Comparing 1-D Sediment Transport Modeling with Field Observations: Simkins Dam Removal Case Study

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Abstract

We present a sediment transport modeling study for the 2010 removal of the 3.3-m tall Simkins Dam on the Patapsco River, MD that released more than 56,000 m^3 of sediment downstream. Our objectives are to validate the pre-removal model forecasts with detailed post-removal monitoring data, and through hindcast modeling, examine the effects of using approximate channel geometry data or more accurate data on model results. Comparisons of DREAM-1 model predictions using approximate data and field observations indicate that reach-scale model predictions were generally accurate, but some discrepancies between predicted and observed magnitudes of sediment deposition at specific locations occurred. A refined model, developed post-dam removal with more accurate channel geometry as model input, produced slightly improved results in reaches where input data were significantly improved. However, more accurate input data did not change the general conclusions nor substantially improve the model

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performance for the entire study reach. In conjunction with two previous studies, our results support a simplified data collection approach that enables timely predictions for decision making and minimizes study costs.

Introduction

Dams of varying sizes have been removed in the U.S. in recent years (O'Connor et al., 2015), and one of the common difficulties for these projects is to find economically and ecologically acceptable solutions to manage the sediment accumulated in the reservoirs (e.g., Gartner et al. 2015). Leaving large volumes of sediment in place for natural erosion after dam removal is often a concern for: increasing downstream flood risks, elevated turbidity that can impact consumptive human use and aquatic biota, and sediment aggradation that can alter a river's physical and biological processes (e.g., Tullos et al. 2016). However, dredging all or most of the reservoir deposit before dam removal is usually economically prohibitive.

To better understand the potential outcome of different sediment management options, engineers and geomorphologists have employed sediment transport models to predict sediment transport dynamics (e.g., erosion rate in the impoundment, magnitude and duration of downstream sediment deposition and increased suspended sediment concentration) following dam removal, allowing stakeholders to select the best alternative among available options. Examples of dam removal projects with significant reservoir deposits that utilized sediment transport modeling for examining alternatives include Elwha Dam and Glines Canyon Dam removal on the Elwha River, WA (BOR 1996; Konrad 2009; East et al. 2015); Marmot Dam removal on the Sandy River, OR (Stillwater Sciences 2000; Cui and Wilcox 2008); Savage Rapids Dam removal on the Rogue River, OR (Bountry and Randle 2001; Bountry et al. 2013); San Clemente Dam removal on the Carmel River, CA (MEI 2003); proposed removal of Matilija Dam on Matilija Creek, CA (BOR 2004; URS and Stillwater Sciences 2014; AECOM and Stillwater Sciences 2015); proposed removal of Iron Gate, Copco 1, Copco 2, and J.C. Boyle dams on the Klamath River in California and Oregon (Stillwater Sciences 2008; Langendoen 2010; BOR 2011); the removal of Simkins Dam and proposed removal of Bloede Dam on the Patapsco River, MD (this paper); and dam removal on the Kalamazoo River, Michigan (Langendoen et al. 2005; Langendoen 2010).

The number of sediment transport modeling examples for dam removals is limited. The known examples where sediment transport modeling was conducted prior to dam removal and field data were collected before and after dam removal to allow comparisons are even fewer (although there are several laboratory cases: e.g., Cui et al. 2008; Ferrer-Boix et al. 2014; Juez et al. 2016). To our knowledge, the only published example of an actual dam removal project is the removal of the Marmot Dam on the Sandy River, Oregon, in 2007. By comparing model predictions (Stillwater Sciences 2000, Cui and Wilcox 2008) with field observations (Major et al. 2012), Cui et al. (2014) concluded that predictions made with a pair of one-dimensional (1D) sediment transport models were accurate in the following respects: (a) the erosion process of impoundment deposits; (b) channel aggradation in a short reach downstream of the dam; (c) the lack of channel aggradation in the majority of the Sandy River where burying spawning habitat was a concern; and (d) an absence of a sustained increase in suspended sediment concentration following dam removal. The predictions were less accurate in other aspects: the models (a) significantly under-predicted the suspended sediment concentration over a short time period (10-hours) immediately following cofferdam breaching; (b) over-predicted gravel deposition in a short reach downstream of a narrow gorge; and (c) potentially over-predicted sand deposition within a 10-km reach near the river mouth where obvious sand deposition was not observed during post-removal field visits while the model predicted a small amount of sand deposition. Overall, Marmot Dam removal predictions were broadly accurate (Downs et al. 2009) and adequate for project planning purposes (Cui et al. 2014). Cui et al. (2014) partially credited project success to credible sediment transport modeling that demonstrated to stakeholders that there would be minimal downstream impact if the most economical removal alternative was chosen, allowing this diverse group to reach a unanimous agreement. Cui et al. (2014) made recommendations for conducting future dam removal sediment transport modeling based on the Marmot Dam modeling and post-removal comparisons.

