

Simulating Sediment Transport in the Patapsco River following Dam Removal with Dam Removal Express Assessment Model-1 (DREAM-1)

Technical Report



Prepared for

Inter-Fluve
3620 Atwood Ave., Suite 3
Madison, WI 53714
www.interfluve.com

&

American Rivers
1101 14th Street NW, Suite 1400
Washington, DC 20005
www.americanrivers.org

Prepared by

Stillwater Sciences
2855 Telegraph Ave., Suite 400
Berkeley, CA 94705
www.stillwatersci.com



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Executive Summary

Introduction

The 10-ft tall Simkins Dam, constructed in the early 1900s, is located at approximately River Mile (RM) 12 on the Patapsco River near Ellicott City, Maryland; the 26-ft tall Bloede Dam was constructed in 1907 and is located less than 1 mile downstream of Simkins Dam (at approximately RM 11.3). Both dams are currently under consideration for removal. Simkins Dam is expected to be removed in the summer or fall of 2010, and Bloede Dam is expected to be removed at a later date. This technical report provides sediment transport modeling results for the proposed removal of both dams, predicting the erosion of reservoir sediment, sediment deposition downstream, and the magnitude and duration of increased suspended sediment concentration due to the release of reservoir deposits following dam removal.

Approach

Sediment transport simulations were conducted with DREAM-1, one of the Dam Removal Express Assessment Models (Cui et al. 2006a,b) developed by Stillwater Sciences in collaboration with scientists from the University of Minnesota, University of California Berkeley, and the National Marine Fisheries Service (NMFS). DREAM-1 is a peer-reviewed sediment transport model that has been examined extensively with both flume and field data (e.g., Cui et al. 2006a, 2006b, 2008; Wooster 2003). This model and previous versions have been used successfully in dam removal evaluations and other related sediment transport applications (e.g., Cui and Parker 1999; Stillwater Sciences 1999; Stillwater Sciences 2008, Cui and Wilcox 2008). For the proposed Simkins and Bloede dam removal model scenarios, inputs to the DREAM-1 model include: a longitudinal profile based on a 2005 Baltimore County LiDAR survey and 2009 Inter-Fluve cross-section survey data, effective channel width extracted from a series of 1:5,350 aerial photos provided by Inter-fluve, grain size distribution of Simkins Reservoir deposit collected in 2009, daily average discharge records from the United States Geological Survey (USGS) gauging station (#01589000) at Hollofield, MD, and National Oceanic and Atmospheric Administration (NOAA) tide elevation data from Baltimore Harbor (Station #8574680). To examine the effect of different hydrologic conditions on sediment transport, flow hydrographs for three water year types (a wet, an average and a dry year) were selected and different combinations were used for model input.

Results Summary

Assuming that dam removal will result in trapezoidal channels with 35° bank angles and 85-ft to 100-ft bankfull width within the former reservoir areas, Simkins Dam removal will release approximately 88,000 – 104,000 yd³ (bulk volume) of sediment over a period of three months to two years depending on hydrological conditions following dam removal. Bloede Dam removal will release approximately 76,000 – 88,000 yd³ (bulk volume) of sediment downstream over a period of two months to one year depending on hydrological conditions following dam removal. Currently, less data is available and more assumptions were required for assessing the removal impact of Bloede Dam, so the model results associated with Bloede Dam removal should be considered preliminary pending further data acquisition.

Following Simkins Dam removal, Bloede Reservoir provides significant attenuation for sediment transport, absorbing sediment eroded from the Simkins deposit during low flow and gradually releasing it downstream during high flow events. The primary depositional area downstream of Bloede Dam is located between River Stations (distance measured from the river mouth) 30,000 and 45,000 ft (RM 5.7 – 8.5) with a maximum depth of sediment deposition less than 2 ft, which dissipates slowly over time. The increased suspended sediment concentration due to Simkins Dam removal is predicted to be on the order of several hundred ppm (part per million, or mg/liter) during the day of dam removal on a daily averaged basis, and will decrease quickly to negligible magnitudes in the following days.

The Bloede Reservoir deposit is predicted to be eroded faster following dam removal than sediment from the Simkins Reservoir deposit. As a result, the increased suspended sediment concentration due to Bloede Dam removal is also higher, on the order of 1,000 ppm (daily-averaged value) on the day of dam removal, then decreasing quickly to negligible magnitudes in the following days. Sediment deposition downstream of Bloede Dam site following the Bloede Dam removal has similar dynamics to that following Simkins Dam removal, except that significant sediment deposition occurs upstream of River Station 45,000 ft (RM 8.5). Maximum sediment deposition occurs immediately downstream of Bloede Dam with a predicted thickness of approximately 8 ft shortly after dam removal that decreases quickly in the following days.

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1. Introduction

The 10-ft tall Simkins Dam, constructed in the early 1900s, is located at approximately River Mile (RM) 12 on the Patapsco River near Ellicott City, Maryland. The 26-ft tall Bloede Dam, constructed in 1907, is located less than 1 mile downstream of Simkins Dam (at approximately RM 11.3) (Figures 1a,b). Simkins Dam is expected to be removed in the summer or fall of 2010, and Bloede Dam is expected to be removed at a later date (to be determined). This technical report provides sediment transport modeling results for the proposed removal of Simkins Dam and preliminary modeling results for the proposed removal of Bloede Dam using DREAM-1 (discussed below).

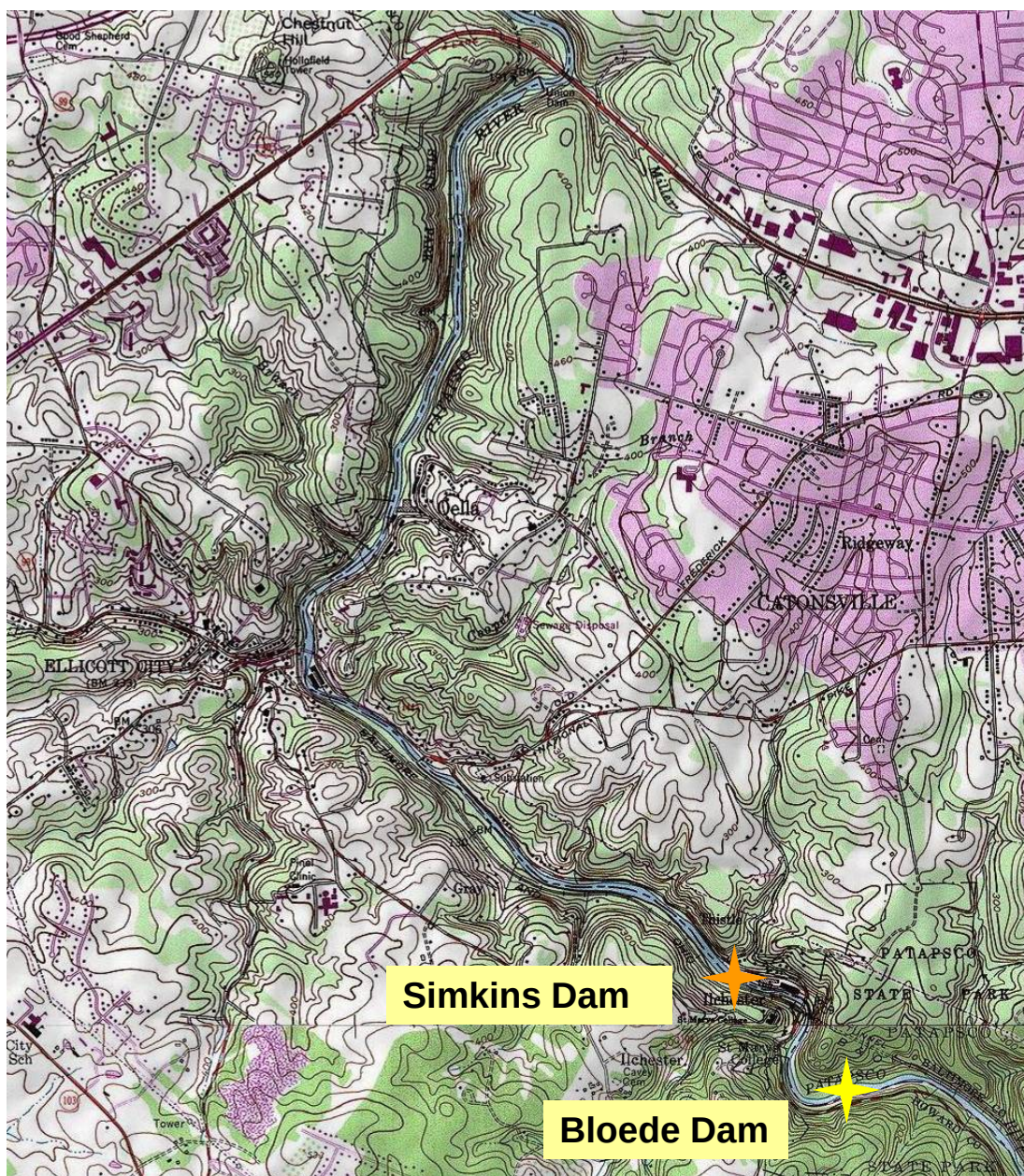


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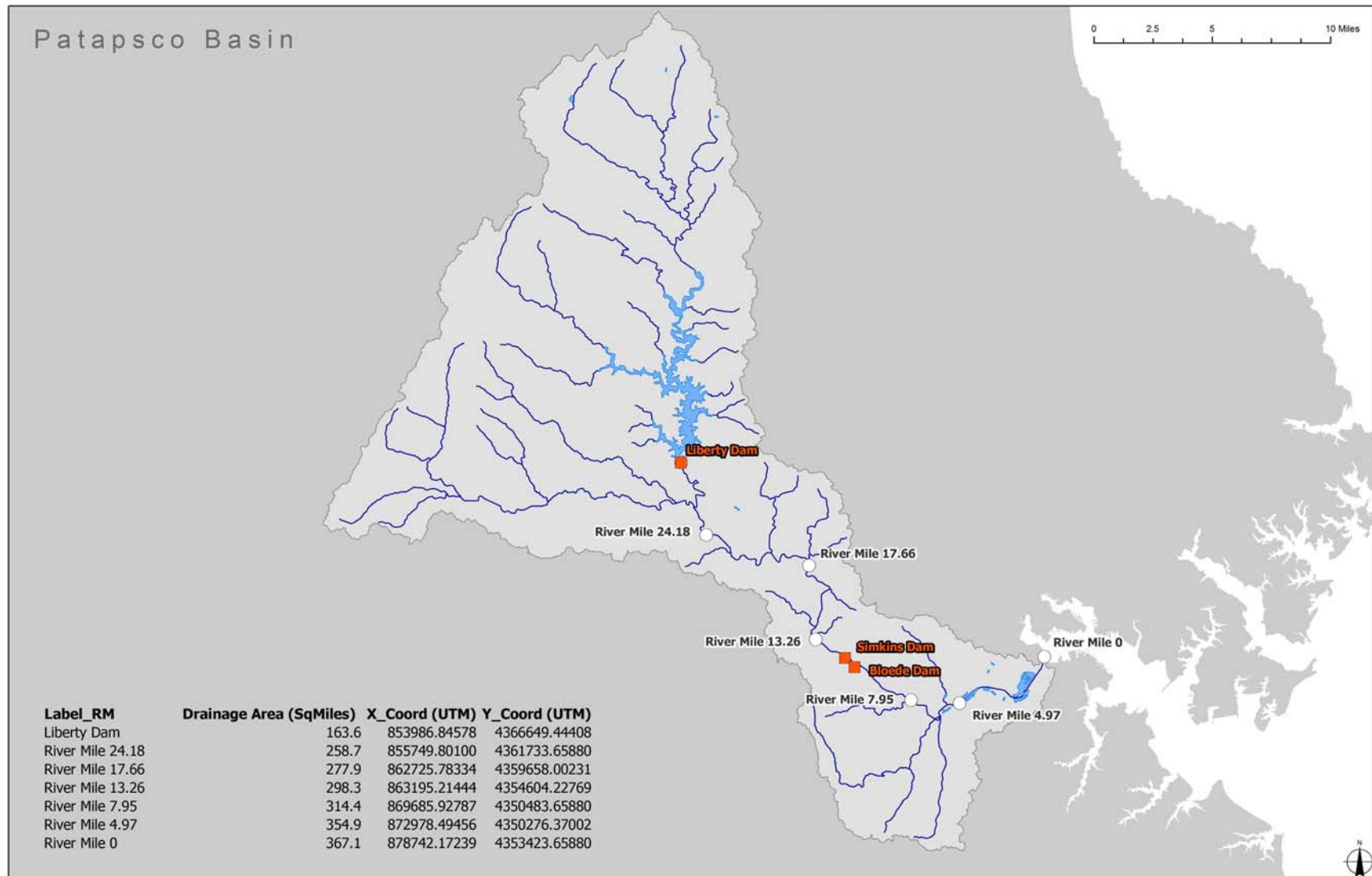


Figure 1b. Patapsco River watershed, Maryland, showing drainage area at selected locations calculated based on 10-m DEM (derived from The National Elevation Dataset, Gesch, D.B. [2007]). USGS gauging station (#01589000) at Hollofield, MD is located at RM 17.66.

