erosional to depositional environments. Beaver-dam failure can locally produce displacement of sediment downstream and rapid entrenchment, while also creating localized outburst—floods that have proven both hazardous and deadly.

Although beaver-dam failure leads to sediment removal and displacement downstream, we have also shown that a great deal of sediment remains in place, upstream of failed dams. As noted much earlier by Ruedemann and Schoonmaker (1938, p. 525), "…beavers are able to aggrade all smaller valleys below the size of navigable rivers and having been active for many thousands of years have accomplished an enormous amount of aggrading work and are important physiographic agents. This work is characterized by complete aggrading of valley floors, originally in small descending steps, which disappear in time and leave a gently graded, even valley plain horizontal from bank to bank. The fine silt gathered in the beaver pools has produced the rich farm land in the valleys of the wooded areas of the northern half of North America." With no scientific measurements of the amount of sediment neither in pre-contact ponds nor of the number of ponds themselves, it is difficult to pinpoint the enormity of the influence of beaver on riparian environments of that period. Observing and measuring the widespread geographic distribution and amount of sediment in modern ponds, however, leads to an appreciation of the tremendous geomorphic influence of beaver dams, and to the amount of landscape adjustment that was necessary as a result of removal. Even as beaver populations continue to flourish, it must be recognized that the fluvial landscape of modern North America is substantially different than that which was in place prior to European contact. The beavers of North America are the reason why.

Acknowledgments

Funding for fieldwork in Glacier National Park was provided through cooperative agreements 99CRAG0032 (Butler) and 99CRAG0030 (Malanson) with the U.S. Geological Survey's Biological Resources Division. We especially thank our U.S.G.S. collaborator, Dr. Daniel Fagre, for his cooperation in arranging field collection permits and logistics. Field assistance was provided by Dr. Matt Bekker (Brigham Young University), Lynn Smollin (Texas State University), William D. Butler (Westlake High School, Austin, TX), and Lynn M. Resler (Virginia Polytechnic Institute and State University). The manuscript benefited from the comments of Dr. Jack Vitek and an anonymous reviewer. This paper is a contribution of the Mountain GeoDynamics Research Group.

References

Anonymous, 1984. Beavers blamed for train wreck. ENR 26 July issue, p. 14.

Anonymous, 2003. Beaver dam collapse leads to derailment. San Antonio Express News, 8 May 2003, p. 2.

Apple, L.L., 1985. Riparian habitat restoration and beavers. In: Johnson, R.R., Ziebell, C.D., Patton, D.R., Ffolliott, P.F., Hamre, R.H. (Eds.), Riparian Ecosystems and their Uses. U.S. Forest Service General Technical Report RM-120, pp. 489–490.

Bigler, W., Butler, D.R., Dixon, R.W., 2001. Beaver-pond sequence morphology and sedimentation in northwestern Montana. Physical Geography 22, 531–540.

Brayton, D.S., 1984. The beaver and the stream. Journal of Soil and Water Conservation 39, 108–109.

Butler, D.R., 1989. The failure of beaver dams and resulting outburst flooding: a geomorphic hazard of the southeastern Piedmont. The Geographical Bulletin 31, 29–38.

Butler, D.R., 1991. Beavers as agents of biogeomorphic change: a review and suggestions for teaching exercises. Journal of Geography 90, 210–217.

Butler, D.R., 1995. Zoogeomorphology—Animals as Geomorphic Agents. Cambridge University Press, Cambridge (231 pp.).

Butler, D.R., Malanson, G.P., 1994. Canadian landform examples—beaver landforms. The Canadian Geographer 38, 76–79.

Butler, D.R., Malanson, G.P., 1995. Sedimentation rates and patterns in beaver ponds in a mountain environment. Geomorphology 13, 255–269.

Cenderelli, D.A., 2000. Floods from natural and artificial dam failures. In: Wohl, E.E. (Ed.), Inland Flood Hazards: Human, Riparian and Aquatic Communities. Cambridge University Press, Cambridge, pp. 73–103.

Collen, P., Gibson, R.J., 2001. The general ecology of beavers (*Castor* spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish—a review. Reviews in Fish Biology and Fisheries 10, 439–461.

Devito, K.J., Dillon, P.J., 1993. Importance of runoff and winter anoxia to the P and N dynamics of a beaver pond. Canadian Journal of Fisheries and Aquatic Sciences 50, 2222–2234.

Doyle, M.W., Stanley, E.H., Harbor, J.M., 2003. Channel adjustments following two dam removals in Wisconsin. Water Resources Research 39, 2-1–2-15.

Graf, W.L., 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35, 1305–1311.

Gurnell, A.M., 1998. The hydrogeomorphological effects of beaver dam-building activity. Progress in Physical Geography 22, 167–189.

Hammerson, G.A., 1994. Beaver (*Castor canadensis*): ecosystem alterations, management, and monitoring. Natural Areas Journal 14, 44–57.