Our main objective for this case study is to compare modeling results using input data from simplified and detailed channel geometry field survey to further test previous suggestions that channel geometry data do not need to be more detailed and accurate than what is implied by the underlying assumptions of such models (Cui and Wilcox 2008; Cui et al. 2008; Cui et al. 2011; and Cui et al. 2014). Using simplified channel geometry data can substantially reduce project costs and the time to complete planning studies. In addition, we compare modeling results with field observations to validate the forecast model and demonstrate what can generally be expected from one-dimensional sediment transport modeling, and discuss potential simplifications for one-dimensional sediment transport modeling using any available model platform. We begin by introducing the study site and describing our methods, and then we present detailed results for our validation and hindcast analyses. Following the modeling comparisons, we discuss implications and provide recommendations for collecting channel geometry data for one dimensional sediment transport models for similar projects.

Project Information and Methods

The 3.3-m tall 66-m wide Simkins Dam, located approximately 19.1 km upstream of the river mouth on the Patapsco River near Ellicott City, Maryland (Figure 1), was removed in the late Fall of 2010, releasing approximately 56,350 m^3 of sediment to the downstream reaches as of November 2013. Before the removal, the DREAM-1 sediment transport model was used to predict reservoir sediment erosion and subsequent deposition downstream (Stillwater Sciences 2010). In addition to the modeling effort, long-term sampling stations that include 29 cross-sections (including 2 reference sections) and 5 digital elevation model (DEM) sites were established to monitor sediment erosion and deposition before, during, and after the dam was removed at an interval of at least twice a year. Two USGS gaging stations (#01589025 and #01589035) were established at approximately 0.5 km and 5.7 km, respectively, downstream from Simkins Dam to record pre- and post-removal continuous discharge and suspended sediment concentration. A previously discontinued third station (#01589000) was re-established approximately 6 km upstream (Figure 1).

The predictions made prior to Simkins Dam removal and the pre- and post-removal field observations provided us with an excellent opportunity to further examine the performance of 1-D sediment transport models. The results of our analysis may be widely applicable because the Simkins Dam removal was shown by Collins et al. (2017) to well represent what appears to be a common erosional response to dam removal sediment releases in a variety of physiographic settings and scales: rapid initial erosion driven by base level fall followed by a second phase more dependent on high flows (Pearson et al., 2011; Major et al., 2012; Bountry et al., 2013; East et al., 2015; Magilligan et al., 2015; Magirl et al., 2015; Warrick et al., 2015). Downstream aggradation responses to dam removal sediment releases have been more variable and depend strongly on site and valley hydrogeomorphic conditions (Zunka et al. 2015; Tullos et al., 2016; Major et al., 2017).

The sediment transport modeling conducted by Stillwater Sciences (2000) and Cui and Wilcox (2008) for the Marmot Dam removal project used the predecessor of the DREAM-2 model (developed for simulating transport of coarser material) because the Marmot Dam impoundment deposit was capped by a gravel/pebble surface layer (Cui and Wilcox 2008). The Simkins Dam removal predictions (Stillwater Sciences 2010) were generated by the DREAM-1 model (developed for simulating transport of finer material, generally < 2 mm particles sizes, discussed in more detail below) because the sediment deposit there was dominated by sand-sized particles. This examination of the DREAM-1 model performance for Simkins Dam removal, in addition to the early examinations of the models with field and experimental data (e.g., Cui et al. 2014; Cui et al. 2006a; Cui et al. 2008), completes field tests of model predictions for both the DREAM-1 and DREAM-2 models.