2. Overview of DREAM-1

DREAM-1 is one of the two Dam Removal Express Assessment Models developed for simulation of sediment transport following dam removal (Cui et al. 2006a, b). DREAM-1 was designed for simulations where the sediment deposit in the reservoir upstream of the dam under consideration for removal is composed primarily of non-cohesive fine sediment (i.e., sand and silt). It simulates the transport and deposition of fine sediment and is applicable to rivers with any combination of sand-bedded, gravel-bedded, and bedrock reaches downstream of the dam. Because DREAM-1 does not simulate the transport of gravel, it treats the gravel-beds downstream of the dam and the pre-dam historical gravel beds upstream of the dam as immobile — fine sediment either passes through or deposits onto the gravel-bedded surface and potentially transforms it into a sand-bedded reach if the sand deposit becomes sufficiently thick. For flow parameter calculations, the model applies a standard backwater equation (e.g., Chaudhry 1993) for low Froude number conditions (i.e., Froude numbers < 0.9 , see Cui et al. 2006a for details) and applies a quasi-normal flow assumption (i.e., friction slope is identical to local bed slope; see Cui and Parker 2005) for high Froude number conditions. The model applies Brownlie's (1982) bed material equation for calculating sediment transport capacity and considers the transport of particles coarser than 0.0625 mm (i.e., sand and coarser) as one unit for mass conservation calculations, and considers particles finer than 0.0625 mm in diameter as wash load that is assumed unable to redeposit onto the channel bed once released into the water column following erosion of the reservoir deposit. Further, it is assumed that reservoir erosion is governed by the mobilization of sand-sized particles and coarser, and at any cross section, eroding the reservoir deposit down to a given elevation by mobilizing sand and coarser particles will also result in the release of all the finer particles (i.e., finer than 0.0625 mm) above that elevation. In addition to standard features briefly discussed above and detailed in Cui et al. (2006a,b), we also applied the roughness and partial sand coverage corrections to DREAM-1 detailed in Cui et al. (2008), which allows for a more accurate simulation of sand transport over the gravel bed when the sand deposit is too thin to completely cover the gravel bed.

The model requires the following input parameters: initial channel profile, initial thickness of fine sediment deposits in the reservoir and downstream reaches, channel cross-sections simplified as rectangles with widths equal to the bankfull channel width, daily average water discharge series, the rate and size of sediment supply, the downstream base-level control (i.e., either downstream water surface elevation or fixed bed elevation), and estimates of surface median bed material size along the river downstream of the dam. Model output includes the evolution of the thickness of sediment deposits within the reservoir and downstream reaches, coarse and fine sediment fluxes, and **daily-averaged** total suspended sediment concentrations (TSS) along the river in response to the specified water discharge and sediment supply conditions. In this particular case, because background TSS to discharge relation is not known, we have assumed zero background TSS, and as a result, the simulated TSS represents **an increase in daily-averaged total suspended sediment concentration**. Detailed model descriptions, model sensitivity tests and model examinations can be found in Cui et al. (2006a, 2006b, 2008) and Wooster (2003), and applications of DREAM-1 or its predecessors are included in Cui and Parker (1999), Cui et al. (2003), Cui and Parker (2005), Stillwater Sciences (1999), and Stillwater Sciences (2008).

3. Model Input Data

3.1. River Longitudinal Profile and Channel Width

The longitudinal profile of the modeled reach of the Patapsco River was obtained by combining field survey data collected in August and September 2009 by an Inter-Fluve survey team (Ben Lee and Nick Nelson, per. comm., August 2009) with 2005 Baltimore County LiDAR survey data processed by Garth Lindner (per. comm., 1 November 2009) (Figure 2). A pre-dam longitudinal profile beneath the sediment deposits of Simkins and Bloede reservoirs is estimated by linking elevations at the base of the dams to upstream points where the thickness of reservoir deposits appear negligible. This estimate should be fairly accurate given the obvious slope breaks between the reservoir deposits and their respective upstream reaches.

As indicated in Figure 2, the Patapsco River exhibits a typical upward concave profile, with a bed slope of approximately 0.003 just downstream of Bloede Dam that decreases to approximately 0.0004 near River Station 40,000 ft (RM 7.6) and continues to decrease gradually in the downstream direction toward its confluence with the Chesapeake Bay.

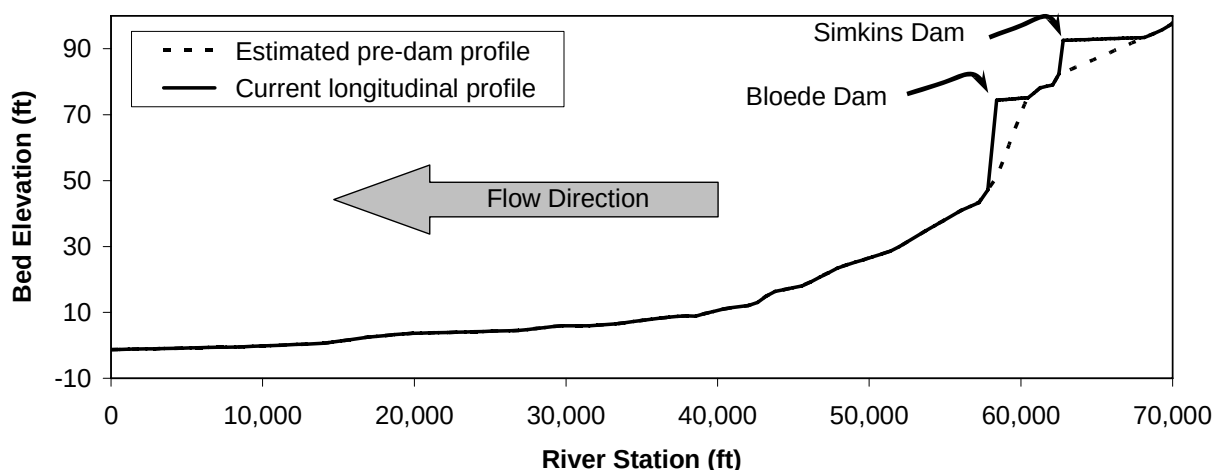


Figure 2. Patapsco River, MD longitudinal profile, obtained by combining field survey data collected in August and September 2009 by an Inter-Fluve survey team with 2005 Baltimore County LiDAR survey data processed by Garth Lindner (per. comm., 1 November 2009). The pre-dam profile is estimated by connecting the bases of the dams and upstream points where reservoir deposits appear negligible.

Active channel widths were estimated using a series of aerial photographs (approximately 1:5350 scale) provided by Inter-Fluve (Nick Nelson, per. comm., 16 August 2009) (Figure 3). In general, channel width increases in the downstream direction, which is typical of natural rivers. In addition, the two reservoir areas are generally wider than their respective downstream reaches, and the channel also widens in the downstream direction within each reservoir area due to the increased thickness of sediment deposition in the downstream direction.

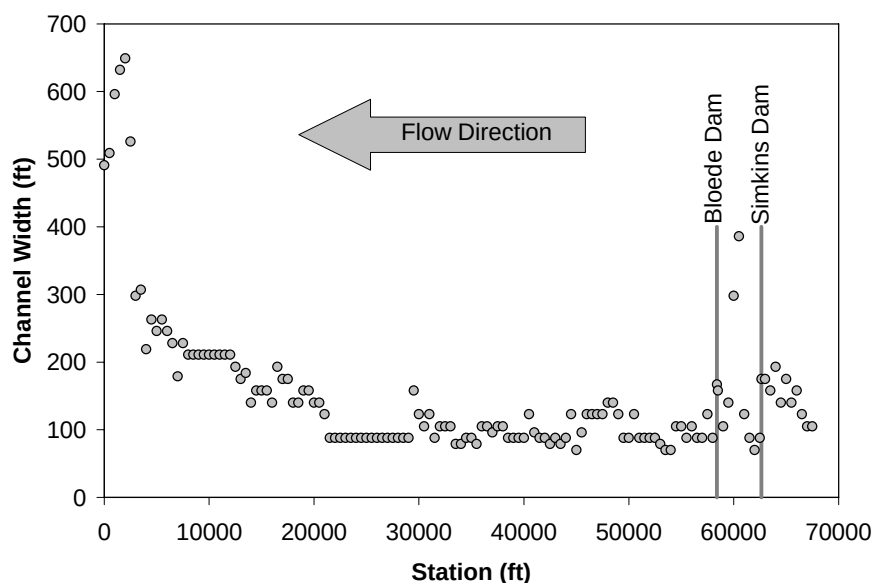


Figure 3. Patapsco River, MD active channel width, measured from aerial photographs of roughly 1:5350 scale, provided by Inter-Fluve (Nick Nelson, per. comm., 16 August 2009).

3.2. Composition of Reservoir Deposit

Inter-Fluve collected 8 core samples within the Simkins Dam impoundment with 2-in PVC pipes that penetrated up to 5 ft into the deposit in August 2009 (see Inter-Fluve 2009a,b for details). Maryland Department of Geological Survey also collected four cores that penetrated up to 9 ft into the deposit. The cores show that the reservoir deposit is predominantly sand-sized (i.e., 0.0625 – 2 mm) with median grain sizes (D_{50}) ranging between approximately 0.5 and 2 mm (Figure 4). The cores had an average median size and average geometric mean size of 1.0 mm and 1.1 mm, respectively, with an average geometric standard deviation of 2.85. None of the samples contained significant amounts of silt-sized sediment (i.e., particles finer than 0.0625 mm): the average silt content of the 8 samples is approximately 1% and the maximum is approximately 2%. The sample with the highest silt content was collected near the bank, where bank erosion likely contributed to the increased silt content. Given the relatively low head of the Simkins Dam (~ 10 ft) and the large discharge in the Patapsco River (2-yr flow is approximately 5,100 cfs, see section 3.3 below), the low silt content in the samples is reasonable and expected, as silt is more likely transported through the reservoir over the dam as wash load. In addition to the 8 core samples within the impoundment, one bulk sample upstream and one downstream of the dam were collected (Inter-Fluve 2009b). Grain size distributions for these two samples are similar to that of the 8 samples collected from the impoundment (i.e., generally within the shaded area in Figure 4). The average grain size distribution shown in Figure 4 is used as DREAM-1 model input.

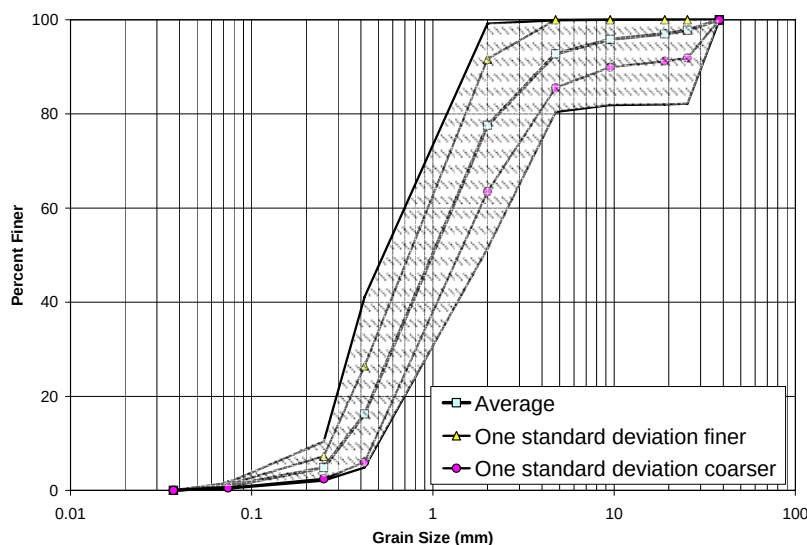


Figure 4. Grain size distribution of the Simkins Dam impoundment deposit, showing the average, one standard deviation finer and coarser than average based on 10 samples. The shaded area indicates the full range of grain size distributions. Grain size distribution data were collected and provided by Inter-Fluve (Marty Melchior, per. comm. 9 September 2009).

3.3. Hydrology

Daily average discharge records for the Patapsco River are available from the United States Geological Survey (USGS) gauging station #01589000 at Hollofield, MD located at RM 17.66. They cover water year (WY) 1945 through 1991, WY 1995, and WY 2001 through WY 2004. Annual peak records are available at the same station for WY 1945 through 1991, WY 1994, and WY 2001 through 2004 (Table 1). Daily average discharge records for the entire recorded period were used to derive a flow duration curve (Figure 5), and the annual peak flow record was used to fit to a Log-Pearson Type III distribution curve to estimate discharge for typical recurrence intervals (Figure 6 and Table 2). On a daily-averaged basis, water discharge exceeds 111 cfs 50% of the time, exceeds 255 cfs 20% of the time, exceeds 408 cfs 10% of the time, and exceeds 1,300 cfs 1% of the time (Figure 5). The 2-yr recurrence interval flow is approximately 5,100 cfs and 5-yr recurrence interval flow is approximately 11,400 cfs (Figure 6 and Table 2).

In order to select typical water years (an average, a dry and a wet year) for model input, the annual run-off and annual peak flow were ranked for the available water years, and their respective exceedance probabilities were calculated (Table 1). The typical water years used as model input were selected so that the average year has exceedance probabilities of approximately 50% for both annual run-off and annual peak flow; the wet year has an exceedance probability of approximately 10% for both annual run-off and annual peak flow; and the dry year has an exceedance probability of approximately 90% for both annual run-off and annual peak flow. The typical water years selected were WY 1983 (an average year), WY 2004 (a wet year) and WY 1965 (a dry year) as shown in Table 1. All the three typical years were selected from years after 1953 to account for any potential altered hydrological conditions in the study reach due to the construction of Liberty Dam upstream of the study reach. Daily discharge for the selected three typical water years is provided in Figure 7. Note that the simulation presented later in this report assumed dam removal in early August, and thus, the discharge record for a selected typical year presented in Figure 7 included two additional months (August and September) from the previous water year.