Harthun, M., 2000. Einflüsse der Stauaktivität des Bibers (*Castor fiber albicus*) auf physikalische und chemische Parameter von Mittelsgebirgs-Bächen (Hessen, Deutschland). Limnologica 30, 21–35.

Hartman, G., 1996. Habitat selection by European beaver (*Castor fiber*) colonizing a boreal landscape. Journal of Zoology, London 240, 235–317.

Hillman, G.R., 1998. Flood wave attenuation by a wetland following a beaver-dam failure on a second order boreal stream. Wetlands 18, 21–34.

Ives, R.L., 1942. The beaver–meadow complex. Journal of Geomorphology 5, 191–203.

Kondolf, G.M., Cada, G.F., Sale, M.J., Felando, T., 1991. Distribution and stability of potential salmonid spawning gravels in steep boulder-bed streams of the eastern Sierra Nevada. Transactions of the American Fisheries Society 120, 177–186.

Krylov, A.V., 2002. Activity of beavers as an ecological factor affecting the zooplankton of small rivers. Russian Journal of Ecology 33, 349–355.

Marston, R.A., 1994. River entrenchment in small mountain valleys of the western USA: influence of beaver, grazing and clearcut logging. Revue de Geographie de Lyon 69, 11–15.

Meentemeyer, R.K., Butler, D.R., 1999. Hydrogeomorphic effects of beaver dams in Glacier National Park, Montana. Physical Geography 20, 436–446.

Meentemeyer, R.K., Vogler, J.B., Butler, D.R., 1998. The geomorphic influences of burrowing beavers on streambanks, Bolin Creek, North Carolina. Zeitschrift für Geomorphologie 42, 453–468.

Naiman, R.J., Jelillo, J.M., Hobbie, J.E., 1986. Ecosystem alteration of a boreal forest stream by beaver (*Castor canadensis*). Ecology 67, 1254–1269.

Naiman, R.J., Johnston, C.A., Kelley, J.C., 1988. Alteration of North American streams by beaver. BioScience 38, 753–762.

Novak, M., 1987. Beaver. In: Novak, M., Baker, J.A., Obbard, M.E., Malloch, B. (Eds.), Wild Furbearer Management and Conservation in North America. Ontario Ministry of Natural Resources, Toronto, Canada, pp. 283–312.

Parker, M., Wood, F.J., Smith, B.H., Elder, R.G., 1985. Erosional downcutting in lower order riparian ecosystems: have historical changes been caused by removal of beaver? In: Johnson, R.R., Ziebell, C.D., Patton, D.R., Ffolliott, P.F., Hamre, R.H. (Eds.), Riparian Ecosystems and their Uses. U.S. Forest Service General Technical Report RM-120, pp. 35–38.

Reid, D.G., Herrero, S.M., Code, T.E., 1988. River otters as agents of water loss from beaver ponds. Journal of Mammalogy 69, 100–107.

Ruedemann, R., Schoonmaker, W.J., 1938. Beaver-dams as geologic agents. Science 88, 523–525.

Rupp, R.S., 1955. Beaver–trout relationships in the headwaters of Sunkhaze Stream, Maine. Transactions, American Fisheries Society 84, 75–85.

Rutherford, W.H., 1953. Effects of a summer flash flood upon a beaver population. Journal of Mammalogy 34, 261–262.

Schipke, K.A., Butler, D.R., 1991. The use of dendrogeomorphic techniques to date a beaver-dam outburst flood in Oglethorpe County, Georgia. The Geographical Bulletin 33, 80–86.

Snodgrass, J.W., 1997. Temporal and spatial dynamics of beaver-created patches as influenced by management practices in a south-eastern North American landscape. Journal of Applied Ecology 34, 1043–1056.

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

Stock, J.D., Schlosser, I.J., 1991. Short-term effects of a catastrophic beaver dam collapse on a stream fish community. Environmental Biology of Fishes 31, 123–129.

Townsend, J.E., 1953. Beaver ecology in western Montana with special reference to movements. Journal of Mammalogy 34, 459–479.

Townsend, P.A., Butler, D.R., 1996. Patterns of landscape use by beaver on the lower Roanoke River floodplain, North Carolina. Physical Geography 17, 253–269.

Transportation Safety Board of Canada, 1994. A Special Study of Main Track Derailments—1994. Online at: http://www.bst.ca/en/reports/rail/studies/sr9401/sr9401.asp.

Vermont Agency of Natural Resources, 1999. Options for State Flood Control Policies and a Flood Control Program. Online at: www.anr.state.vt.us/flood_control/.

Wheatley, M., 1997. Beaver, *Castor canadensis*, home range size and patterns of use in the taiga of southeastern Manitoba: III. Habitat variation. Canadian Field-Naturalist 111, 217–222.

Wright, J.P., Jones, C.G., Flecker, A.S., 2002. An ecosystem engineer, the beaver, increases species richness at the landscape scale. Oecologia 132, 96–101.

Żurowski, W., 1992. Building activity of beavers. Acta Theriologica 37, 403–411.