Patapsco River Hydrology and Geomorphology

The 950 km^2 watershed west of Baltimore, Maryland (Figure 1) is mostly in the Piedmont physiographic province (85%), a dissected, gently rolling landscape with maximum basin elevations generally less than

300 m (Smith and Wilcock 2015). The river is primarily gravel-bedded, except the downstream-most 12 km where it becomes sand-bedded. The gravel-sand transition occurs roughly at the contact between the Piedmont and the Atlantic Coastal Plain, a regional physiographic feature called the Fall Line. Upstream of the Fall Line in the study area the river flows through an incised, confined, and comparatively high gradient valley and the bed is close to the igneous bedrock (Costa 1975; MDNRWS 2005). Downstream, the valley is lower gradient and unconfined and the channel is formed in relatively thick, unconsolidated Quaternary sediments (Cleaves et al. 1968).

The Patapsco River longitudinal profile in the study reach reflects the regional physiography and is typical of natural rivers. The channel gradient decreases from approximately 0.003 immediately downstream of Bloede Dam (Reach 3, Figure 2) to less than 0.00015 near the river mouth (Reach 6). The active natural channel width generally ranges between 25 and 35 m in the Piedmont section of the study reach and widens gradually in the Coastal Plain section to approximately 200 m at the mouth of the river. The active channel widths in the Simkins Dam and Bloede Dam impoundments (Reaches 1 and 2) are wider than the nearby reaches due to water impoundment and sediment accumulation (Figure 3). Note the reach delineations shown in Figures 2 and 3 are devised to facilitate presentation and discussion and are not necessarily based on stream or valley geomorphic characteristics.

Maryland's climate is humid subtropical (Cfa in Köppen classification system). Precipitation is relatively evenly distributed throughout the year and totals about 1,065 mm annually at Baltimore Washington International Airport, approximately 15 km from the dam removal sites (http://www.ncdc.noaa.gov/cdo-web/datatools/normals). The highest daily median stream flows at Hollofield, MD (USGS #01589000) are associated with the late-winter/spring runoff period and the lowest flows occur from August through early October, an annual hydrograph typical for Northeast U.S. rivers. Patapsco River flows in the project reach are flashy: median annual discharge at Hollofield is 3.2 m^3/s while the mean annual flood is approximately 250 m^3/s. Floods can occur throughout the year and are generated by a variety of mechanisms including winter-spring extra-tropical cyclones, convective rainfall, and tropical cyclones (Miller 1990; Smith et al. 2010, 2011). Discharges in the study reach are affected by upstream regulation at Liberty Reservoir, a municipal supply for the City of Baltimore, and two additional diversions for municipal water supplies (Collins et al., 2017).

The highest peak discharge recorded at USGS #01589000 (Figure 1) since 1945 is slightly under 2,300 m^3/s, while the 2-year and 10-year recurrence peak flows are estimated to be approximately 145 m^3/s and 515 m^3/s, respectively (Stillwater Sciences 2010). Figure 4 presents daily average discharge for three typical years selected from the available discharge record at USGS #01589000, where wet, average, and dry years were selected for model simulations (described below) so that the annual peak flow and annual runoff exceedance probabilities are approximately 0.1 for the wet year, 0.5 for the average year, and 0.9 for the dry year. Different combinations of these three years were used as modeling input to represent potential variations of hydrological conditions following dam removal.