For modeling purposes, we assumed that discharge is proportional to contributing catchment area presented in Figure 1b.

Table 1. Patapsco River annual run-off and peak flow, based on USGS gauging station “Patapsco River at Hollofield, MD” (#01589000) daily average discharge records and annual peak flow records

Water Year	Annual Run-off (acre-ft)	Rank	Exceedance Probability (%)	Peak	Rank	Exceedance Probability (%)	Note
1945	213,104	11	20.8	9,700	13	24.5	
1946	278,886	5	9.4	13,500	6	11.3	
1947	165,777	20	37.7	4,540	28	52.8	
1948	247,192	9	17.0	7,080	19	35.8	
1949	302,146	4	7.5	4,540	29	54.7	
1950	188,749	15	28.3	7,590	17	32.1	
1951	267,295	6	11.3	6,060	24	45.3	
1952	373,519	2	3.8	12,300	8	15.1	
1953	323,133	3	5.7	10,800	10	18.9	Liberty Dam constructed upstream
1954	125,020	23	43.4	2,900	40	75.5	
1955	70,850	39	73.6	7,860	16	30.2	
1956	178,370	19	35.8	19,000	3	5.7	
1957	123,622	24	45.3	3,260	35	66.0	
1958	178,417	18	34.0	2,830	43	81.1	
1959	55,579	49	92.5	2,840	42	79.2	
1960	79,985	34	64.2	1,940	47	88.7	
1961	101,609	27	50.9	2,200	46	86.8	
1962	65,415	44	83.0	1,800	49	92.5	
1963	57,758	46	86.8	2,570	44	83.0	
1964	69,844	41	77.4	3,960	31	58.5	
1965	57,312	47	88.7	1,920	48	90.6	Dry
1966	46,556	51	96.2	2,980	37	69.8	
1967	78,044	37	69.8	5,240	26	49.1	
1968	80,719	33	62.3	3,900	32	60.4	
1969	56,848	48	90.6	2,360	45	84.9	
1970	73,678	38	71.7	1,670	50	94.3	
1971	150,704	22	41.5	12,700	7	13.2	
1972	380,253	1	1.9	80,600	1	1.9	
1973	256,838	7	13.2	4,900	27	50.9	
1974	95,207	28	52.8	2,870	41	77.4	
1975	235,874	10	18.9	46,500	2	3.8	
1976	181,573	16	30.2	6,330	22	41.5	
1977	78,258	36	67.9	3,150	36	67.9	
1978	156,966	21	39.6	6,770	21	39.6	
1979	191,119	14	26.4	10,500	11	20.8	
1980	181,315	17	32.1	9,900	12	22.6	
1981	61,103	45	84.9	5,680	25	47.2	
1982	67,821	43	81.1	2,950	39	73.6	
1983	105,860	26	49.1	4,450	30	56.6	Average
1984	198,020	13	24.5	6,270	23	43.4	

Water Year	Annual Run-off (acre-ft)	Rank	Exceedance Probability (%)	Peak	Rank	Exceedance Probability (%)	Note
1985	69,842	42	79.2	7,950	15	28.3	
1986	53,841	50	94.3	890	51	96.2	
1987	78,782	35	66.0	3,740	33	62.3	
1988	85,490	32	60.4	6,940	20	37.7	
1989	111,112	25	47.2	11,800	9	17.0	
1990	94,818	29	54.7	2,960	38	71.7	
1991	93,614	30	56.6	7,410	18	34.0	
1994		N/A		15,700	4	7.5	
1995	70,719	40	75.5		N/A		
2001	89,494	31	58.5	3,410	34	64.2	
2002	36,017	52	98.1	714	52	98.1	
2003	207,939	12	22.6	9,010	14	26.4	
2004	255,709	8	15.1	14,800	5	9.4	Wet

Table 2. Annual peak flow for typical recurrence intervals in the Patapsco River, based on a log-Pearson III fit of annual peak flow series at USGS gauging station #01589000 for the period of 22 May 1944 through 30 September 2004.

Recurrence Interval (year)	Discharge (cfs)
1.2	2,300
1.5	3,500
2	5,100
5	11,400
10	18,200

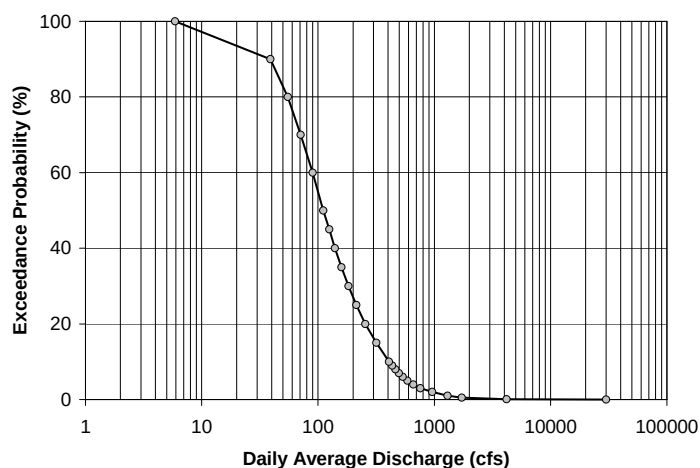


Figure 5. Patapsco River flow duration curve, based on daily average discharge record at USGS gauging station #01589000 for the period of 22 May 1944 through 30 September 2004.

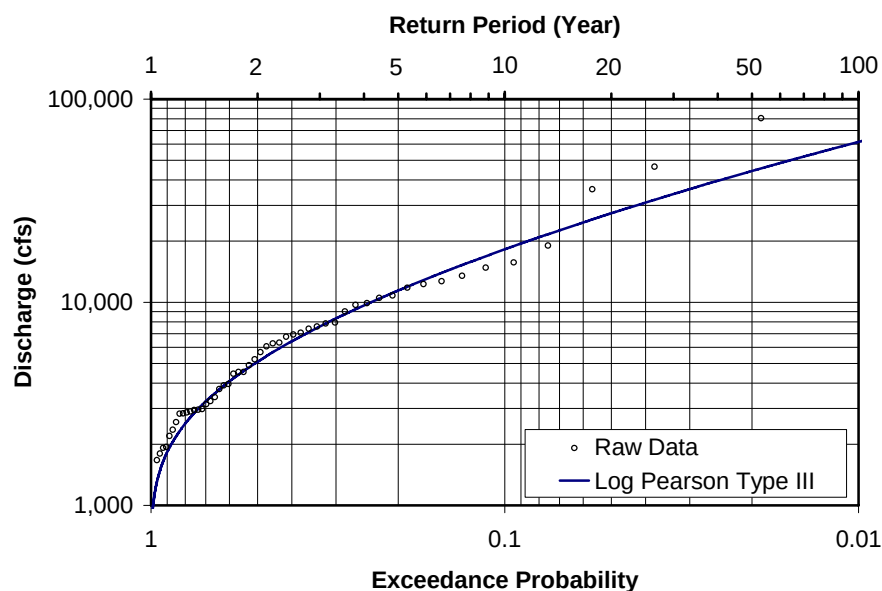


Figure 6. Patapsco River annual peak flow exceedance probability and recurrence interval, based on annual peak flow record at USGS gauging station #01589000 for the period of 22 May 1944 through 30 September 2004.

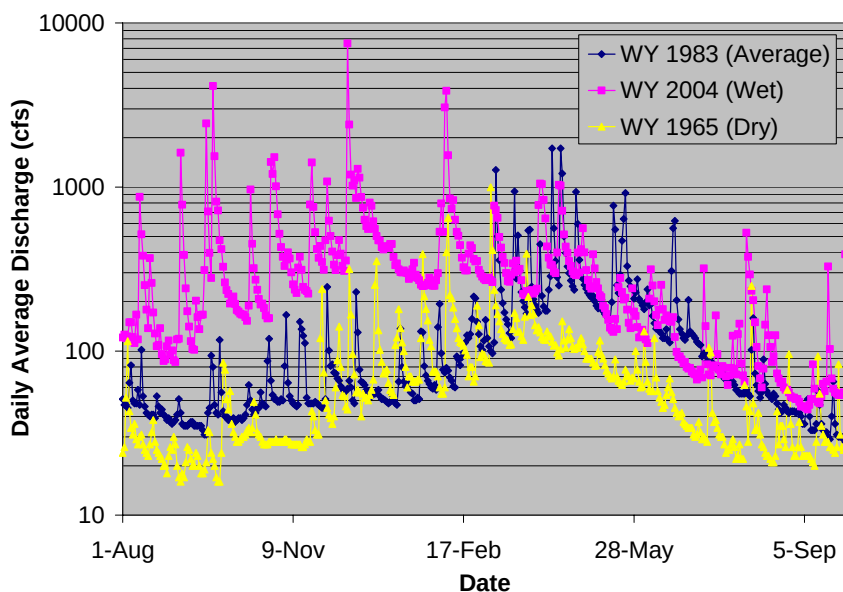


Figure 7. Patapsco River daily average discharge at USGS gauging station #01589000 for three typical water years (including two months [August and September] of previous water year).

3.4. Tidal Effect from Chesapeake Bay

The Patapsco River drains into the Chesapeake Bay, and as a result, tidal level at Chesapeake Bay may affect sediment transport dynamics near the mouth of the river. The closest tidal gauge station to the Patapsco River mouth in the Chesapeake Bay is the NOAA tidal gauge station at Baltimore, MD

(#8574680) located approximately 2 miles from the river mouth directly across the bay at Baltimore harbor. Recorded tidal level was used to provide base level control for the modeling. Hourly tidal level at the Baltimore gauge for WY 1983, 1946 and 1965 are presented in Figure 8. Similar to Figure 7, Figure 8 also included the month of August and September from the previous water year because the modeling assumed dam removal in early August.

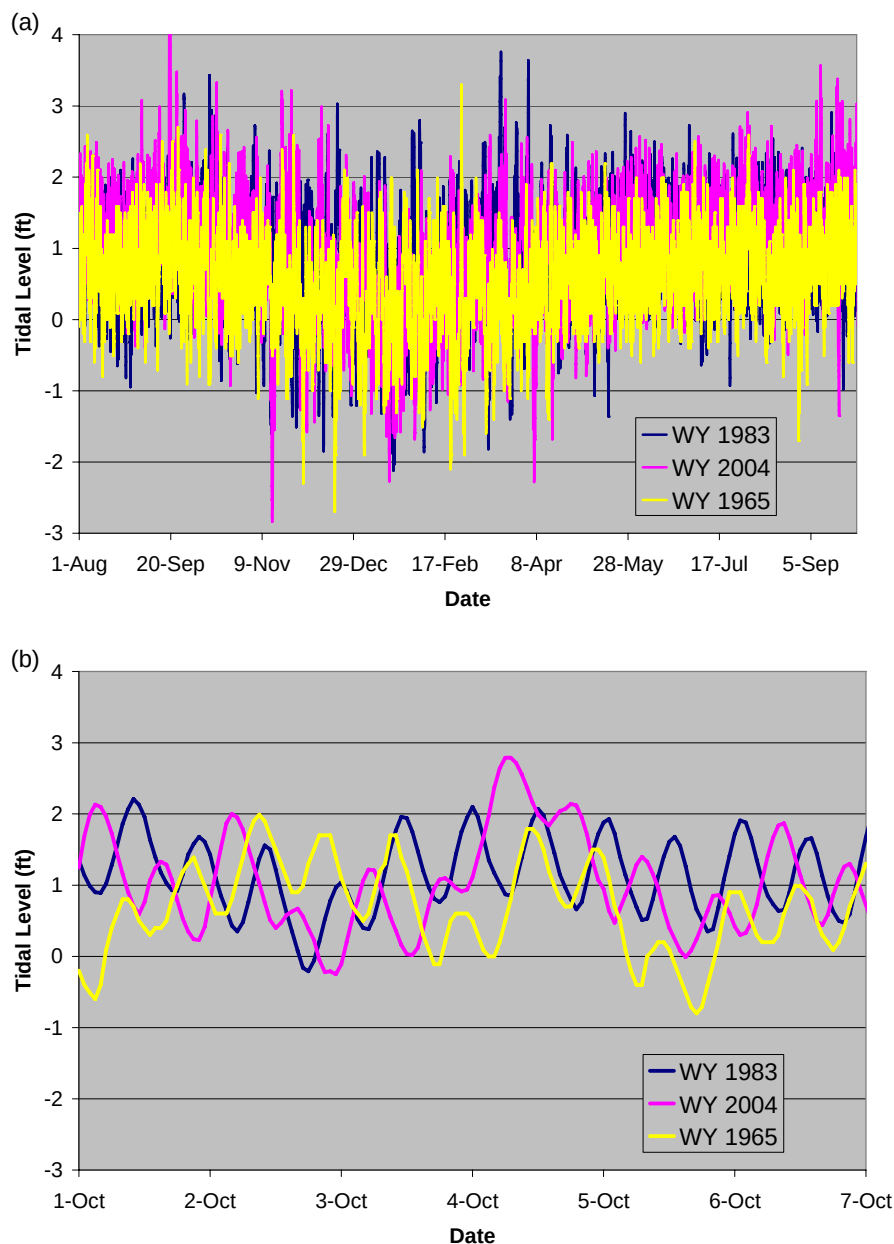


Figure 8. Chesapeake Bay hourly tidal level at NOAA tidal gauge Baltimore, MD station (#8574680). (a) The selected three typical water years (including two months [August and September] of the previous water year); and (b) during a one-week period for each of the selected three typical water years.