Grain size distributions of the impoundment deposit were quantified by Interfluve, Inc. (Interfluve) (2009a,b) through collection of sediment samples at eight locations using 5-cm diameter PVC pipes that penetrated up to 1.5 m into the deposit. All but one of the eight cores were distributed across the impoundment within 150 m of the dam where the sediment deposit was deepest, while the eighth core was located approximately 500 m upstream of the dam at the upper extent of the reservoir deposit. The purpose of the eighth core was to confirm the observation that sediment grain size distributions were rather homogeneous throughout the reservoir area. The Maryland Geological Survey also collected core samples at four locations that penetrated up to 2.7 m into the deposit (Richard Ortt, per. comm., Sept. 2009). Interfluve core samples indicated that the impounded sediments were predominantly sand-sized (i.e., 0.0625 - 2 mm) with median size (D_{50}) ranging between approximately 0.5 and 2 mm. The average median size and geometric mean size of the samples are 1.0 mm and 1.1 mm, respectively, and the average geometric standard deviation is 2.85.

Observed Post-Removal Channel Evolution

One pre-removal and six post-removal field campaigns of cross-section and/or DEM surveys up until January 2013 were conducted as shown in Figure 6, where the recorded discharge at USGS #01589000 is also presented. The highest peak discharge over the monitoring period occurred on September 7, 2011 during Tropical Storm Lee with a peak discharge of 530 m^3/s at USGS #01589000, which is estimated to be slightly higher than a 10-year recurrence interval event (exceedance probability 0.09) (Stillwater Sciences 2014).

Figures 7 and 8 broadly illustrate the channel response to dam removal documented in the monitoring data. Upstream of the former Simkins Dam, impounded sediments were rapidly eroded through incision and widening (Figure 7). By the end of the monitoring period nearly all of the stored sediments had been transported downstream. Immediately downstream, a reach that includes the Bloede Dam impoundment, the channel was first substantially aggraded and then eroded again (Figure 8b). Reach 3 saw modest aggradation and subsequent remobilization, but was largely a transport reach (Figure 8c). Further downstream where the Piedmont meets the Coastal Plain (Reach 4), moderate aggradation began later in the monitoring period but persisted (Figure 8d). Average channel aggradation at all the monitoring sites is presented in Figure 9, showing less than 0.5 m of sediment deposition at all times downstream of Bloede Dam. More details of the topographic surveys can be found in Collins et al. (2017).

DREAM-1 Model

The DREAM-1 model simulates sand transport in bedrock, gravel-bedded, and sand-bedded rivers and treats gravel-beds as immobile – sand particles either pass through, or deposit onto, the immobile bedrock or gravel-bedded surface and potentially transform the channel bed into a sand-bedded reach if the sand deposit becomes sufficiently thick. For flow parameter simulations, the model applies a standard backwater equation (e.g., Chaudhry 1993) under low Froude number conditions (i.e., for Froude number < 0.9, see Cui et al. 2006a for details) and applies a quasi-normal flow assumption (i.e., friction slope is assumed to be identical to local bed slope, see Cui and Parker 2005) for high Froude number conditions. For the sediment transport capacity calculation, the model utilizes Brownlie's (1982) bed material equation and considers the transport of sand and coarser particles (i.e., > 0.0625 mm) as one unit (i.e., no particle sorting) for mass conservation calculations. Silt and clay-sized particles (i.e., < 0.0625 mm) are assumed to be transported as wash load that is unable to redeposit onto the channel bed once released into the water column following erosion of the impoundment deposit. The model simulates the erosion of reservoir sediment by assuming a trapezoidal channel shape. As such, the channel widens as it degrades over time following dam removal. Downstream of the dam the model assumes rectangular channel shape, which can be different from node to node but does not change over time. 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 the DREAM-1 model 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.

Primary input parameters for DREAM-1 include initial channel profile, initial sand deposit thicknesses both in the impoundment area and downstream, channel cross-sections simplified as rectangles represented by active channel widths, daily average water discharge, the rate and grain size distribution (assumed to be identical to that of the impoundment deposit) of background sand supply (i.e., upstream input), the downstream base-level control (i.e., either downstream water surface elevation as a function of time or a fixed channel bed elevation), and estimates of surface bed material median size along the river downstream of the dam. Model output includes the evolution of sand deposit thickness in the impoundment area and downstream of the dam, sediment transport rates over time, and daily-averaged total suspended sediment concentration along the river in response to the specified water discharge and sediment supply conditions.

We choose the DREAM-1 model primarily because Cui et al. (2008) showed that it can accurately reproduce sand pulse evolution similar to that following dam removal, even without model calibration.

Model validation, hindcasting, and refined sediment transport modeling

To validate model performance, we compare predicted thickness of sediment deposition (area of sediment deposition divided by active channel width) from three runs (Runs 1 through 3) (Table 1). Model input for these runs was developed from a combination of publicly available DEMs and a water surface elevation survey for the initial longitudinal profile (Figure 2) and aerial photographs for the active channel width (Figure 3). We then rerun the model by progressively replacing the input data used for model prediction with improved ones: first replacing the assumed water discharge with recorded series following dam removal (Run 4), then replacing the initial longitudinal profile and active channel width measured from aerial photographs and publicly available information with refined values derived from field surveys (Run 5), and finally reducing the available impoundment deposit for erosion to match the observations (Run 6) (Table 1).

For the runs with refined channel geometry data (Runs 5 and 6), we use the data developed by DeTemple and Wilcock (2014) using DEM and cross-section surveys made available from the field monitoring campaigns, most of which were not available at the time the DREAM-1 forecasts (i.e., Runs 1 through 3) were conducted. The cross-sections in DeTemple and Wilcock (2014) likely represent the best quality channel cross-section data that could be expected for a forecast model. The node locations for simulation are exactly the same among all the runs to facilitate result comparisons.

Results

Prediction of Sediment Transport Dynamics and Comparison with Observations

Figure 10 compares the results of the three prediction runs (Runs 1, 2 and 3) with field observations, where Run 1 applied discharges of a wet year (WY 2004) followed by an average year (WY 1983) then a dry year (WY 1965); Run 2 an average year followed by a second average year then a wet year (average-average-wet); and Run 3 a dry year followed by an average year then a wet year (dry-average-wet) (see Figure 4 for discharge records for average, wet, and dry years). Discharge at each node during the modeling was assumed to be proportional to local drainage area based on discharge record at the Hollofield station (USGS #01589000).

A fourth run (Run 4) that was conducted using the recorded discharge at USGS #01589025 (Patapsco River near Catonsville, applied to Simkins impoundment area and within 3.1 km downstream of Simkins Dam) and USGS #01589035 (Patapsco River near Elkridge, applied to the rest of the modeled reach) are also presented in Figure 10.

DREAM-1 modeling over-predicted the amount of impoundment (Reach 1) erosion by approximately 20% (67,280 m^3 vs. 56,350 m^3 observation by January 2013). The over-prediction can largely be attributed to an over-estimate of the stored, mobile sediment volume which was the basis for the assumption of post-removal channel geometry that determines how much sediment can potentially be eroded from the impoundment in the model. Interfluve (2009) estimated there was a total of 86,400 m^3 of sediment in the Simkins impoundment, of which 48,200 – 76,500 m^3 could potentially erode with dam removal. That is, the observed erosion volume is close to the lower limit of the pre-removal estimate of erodible sediment, while the modeling assumed the average of these estimates would be released. Stillwater Sciences (2010) also included sensitivity test runs that assumed a release of 79,500 m^3, which is slightly higher than the upper limit of the Interfluve (2009) estimate, but a sensitivity run was not conducted assuming the lower prediction limit.

The simplified assumptions with regard to channel geometry in the DREAM-1 model may also have contributed to the over-prediction of sediment erosion. The DREAM-1 model makes all of the erodible sediment available for erosion once a dam is removed, but in the field some sediment may stay in place for an extended period of time until it is accessed, and mobilized, by a sufficiently large flow. In the former Simkins impoundment, a significant (but unknown) amount of sediment on the right bank between 0.3 and 0.8 km upstream of Simkins Dam progressively eroded after dam removal yet a gravel-armored core remained in place after the January 2013 survey. We anticipate this material will eventually erode incrementally, or en masse, but delayed sediment erosion like this is not represented in the DREAM-1 model. Conlon (2013), who compared a DREAM-1 hindcast of the Merrimack Village Dam removal to monitoring results (Pearson et al., 2011), attributed a similar overestimate of impoundment erosion to this model simplification.