3.5. Sediment Supply at Simkins Dam

A quantitative estimate of the supply rate of sand-sized sediment at Simkins Dam is not available. Sensitivity tests conducted by Cui et al. (2006b), however, indicated that modeling results for sediment transport following dam removal is not particularly sensitive to background sediment supply. With that, we selected a sand supply rate for model input through trial-and-error during the zeroing process (described below in Section 4) so that the DREAM-1 model produced a longitudinal profile similar to the currently observed profile. The sediment supply at Simkins Dam site selected through this process is 3,400 yd³/yr solid, or 5,200 yd³/yr (bulk volume) if deposited in the reservoir, assuming a porosity of 0.35.

3.6. Surface Gravel Median Size

The implementation of roughness and partial sand coverage corrections to modeled sand transport rates over a gravel bed river (as detailed in Cui et al. 2008) requires a **rough** estimate of surface gravel median size. This correction provides a slightly more accurate modeling result when the predicted thickness of sand deposition is too thin to cover the entire gravel bed. The surface gravel median size in the Patapsco River is estimated based on three pebble counts collected from exposed gravel bars, and by assuming surface gravel median size decreases exponentially in the downstream direction (Figure 9). It should be noted that the estimated surface gravel median size downstream of River Station 40,000 ft (RM 7.6) has minimal effect on modeling results because this reach is generally covered by a layer of sand.

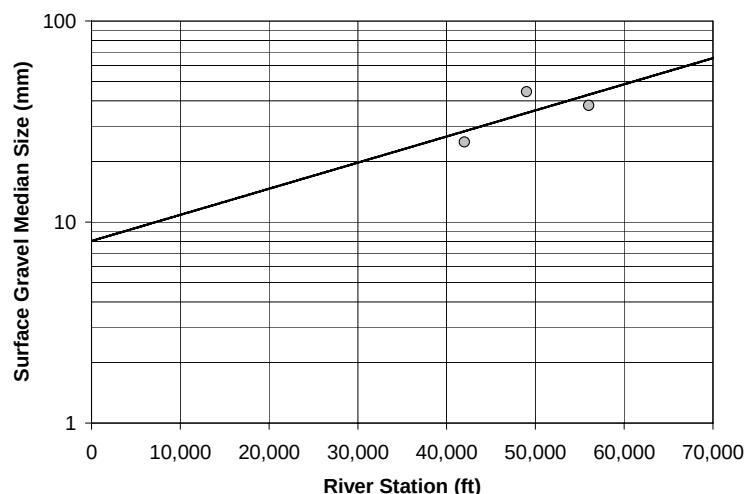


Figure 9. Estimated surface gravel median size in the Patapsco River based on three pebble counts (collected by Inter-Fluve, Marty Melchior, per. comm. 21 August 2009) and the assumption that surface gravel median size decreases exponentially in the downstream direction.

4. Zeroing Process: Simulating Current Conditions in the Project Area and Downstream

Prior to simulating dam removal scenarios, the model must be tested (and calibrated, if necessary) so that it can reasonably reproduce the current longitudinal profile downstream of the dams with the assumed input parameters (Cui et al., 2006a,b; Cui and Wilcox 2008). Because there is no reliable information pertaining to sand supply in the Patapsco River, the input sand supply to the model was adjusted through a trial-and-error process so that the model produced a longitudinal profile similar to that currently observed.

The simulated longitudinal profile under the current condition (Run 0) by assuming a 5,200 yd³/yr (bulk volume) long-term averaged sand supply is presented in Figure 10 in comparison with the surveyed profile. The simulated longitudinal profile is presented as a range (i.e., maximum and minimum bed elevations) to characterize the natural channel aggradation and degradation responses to different flow events. While the simulated longitudinal profile under current condition generally follows the surveyed profile, there are localized differences between simulated and surveyed longitudinal profiles. The differences in simulated and observed longitudinal profiles are normal in long-term large-scale simulations (e.g., Cui and Wilcox 2008) that reflect imperfections in numerical modeling. Rather than directly applying the surveyed profile as modeling input for dam removal simulations, the model uses the simulated current longitudinal profile as the initial profile, and because this profile is in a quasi-equilibrium state within the model (i.e., it only varies slightly within the predicted range in response to different flow events), any additional changes to this initial profile will be due to dam removal related sediment release.

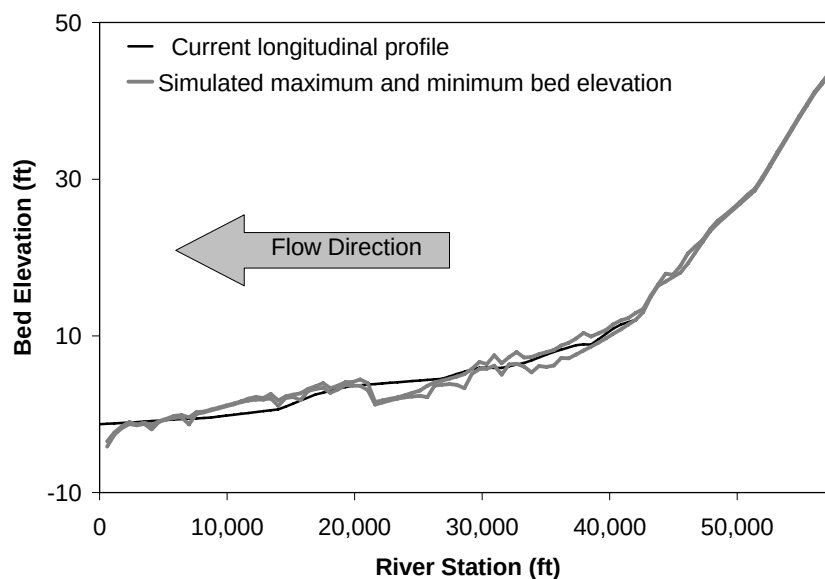


Figure 10. Simulated longitudinal profile downstream of Bloede Dam under the current condition (Run 0), provided as a range (i.e., maximum and minimum bed elevations) to characterize the regular channel aggradation and degradation oscillations in response to different flow events. Surveyed longitudinal profile is provided for comparison purposes.

5. Modeling Sediment Transport Following Simkins Dam Removal

Model simulations assume that dam removal will result in the formation of a trapezoidal channel in the former reservoir area with a 35° bank angle for both banks and an 85-ft bankfull width^a, which is the estimated average bankfull channel width just downstream of Bloede Dam. Three runs were conducted using different combinations of typical hydrological years (discussed in Section 3.3):

- Run 1: a wet year, followed by an average year and a dry year (wet-average-dry);
- Run 2: an average year, followed by another average year and a wet year (average-average-wet); and
- Run 3: a dry year, followed by an average year and a wet year (dry-average-wet).

Time periods in excess of three years are achieved by looping the data through the three-year sequence described above.

Simulated results following Simkins Dam removal for Run 1 upstream of Bloede Dam are presented in Figure 11 for the first year (a wet year) following dam removal, indicating that all the sediment within Simkins Reservoir can be eroded downstream within three months. The released sediment results in approximately 4 ft of sediment deposition just downstream of Simkins Dam and subsequently builds up in the Bloede Reservoir, gradually filling the reservoir to the crest of the dam, and then erodes it away, partially redeveloping the scour hole just upstream of Bloede Dam.

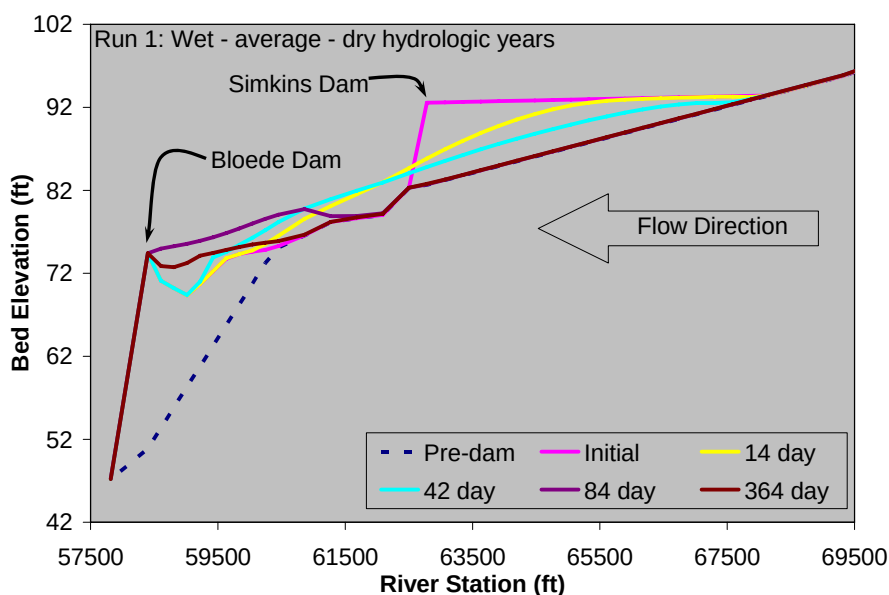


Figure 11. Simulated sediment erosion and deposition upstream of Bloede Dam following Simkins Dam removal for the first year of simulation (wet year) (Run 1), showing that sediment within Simkins Reservoir is emptied within one year following dam removal.

Simulated sediment deposition dynamics downstream of Bloede Dam following Simkins Dam removal for Run 1 (wet-average-dry year scenario) are presented as cumulative change in bed elevation in Figure

^a Bankfull depth is assumed to be 3.3 ft, and thus, bankfull width is the channel width 3.3 ft above channel bed.

12(a), and comparatively, the same results for the background condition (Run 0) are shown in Figure 12(b). Simulated long-term channel aggradation/degradation processes following Simkins Dam removal at selected stations are presented in Figure 13. Simulation results presented in Figures 12 and 13 indicate that there will be a maximum of 2.5 ft of sediment deposition downstream of Bloede Dam following the removal of Simkins Dam, and the maximum deposition occurs near River Station 40,000 ft. Moving downstream, channel aggradation becomes progressively delayed as the sediment pulse resulting from Simkins Dam removal gradually works its way downstream with decreased magnitude and increased duration. Between Simkins and Bloede dams, the amount of channel aggradation is up to 6.2 ft, which occurs near River Station 59,000 ft just upstream of Bloede Dam. Note that channel aggradation between Simkins and Bloede dams are presented only for one year while it appears that there is still significant amount of channel aggradation at River Station 59,000 ft. This is because the channel bed aggrades and degrades regularly within Bloede Reservoir area, and the simulation started with a profile with the Bloede Reservoir area degraded to a rather low level. As a result, the simulated channel bed at River Station 59,000 ft aggrades significantly under the current conditions without removing the Simkins Dam. Subtracting the maximum amount of channel aggradation under the current conditions (without Simkins Dam removal) from the simulated change in bed elevation following Simkins Dam removal produces the net channel aggradation due to Simkins Dam removal, which is presented in Figure 14 at the same stations. Results in Figure 14 indicate that Simkins Dam removal will result in less than 1.5 ft of additional sediment deposition (i.e., Figure 12a minus Figure 12b) near River Station 40,000 ft (RM 7.6) (Figure 14a) while all other reaches show less than 1-ft of maximum deposition following removal. Figure 14(a) indicates that using the looped “wet-average-dry” scenario, the maximum thickness of sediment deposition of 1.5 ft at River Station 40,000 ft (RM 7.6) is predicted to persist for up to 5 years before fully transporting downstream. Subsequent stations downstream then receive the sediment in following years, with up to 1 ft of deposition predicted at River Station 35,00 ft in years 4-6, and less than 0.5 of maximum deposition anywhere further downstream. The slow dissipation of the sediment deposit is expected because the small amount of deposited sediment has a very limited impact on the reach-averaged channel gradient (e.g., a 2 ft deposition at one end of the 40,000 ft station would only change the average channel gradient by 0.00005 from the current condition). Therefore, the net sediment transporting capacity changes only very modestly from the current condition. Between Simkins and Bloede dams, the additional sediment deposition due to Simkins Dam removal has a simulated maximum thickness of approximately 4 ft with deposition persisting for a short duration (erodes away within six months) (Figure 14b).

Simulated suspended sediment concentrations (TSS) following Simkins Dam removal for Run 1 (wet-average-dry water year scenario) is presented in Figure 15, indicating that there will be approximately 370 ppm (part per million, or mg/liter) of additional (i.e., increase from the background condition) TSS on the first day of dam removal on a daily-averaged basis. The additional TSS decreases quickly in the following days and becomes less than 50 ppm in about 4 days following dam removal. After that, increased TSS occurs only during the large flow events until all the sediment within the Simkins Reservoir is eroded downstream. Limited data to characterize suspended sediment concentration in the Patapsco River under current conditions are available, but MDNRWS (2005) reported a TSS of 1,200 ppm collected during a storm event, which is higher than the predicted increase in suspended sediment concentration following Simkins Dam Removal.