As expected, simulations with wetter years of the discharge record produced faster evacuation of the impoundment sediment compared to dryer years (Figure 10): full evacuation by April 2011 for Run 1 (starting with wet year) and Run 2 (starting with average year), by September 2011 for Run 4 (recorded discharge), and November 2012 for Run 3 (dry year, followed by an average year). Note the recorded post-removal discharge (Run 4) is wetter than the average year (Run 2), but the high discharge in Run 4 did not occur until after the April 2011 survey, which is why erosion for Run 4 is slower compared to Run 2 up until April 2011.

Downstream of Simkins Dam, the model predicted significant sediment deposition (up to 1.7 m) in Reach 2 just upstream of Bloede Dam, while observations showed up to 0.9 m of sediment deposition (Figure 10). The model predicted minimal sediment deposition in the steep Reach 3 and the upstream one third of

Reach 4, but observations showed up to 0.4 m of sediment deposition at times. The model predicted up to 0.7 m of sediment deposition in the downstream two thirds of Reach 4 that appeared soon after dam removal (April 2011), while the observation showed up to 0.5 m of sediment deposition that did not begin to arrive until April 2012. Both the model prediction and observations showed minimal sediment deposition farther downstream in Reach 5.

Refined Sediment Transport Modeling

Comparing the refined initial longitudinal profile with that used for Runs 1 through 4 shows that the two profiles are fairly similar to each other (Figure 11), with the one used for initial modeling (i.e., Runs 1 through 3) slightly higher and smoother than the refined longitudinal profile. The similarity in the profile shape is expected because both efforts relied heavily on the publicly available DEM data, and the height difference is also expected because the profile used for Runs 1 through 4 was based on water surface elevation (Stillwater Sciences 2010) while the refined profile represents true ground elevations.

Comparison of the refined active channel widths with those used for Runs 1 through 4 (Figure 3) indicates that the early, aerial photograph-based estimates are similar to refined values except for a short reach upstream of the Simkins Dam impoundment (i.e., upstream of -1 km in Figure 2) and a short reach within Bloede Dam impoundment (i.e., approximately between 0.5 and 1 km in Figure 2). The poor quality estimate for active channel width upstream of Simkins Dam impoundment used for Runs 1 through 4 modeling did not affect modeling quality because there was negligible sediment deposited in that reach. The channel width estimate errors within Bloede Dam impoundment were likely caused by misidentifying floodplains with no vegetation as part of the main channel.

Two model runs, Runs 5 and 6, were conducted using the refined bed elevation and channel width and the recorded discharge as model input - i.e., a hindcast model. Run 5 was executed with the same assumptions about the quantity of Simkins Dam removal sediment release as the previous four runs while for Run 6 the quantity of sediment available for release matched the erosion quantity observed by January 2013. The predicted change in bed elevations for Runs 5 and 6 are presented in Figure 12 along with Run 4 results and field observations. The comparison shows that the significantly reduced active channel width in Reach 2 did not result in a significant difference in the predicted thickness of sediment deposition (i.e., comparing Run 4 with Run 5 in Figure 12). In spite of the similarities in simulated thickness of sediment deposition, the overall sediment deposit in Reach 2 is consistently smaller for Run 5 compared to Run 4 due to the refined narrower active channel width (Figure 13). The increased variation in bed elevation for the refined channel geometry in combination of reduced sediment deposition in Reach 2 for Run 5 has resulted in more sediment deposition in the steep Reach 3 and the upstream one third of Reach 4 over a short period of time (e.g., Figure 12c) compared to Runs 1 through 4, which provided a slightly better match with field observation. Reduced impoundment erosion simulated in Run 6 resulted in slightly less downstream sediment deposition compared with Run 5, as expected, but the difference is not enough to alter the main conclusions of the original modeling study that managers and stakeholders should expect that the thickness of sediment deposition downstream of Bloede Dam would be less than 0.6 m.