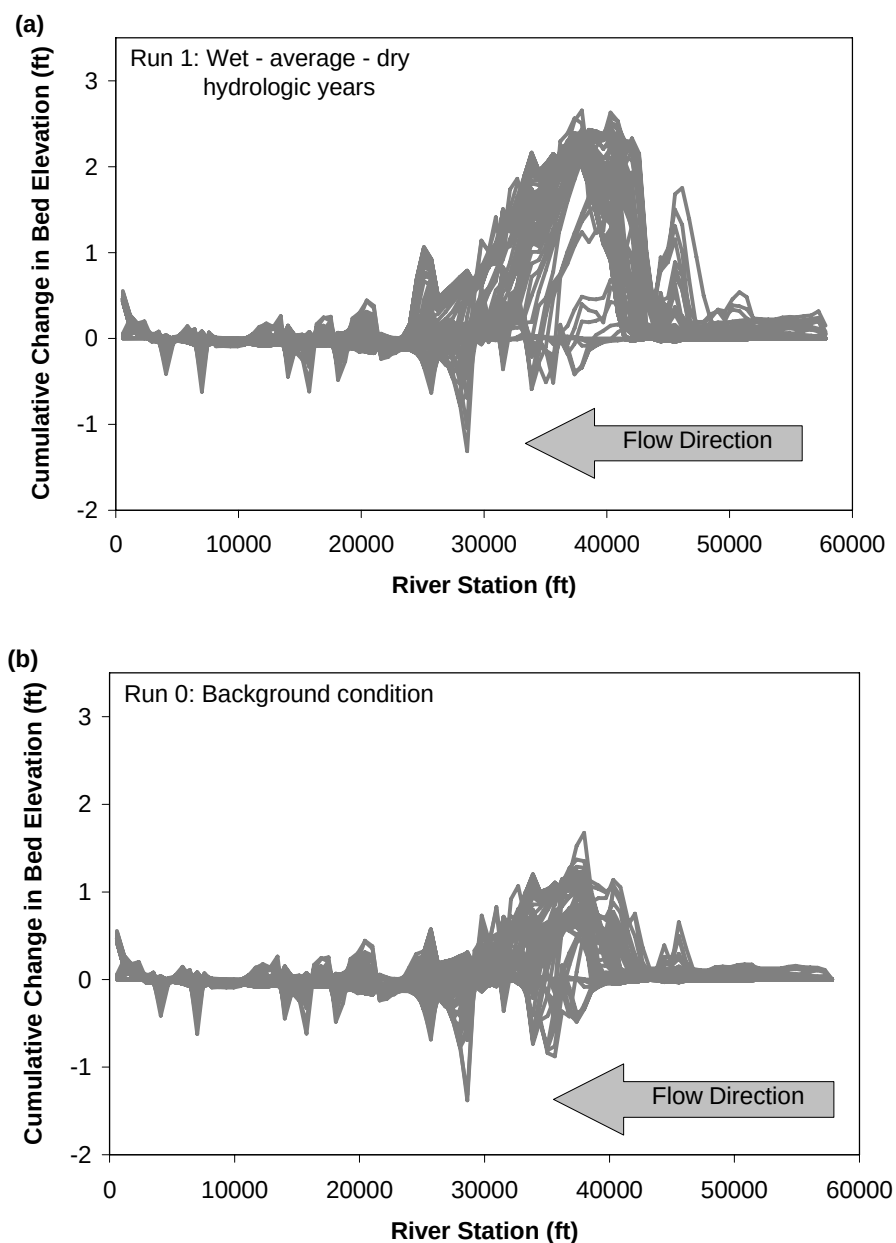


Figure 12. Simulated range of channel aggradation and degradation downstream of Bloede Dam following Simkins Dam removal for (a) Run 1 (wet-average-dry year scenario) in comparison with (b) the background condition (Run 0). Diagrams are intended only for depicting the range of sediment deposition and not intended for identification of sediment deposition in individual years.

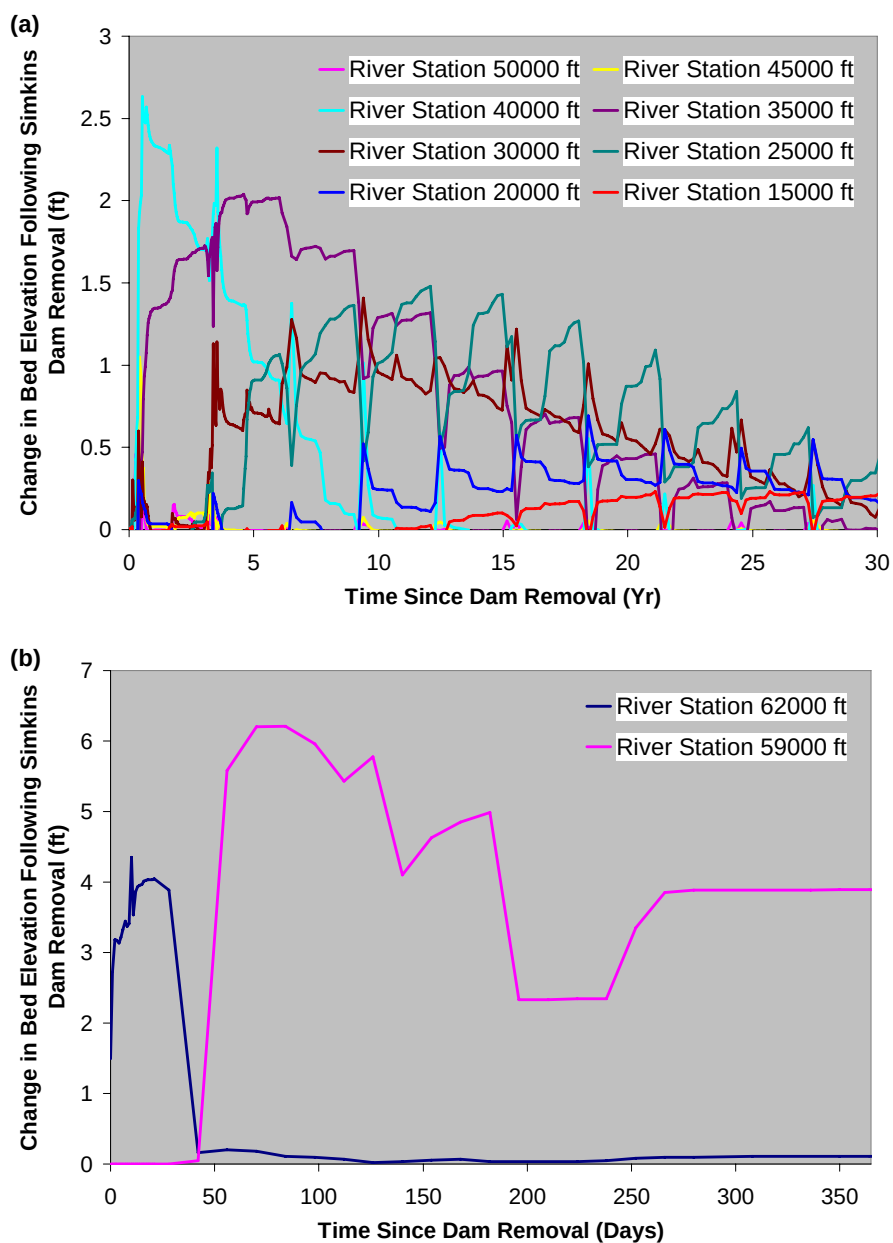


Figure 13. Simulated change in bed elevation at selected stations: (a) downstream of Bloede Dam; and (b) between Simkins and Bloede dams. Diagram (b) is presented only for one year while River Station 59,000 ft is seen to have almost 4 ft of deposition, because this deposition is also observed under current conditions and thus, is not attributed to Simkins Dam removal as shown in Figure 14.

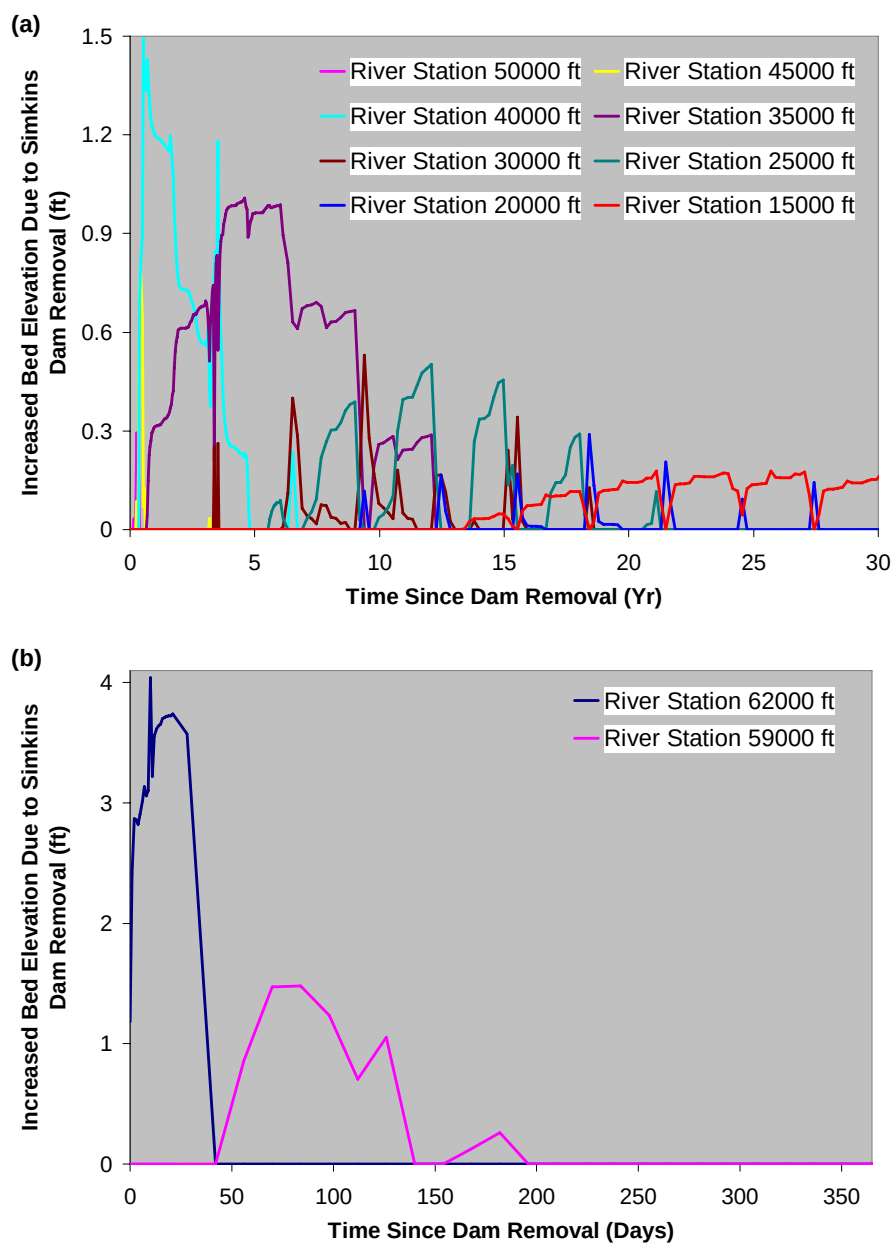


Figure 14. Simulated channel aggradation due to Simkins Dam removal (i.e., by removing simulated changes from background conditions) at selected stations: (a) downstream of Bloede Dam; and (b) between Simkins and Bloede dams.

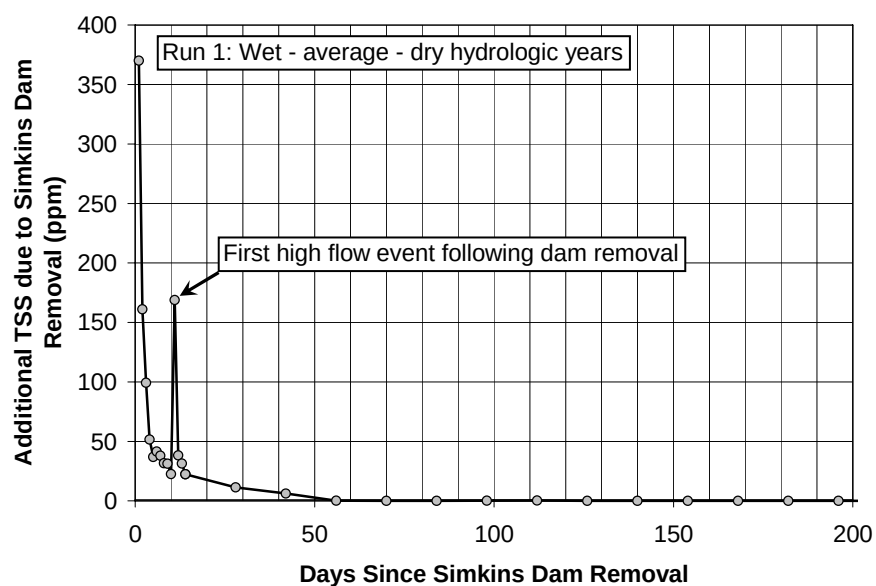


Figure 15. Simulated additional suspended sediment concentration due to Simkins Dam removal for Run 1 (wet-average-dry year scenario).