Discussion

Our model validation comparisons between model forecast runs (Runs 1 to 3), a hindcast run (Run 4), and field observations reflect the general level of accuracy and uncertainty of one-dimensional sediment transport models in sand-bedded rivers. These models provide a relatively reliable pattern of sediment deposition, but they cannot accurately predict the thickness and timing of sediment deposition at a fine spatial resolution because of the reach-averaged nature of the modeling (e.g., Cui et al. 2008, Cui et al. 2011). Nonetheless, the prediction most useful for stakeholders during the Simkins project planning phase was that sediment deposition would generally be less than 0.6 m downstream of Bloede Dam, which was confirmed by field observations showing that sediment deposition was less than 0.5 m at all observed locations in the lower reaches (Figure 9). Predictions with greater spatial resolution were not required in this instance.

The Simkins case study confirms that one-dimensional sediment transport models are generally accurate only on a reach-averaged basis, as suggested by Cui et al. (2008) and Cui et al. (2011), primarily because such models are simplifications of complex, three-dimensional physical processes of natural rivers such as meander bend hydraulics and sediment transport that produce lateral migration and alternate bars. Our contention is supported by other dam removal projects where both pre-removal sediment transport modeling and post-removal monitoring data are available (e.g., Bountry et al. 2013; Cui et al. 2014; East et al. 2015). As such, attempts to use these models beyond their resolution usually provide disappointing results as demonstrated in Cui et al. (2008). This limitation suggests the quality of input data that should be sought for such models: input data resolution only needs to be commensurate with the reach-averaged resolution of one-dimensional sediment transport modeling, as discussed below.

In previous DREAM-1 and DREAM-2 modeling practices (e.g., Stillwater Sciences 2000, Cui and Wilcox 2008, Stillwater Sciences 2010, and Cui et al. 2014), active channel widths were estimated from aerial photographs (e.g., Google Earth in the recent cases) while channel longitudinal profiles were obtained from readily available field data (e.g., existing thalweg or water surface longitudinal survey data, existing cross-sections, existing HEC-RAS model input, DEMs, photogrammetry survey data, and Lidar survey data). If field data were not available, longitudinal profile data were collected via the most economical method (e.g., water surface photogrammetry, water surface elevation ground survey, or thalweg elevation ground survey), while more detailed and expensive cross-section or topographic surveys were avoided. This approach to input data collection comports with the reach-averaged nature of 1D sediment transport modeling and provides reasonably accurate results as demonstrated here and in other DREAM model validation studies (e.g., Cui et al., 2014; Cui et al. 2008).

We tested this approach with the Simkins case study by comparing hindcast model results using refined geometry with field monitoring data and forecast model runs. Despite the slight improvement in modeling results using refined channel geometry data and a better estimate of erosion volume, comparable conclusions about the likely impacts of the sediment release would have been reached had the improved input data been available during the project planning phase. Thus, we recommend the simplified field data collection approach for sediment transport modeling using DREAM and similar one-dimensional models that use simplified channel cross sections as model input. For one-dimensional models using full cross sections (e.g., HEC-RAS), an appropriate reduction in field effort is also likely warranted given their reach-averaged nature of modeling practice and because each require a zeroing process or an equivalent procedure. Procedures similar to a zeroing process (e.g., "warm-up period" in Randle and Bountry 2005, "base test" in Thomas and Chang 2008, "model priming" in Bountry and Randle 2001, and "spin-up" in Ferguson and Church 2009) are widely used in one dimensional sediment transport modeling and they all require modifying the surveyed channel cross sections through modeling, and failing to apply such a procedure usually provides false predictions as demonstrated in Cui et al. (2008). It is reasonable to ask, then, what is the value of a detailed cross section survey if we know they will be subsequently modified by the modeler? Providing a protocol for the simplification of field survey for sediment transport modeling that employs full cross sections is beyond the scope of this paper, but one can imagine that roughly one tenth to one fifth of the total number of survey points typically attained would be adequate based on our understanding of general survey practices. Or, as with the DREAM model, measuring channel width from aerial photos and assuming a simple trapezoidal channel would also be potentially sufficient.