Results for Runs 2 and 3 are similar to Run 1, with the exception that erosion of the reservoir deposit becomes progressively slower as the hydrology for the first year of simulation becomes progressively drier (Figure 16). Results for the reach downstream of Bloede Dam and the suspended sediment concentration for Runs 2 and 3 are also similar to that of Run 1, as shown in Figures 17 and 18.

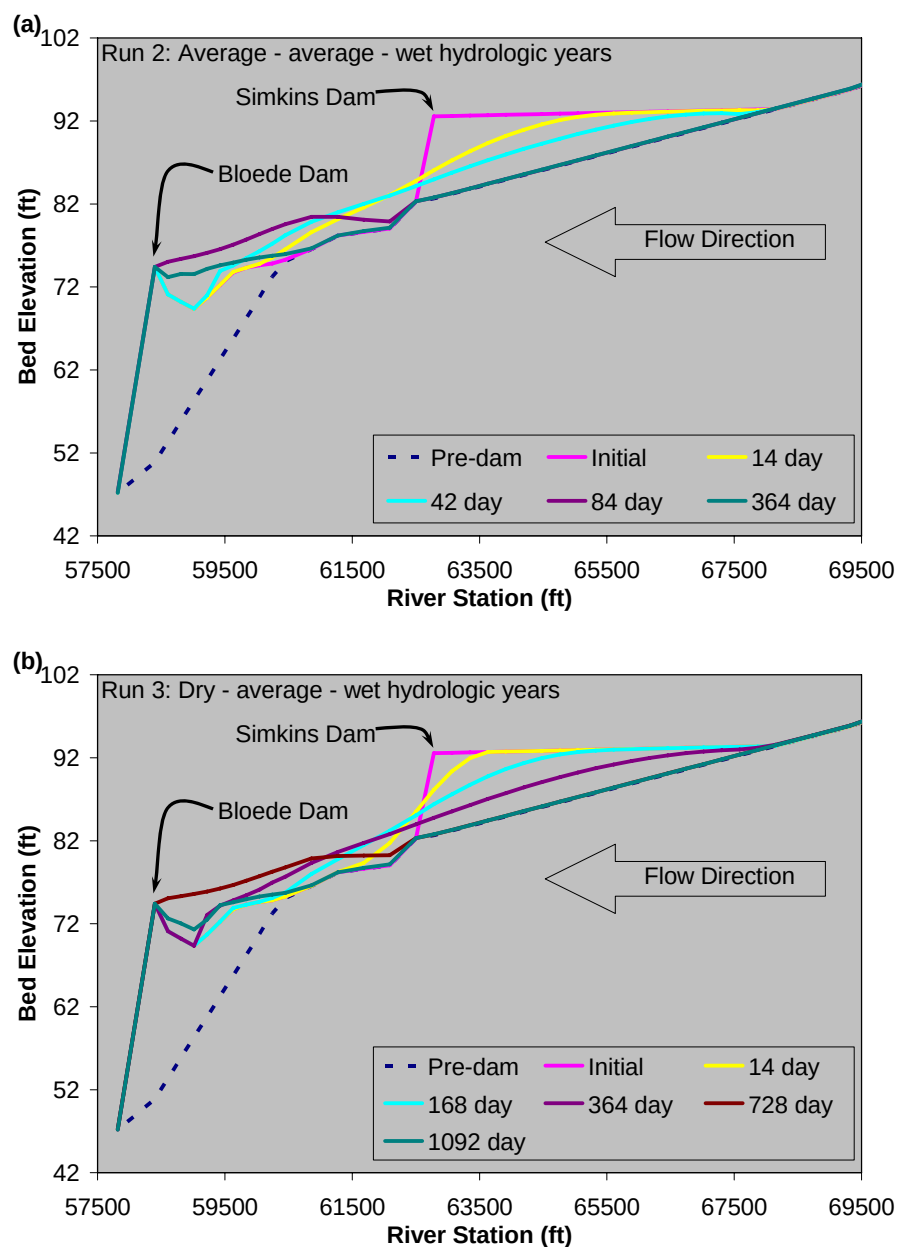


Figure 16. Simulated sediment erosion and deposition upstream of Bloede Dam following Simkins Dam removal for (a) Run 2 (average-average-wet year scenario); and (b) Run 3 (dry-average-wet year scenario).

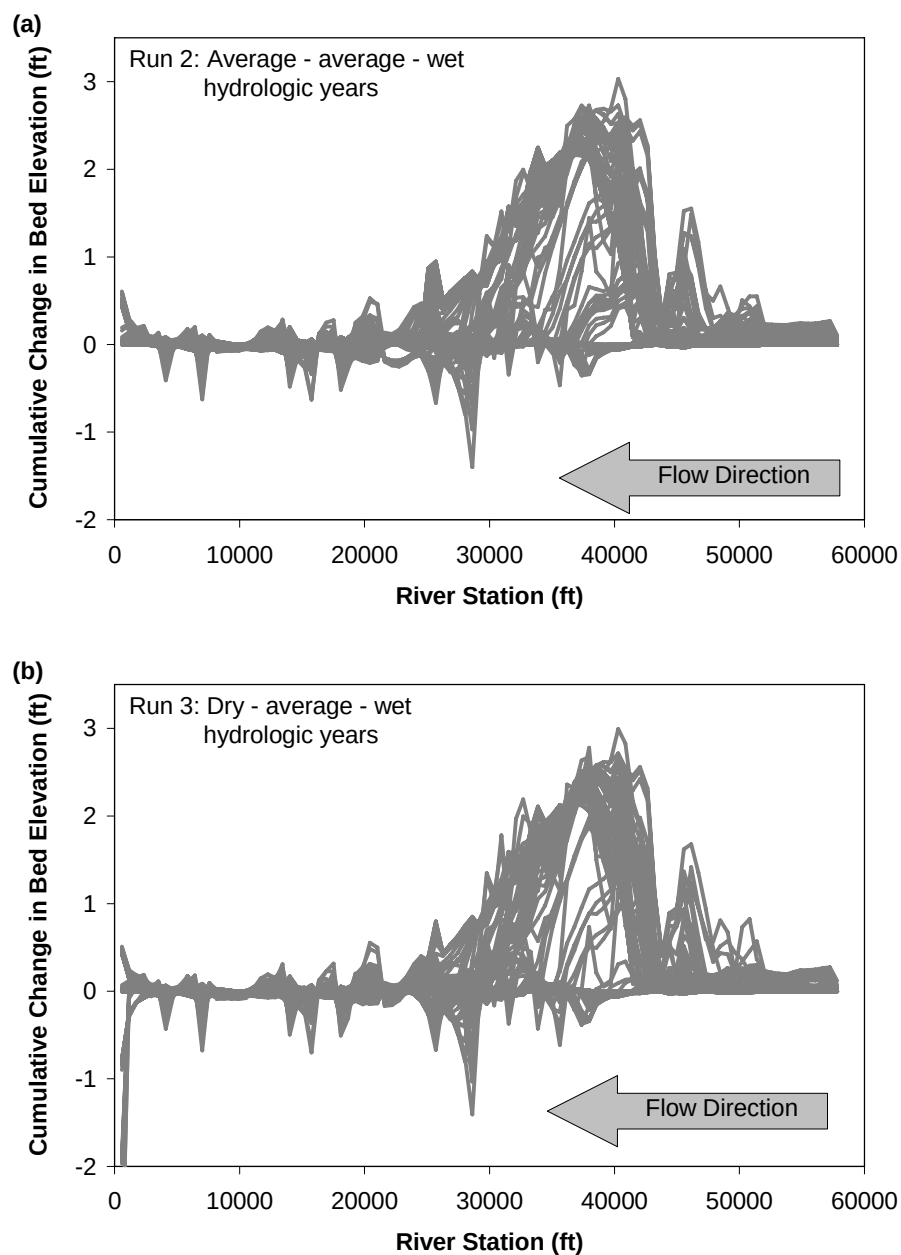


Figure 17. Simulated range of sediment deposition downstream of Bloede Dam following Simkins Dam removal for (a) Run 2 (average-average-wet year scenario); and (b) Run 3 (dry-average-wet year scenario).

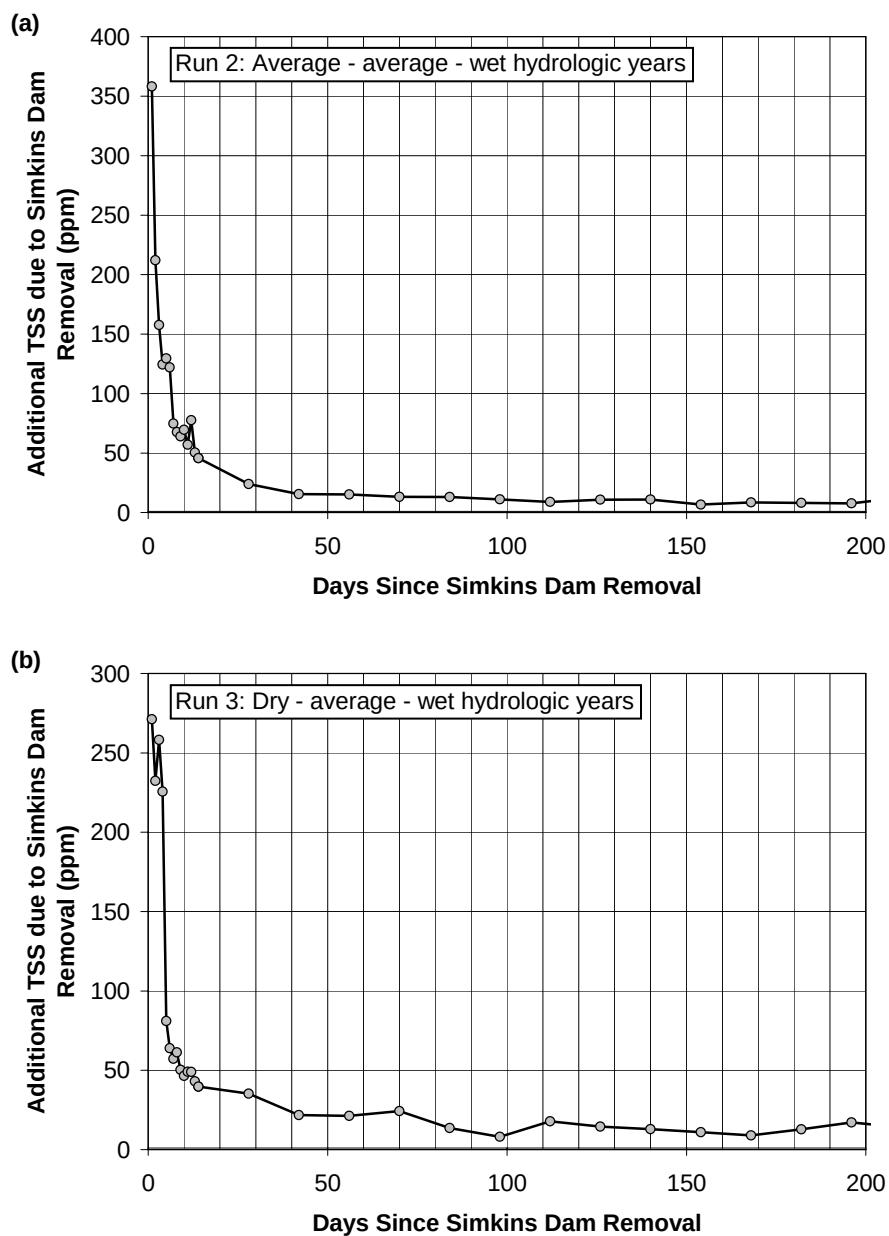


Figure 18. Simulated additional suspended sediment concentration due to Simkins Dam removal for (a) Run 2 (average-average-wet year scenario); and (b) Run 3 (dry-average-wet year scenario).

6. Sensitivity Tests on Volume of Sediment Release

There are many uncertainties in sediment transport modeling, and a primary one relates to unknown future flow conditions. In Section 5, we presented three runs with different combinations of future flow conditions to provide a boundary on the likely range of river bed responses.

One uncertainty specific to sediment transport modeling following dam removal is the future channel geometry that will form within the former reservoir area (Cui et al. 2006a). The model runs conducted in Section 5 assumed the formation of a trapezoidal channel within the former reservoir area following dam removal with a 35° bank angle for both banks and an 85-ft bankfull width. This assumption results in a total of 88,000 yd³ (bulk volume) of sediment released from Simkins reservoir. While the above assumptions are reasonable, the possibility of additional sediment release following dam removal can not be eliminated. As a sensitivity check, we performed additional model runs where the channel formed within the former reservoir area was increased in width from 85 ft to 100 ft, or approximately an 18% increase, which will increase the overall amount of eroded sediment to 104,000 yd³ (bulk volume). Note the simulated volumes of sediment erosion are comparable to Inter-Fluve's (2009a) estimate that there is a total of 113,000 yd³ of sediment stored within the Simkins impoundment and approximately 63,000 to 100,000 yd³ of the total volume will potentially be released downstream following dam removal under various sediment management scenarios.

Three runs were conducted with the wider channel width in the former reservoir area assumption, using wet-average-dry (Run 4), average-average-wet (Run 5), and dry-average-wet (Run 6) year combinations. Only the results for Run 4 are presented below in Figure 19 because the comparison of each run with its respective narrower bankfull width run is similar.

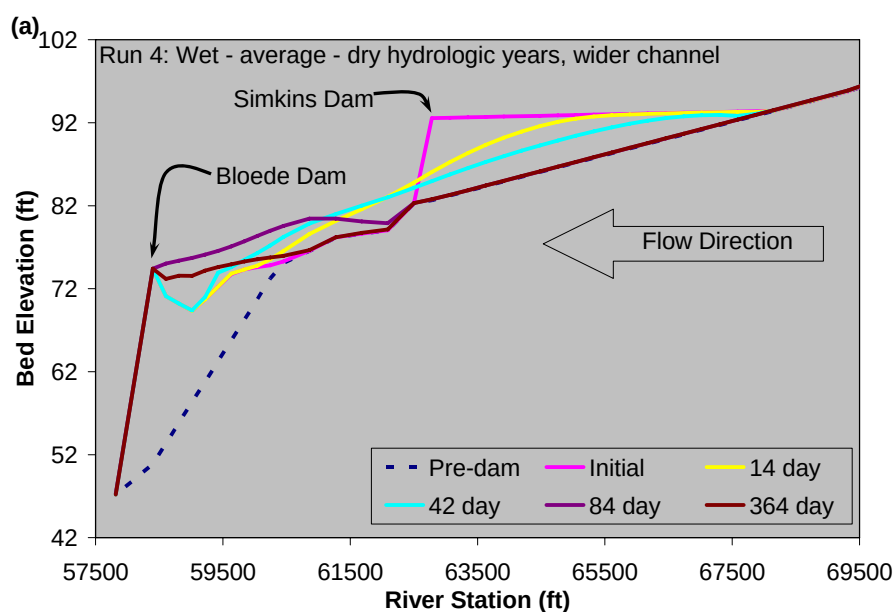


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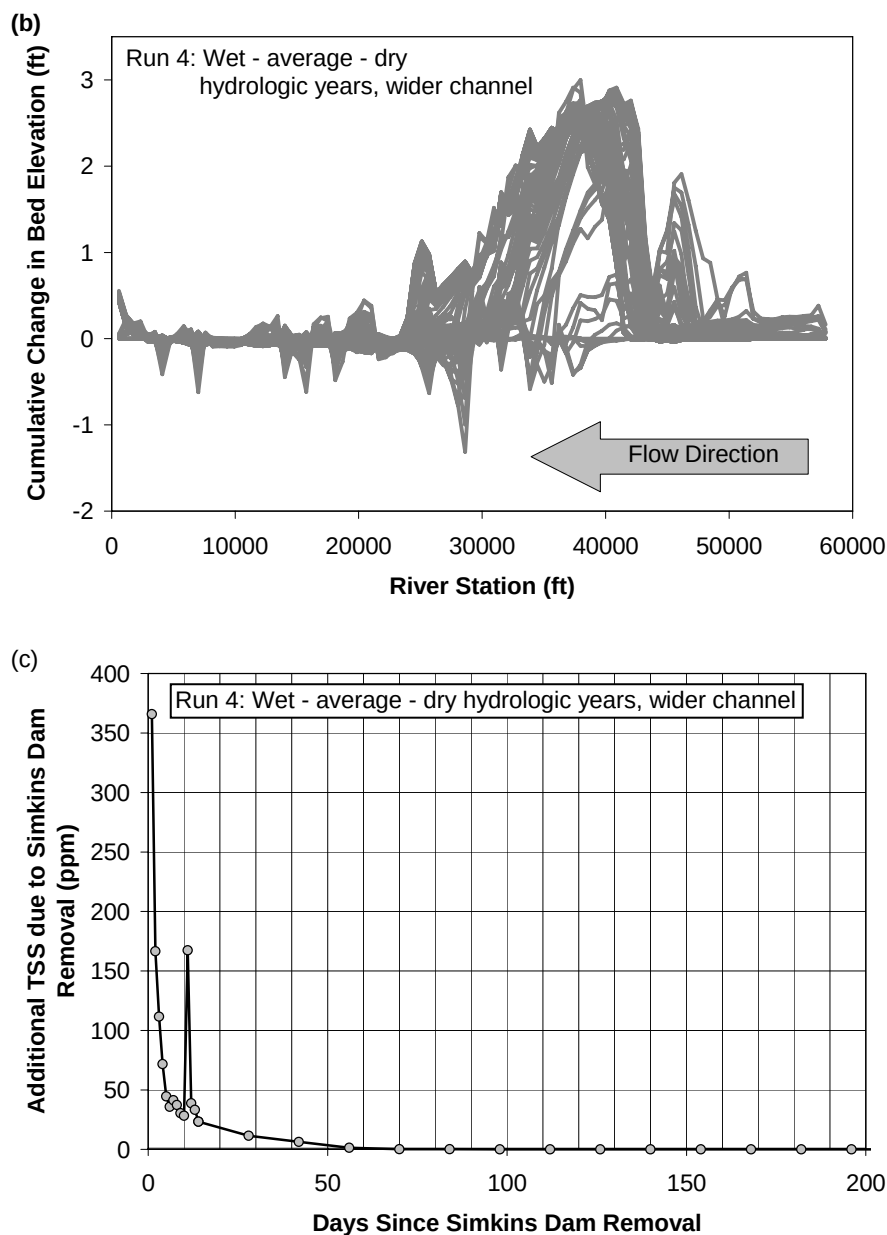


Figure 19. Simulated (a) sediment erosion and deposition upstream of Bloede Dam; (b) range of channel aggradation and degradation downstream of Bloede Dam; and (c) simulated additional suspended sediment concentration due to Simkins Dam removal for Run 4 (wet-average-dry year scenario) that assumed a wider post-dam-removal channel within the former Simkins Reservoir area to allow for more sediment release following dam removal.

Comparing results for Run 4 in Figure 19 with results for Run 1 in Figures 11, 12 and 15 indicates that simulated reservoir sediment erosion processes, downstream deposition, and additional suspended sediment concentration due to dam removal are not particularly sensitive to the assumption of bankfull channel width (and thus, volume of sediment release) within the range of widths evaluated. This lack of sensitivity to channel width, or volume of sediment release, within a reasonable range is in agreement with previous sensitivity test runs for other dam removal scenarios presented in Cui et al. (2006b) and in

Stillwater Sciences (2002) where it was concluded that limited dredging of sediment ahead of dam removal (to reduce the volume of sediment released downstream) had little impact on the overall channel morphological response.

7. Preliminary Modeling of Sediment Transport Following Bloede Dam Removal

To provide a preliminary evaluation of potential sediment transport dynamics following the removal of Bloede Dam after Simkins Dam is removed, we conducted three DREAM-1 runs using similar combinations of hydrologic years (for both discharge and tidal level) used for the Simkins Dam removal simulations.

- Run 7: wet – average – dry years;
- Run 8: average – average – wet years; and
- Run 9: dry – average – wet years.

In the absence of grain size data for Bloede Reservoir, we assumed that the grain size distribution within the Bloede Reservoir deposit is identical to that in the Simkins Reservoir deposit. Because of the relatively larger dam height of Bloede Dam (26-ft high compared to 10-ft high for Simkins Dam), there may be a layer of finer sediment deposited just upstream of the dam near the base of the deposit (typically referred to as a bottomset deposit). If such a layer exists, the suspended sediment concentration will likely be slightly higher than calculated, but the erosion and deposition dynamics should be similar to that predicted from the various runs.

Similar to the simulation of Simkins Dam removal, model runs assumed that removal of the Bloede Dam will result in the formation of a trapezoidal channel with 35° bank angles for both banks and an 85-ft bankfull width (estimated based on the channel width just downstream of Bloede Dam), eroding approximately 76,000 yd³ (bulk volume) of sediment from the reservoir area. Note predicted volume of sediment release following Bloede Dam removal is less than that following Simkins Dam removal despite the fact that Bloede Dam is 2.6 times the height of Simkins Dam. The smaller predicted volume of sediment release following Bloede Dam removal is due to the fact that Bloede impoundment is located in a much steeper pre-dam-construction river reach than the Simkins impoundment, and thus its longitudinal extent is much shorter.

Predicted reservoir deposit erosion processes are presented in Figure 20 for the three runs, indicating that

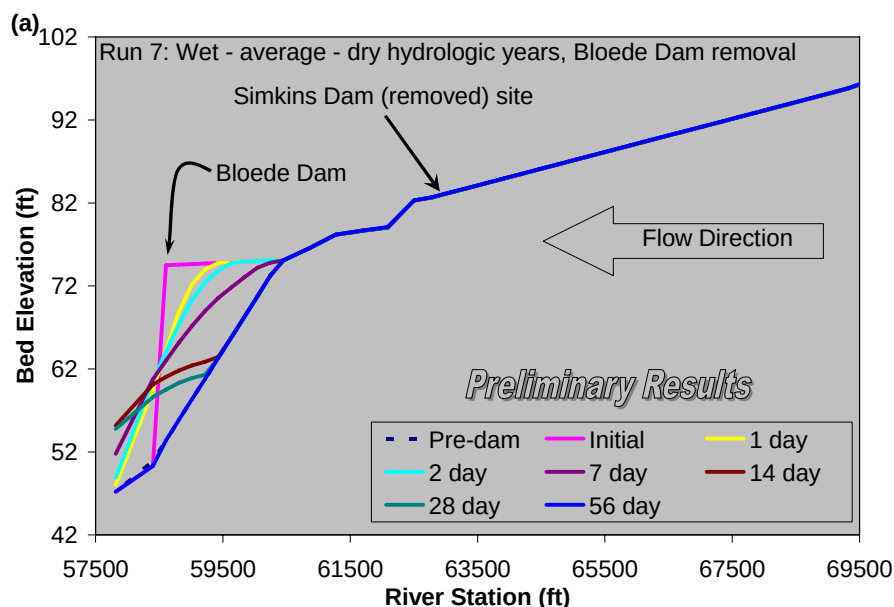


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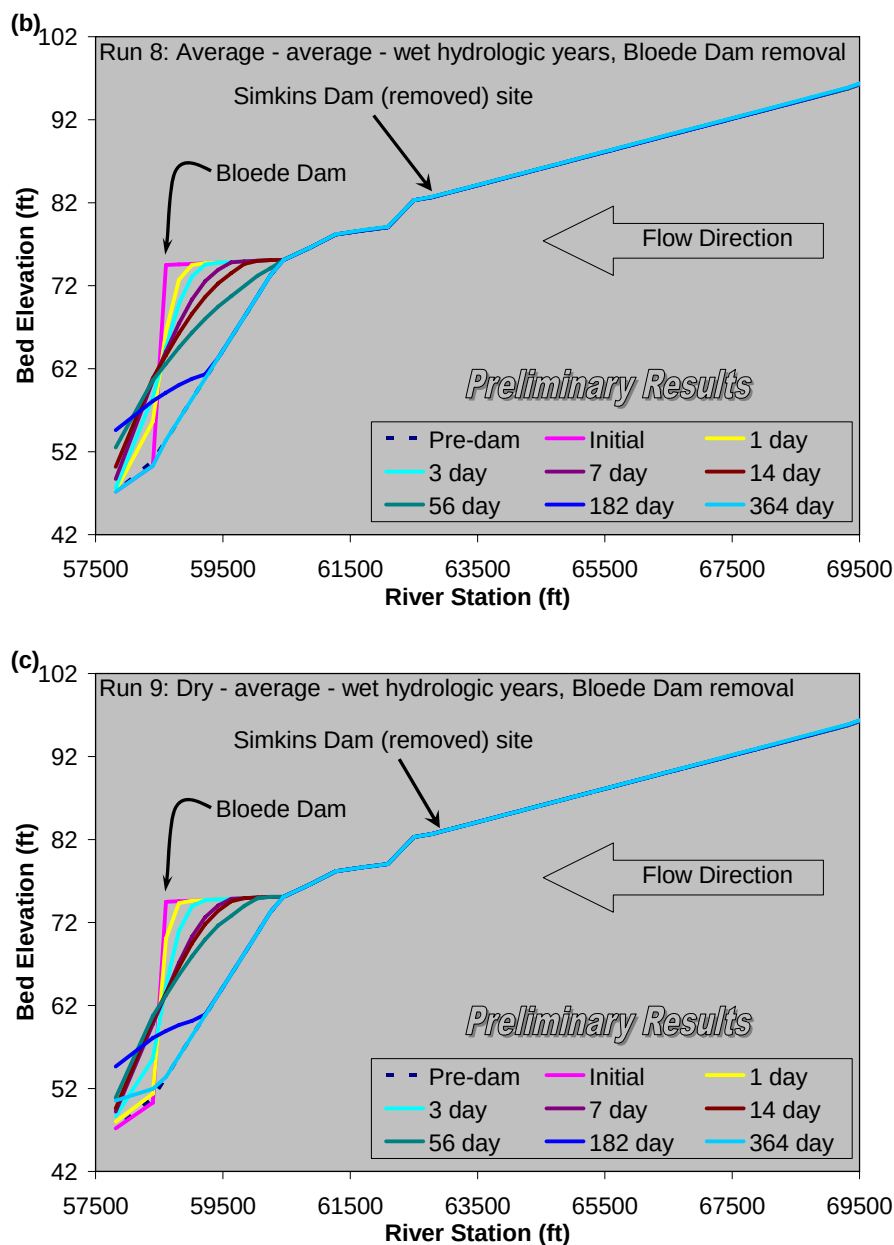


Figure 20. Simulated reservoir sediment erosion processes following Bloede Dam removal. (a) Run 7: wet – average – dry year scenario; (b) Run 8: average – average – wet year scenario; and (c) Run 9 dry – average – wet year scenario. Results are preliminary because no grain size samples were collected from Bloede Reservoir deposit.

wetter years allow for the sediment to be eroded faster than drier years, but in all cases sediment erosion from the former reservoir is complete within one year. Compared to the simulated reservoir deposit erosion process for Simkins Dam removal presented in Section 5, erosion of the Bloede deposit following dam removal is faster because Bloede Reservoir area is located in a much steeper reach (pre-dam construction topography).

Simulated ranges of sediment deposition following Bloede Dam removal are presented in Figure 21(a) and (b) for Run 7, and increased bed elevations due to sediment release following dam removal (i.e.,

simulated change in bed elevation following dam removal less the maximum simulated bed elevation under current conditions) are presented in Figure 21(c). Results in Figure 21 show almost 8 ft of sediment deposition immediately downstream of Bloede Dam that dissipates within one year. Compared to the predicted sediment deposition following Simkins Dam removal, more sediment deposition occurs in the reach immediately downstream of Bloede Dam to approximately River Station 48,000 ft (RM 9.1). Less sediment deposition is predicted in this reach following Simkins Dam removal because of the attenuation effect of the still-existing Bloede Reservoir that absorbs the sediment released from Simkins Reservoir before gradually re-releasing it downstream. Simulated additional daily-averaged TSS due to dam removal for Run 7 is presented in Figure 21(d), showing approximately 1,200 ppm of increase in suspended sediment concentration during the first day following dam removal that decreases quickly in the following days. The 1,200 ppm increase in suspended sediment concentration is comparable to the single suspended sediment concentration sample under the current conditions during a storm event provided in MDNRWS (2005). The additional TSS due to Bloede Dam removal is higher than that due to Simkins Dam removal on the day of dam removal because Bloede Reservoir deposit is eroded downstream more rapidly. As discussed earlier, the actual additional TSS may be higher than predicted if a layer of finer particles exist at the bottom of the deposit near Bloede Dam. Improved model runs can be conducted in the future once sediment cores are collected from the Bloede Reservoir deposit. Simulated sediment deposition downstream of Bloede Dam and additional TSS due to dam removal for Runs 8 and 9 are not presented as they are very similar to that for Run 7 (Figure 21).

Sensitivity test runs (Runs 10, 11 and 12) to evaluate the effect of increasing the channel width in the reservoir deposit (and so increasing the total released sediment volume) were also conducted for Bloede Dam removal simulation by increasing the assumed future bankfull width within Bloede Reservoir from 85 ft to 100 ft. This increased width results in approximately 88,000 yd³ (bulk volume) of sediment erosion from Bloede Reservoir. Results from these runs indicate that the morphological response is not particularly sensitive to this increase, similar to the findings for Simkins Dam removal simulations.

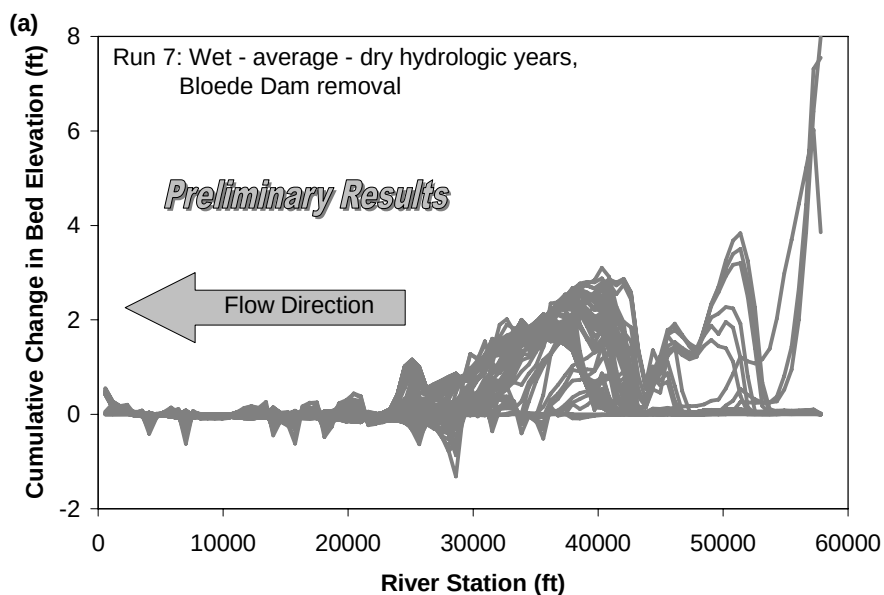


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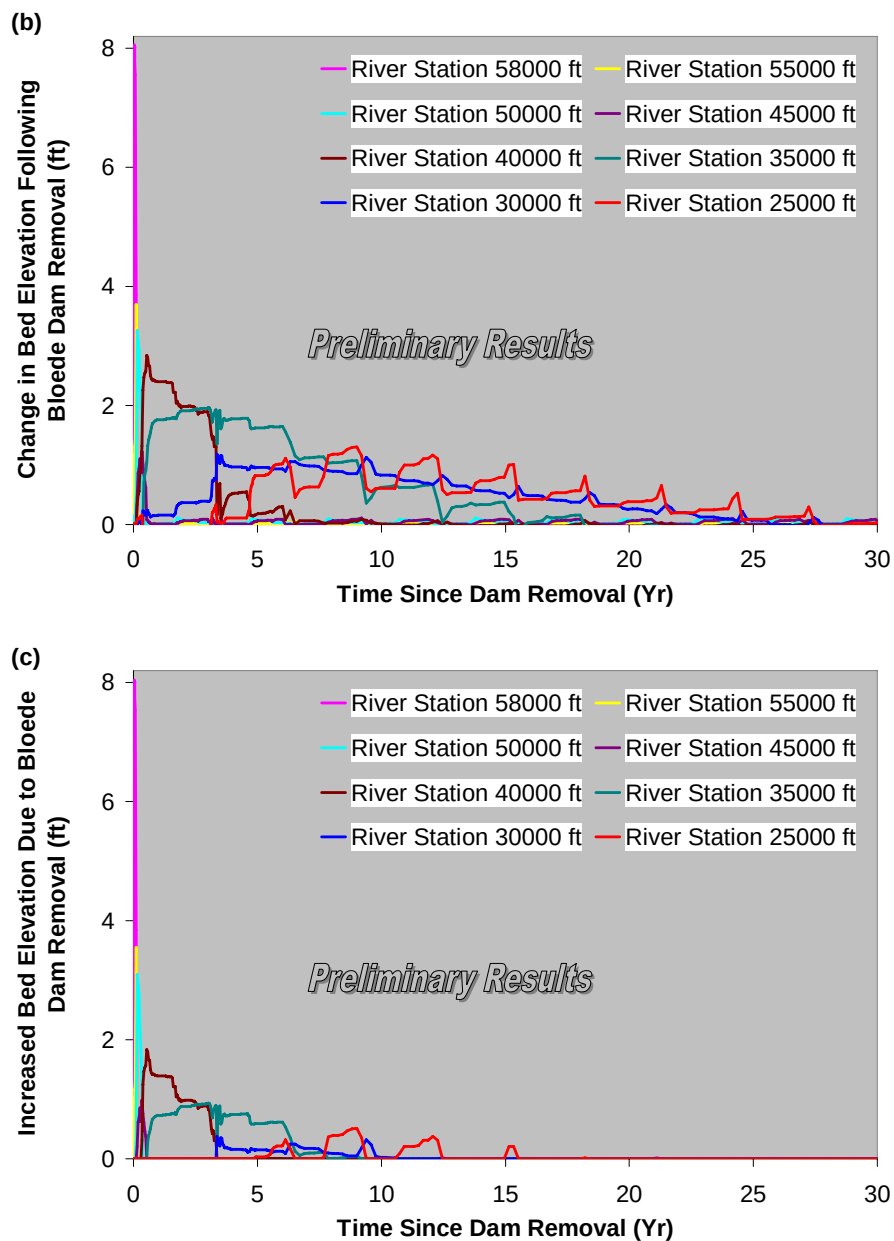


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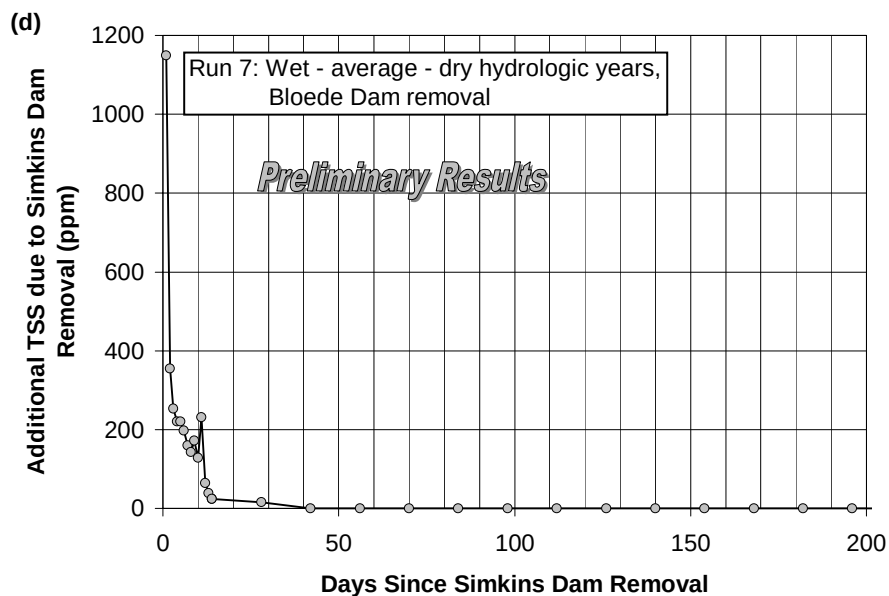


Figure 21. Simulated (a) range of sediment deposition downstream of Bloede Dam; (b) change in bed elevation following dam removal; (c) increased bed elevation due to dam removal; and (d) increased daily averaged suspended sediment concentration following Bloede Dam removal under the wet – average – dry year scenario (Run 7). Results are preliminary because no grain size samples were collected from Bloede Reservoir deposit.

8. Model Results Summary and Discussions

Simulation of sediment transport dynamics following the removal of Simkins Dam indicates that the sediment within Simkins Reservoir will be eroded downstream within a 3-month to 2-year period, depending on hydrologic conditions following dam removal. The total volume of sediment release following dam removal is approximately 88,000 – 104,000 yd³ (bulk volume), assuming an 85-ft to 100-ft bankfull width for the channel that develops in the former reservoir area. The erosion of Simkins Reservoir deposit will result in only limited (< 2 ft) sediment deposition downstream of Bloede Dam with the highest sediment deposition near River Station 40,000 ft (RM 7.6). The limited sediment deposition is at least partially due to the attenuation effect from the Bloede Reservoir that temporarily stores the sediment released from Simkins Dam and subsequently re-releases it downstream more gradually and during relatively high flow events. Once deposited downstream of Bloede Dam, sediment from the release of Simkins Reservoir deposit is predicted to move out of the system rather slowly because the overall thickness of deposition produces a minimal increase in channel bed slope and sediment transport capacity, hence there is a fairly slow recovery of the system back to the current condition. Simulated additional suspended sediment concentration due to Simkins Dam removal is on the order of several hundred ppm on a daily-averaged basis during the day of dam removal and decreases quickly to a negligible magnitude in the following days.

Preliminary simulations of sediment transport dynamics following the removal of Bloede Dam indicate that sediment within Bloede Dam will be eroded downstream within about two months to a year, depending on hydrologic conditions following dam removal. The total volume of sediment erosion is approximately 76,000 – 88,000 yd³ (bulk volume), assuming an 85-ft to 100-ft bankfull width for the channel that will develop in the former reservoir area. The erosion of Bloede Reservoir sediment will generally result in sediment deposition in the same reaches as Simkins Dam removal with a similar magnitude of sediment deposition and duration. However, Bloede Dam removal will result in sediment deposition upstream from approximately River Station 45,000 ft (RM 8.5) to the Bloede Dam site, whereas minimal sediment deposition was predicted in this reach following Simkins Dam removal. The maximum amount of deposition has a predicted thickness of approximately 8 ft immediately downstream of the current Bloede Dam site, but this deposit diminishes quickly in magnitude and is completely eroded within one year. Due to the faster release of sediment following Bloede Dam removal, additional suspended sediment concentration is predicted to be higher than that for the Simkins Dam removal, on the order of about 1,000 ppm on the first day following dam removal on a daily-averaged basis. This additional suspended sediment concentration decreases quickly to negligible amounts in the following days.

An aggressive monitoring plan is being established in conjunction with the removal of the dams on the Patapsco. During the summer of 2009, biological monitoring was initiated at 20 sites throughout the watershed to examine fish and benthic populations, as well as water quality changes. This monitoring work is expected to continue for the next three to five years. Physical monitoring will also accompany the biological monitoring for the same time period and be used to assess fluvial geomorphic changes in the system as a result of the dam removals and resulting release of sediment. Monumented cross sections will be established throughout the system. The purpose of this monitoring will be to assess stream health and examine how sediment is actually moving through the system. Not only will monitoring of this type add to the state's knowledge base on sediment transport, it will allow the project partners to adopt an adaptive management approach and address any unforeseen issues that arise.

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