Modeling results indicated that higher discharge would result in quicker erosion of the reservoir deposit as expected. The implication is that, if possible, dam removal should be scheduled just before the occurrence of a large storm event, preferably during a wet year, in order to reduce the duration of the impact from sediment release following dam removal. This concept was implemented during our study of Matilija Dam removal project, where it was recommended that sediment release be scheduled before the occurrence of a 4-year recurrence event (Cui et al. 2017).

Note that the DREAM models lack a mechanism to handle any delayed erosion of the reservoir deposit located away from the newly-formed main channel (e.g., “event-driven” erosion; Collins et al., 2017). We believe this shortcoming is relatively unimportant in modeling sediment transport for dam removal projects, at least in terms of providing advice for dam removal decisions, for these reasons: a) sensitivity tests show that modeling results are relatively insensitive to the estimated reservoir deposit volume (Cui et al. 2006b); and b) the sediment that was left behind during the initial erosion (and thus, not simulated in the model) will be released only during large storm events when the river is capable of carrying more sediment, making its impact relatively small. Nonetheless, the potential impacts of any delayed releases of reservoir sediments following dam removal should be evaluated on a project-by-project basis to make sure any impacts are acceptable.

Conclusions

We compared Stillwater Sciences (2010) DREAM-1 predictions of sediment transport dynamics following Simkins Dam removal based on assumed hydrology with post-dam-removal monitoring data and found that the general conclusions made during pre-removal modeling were accurate. These conclusions included a) greatest sediment deposition would occur between Simkins and Bloede dams; b) sediment deposition downstream of Bloede Dam would generally be less than 0.6 m; and c) sediment deposition downstream of Bloede Dam would be persistent, and the system would recover to the pre-dam-removal condition rather slowly. We also re-ran the DREAM-1 model using the observed, post-dam-removal discharge records in the Patapsco River as model input (i.e., a hindcast) while keeping all the other input data identical. Comparing forecast and hindcast results with field observations shows

1. The DREAM-1 model with simplified field data collection successfully predicted the main erosion and deposition features following dam removal. These include: a) the limited thickness of sediment deposit downstream of Bloede Dam (i.e., less than 0.6 m); b) rapid erosion to near equilibrium conditions in the Simkins Dam impoundment; and c) the general magnitude (with potential error of approximately a factor of 2 in certain locations) and pattern of sediment deposition in Bloede Dam impoundment.
2. Model accuracy diminishes in the downstream direction, likely due to the accumulation of errors in the downstream direction: a) the model failed to predict the less than 0.4 m of sediment deposition in Reach 3; b) The model over-predicted the magnitude of sediment deposition in Reach 4 by up to half a meter. Note that the under- or over-predicted sediment deposition may be comparable to seasonal and/or interannual natural variations at least in some of the reaches as indicated in XS-22 surveys between September 2010 and February 2011 (Figure 8f)
3. The DREAM-1 model predicted minimal sediment deposition in Reaches 5 and 6 for the field monitoring period. Field observations show minimal sediment deposition in Reach 5 and it is reasonable to assume sediment deposition in Reach 6 is also minimal.

To examine whether improved channel geometry estimates (i.e., longitudinal profile and active channel width) improve modeling results, we developed a revised DREAM-1 model for the Simkins Dam removal using field-surveyed cross-sections and other detailed topographic data not available pre-project. The improved geometry improved the results in a short reach where substantial corrections were made to the active channel width, and increased transient sediment deposition in another short reach where observed deposition was under predicted. Overall, however, the improved geometry did not substantially improve the results and the same general conclusions described above would have been reached had the more detailed data been available for the pre-removal prediction. The sediment transport predictions for the Simkins Dam removal applied the same principles as the sediment transport predictions for the Marmot Dam removal project on the Sandy River in Oregon (Cui et al. 2014), both with satisfactory results.

Notably, both of these sites are good examples of a two-phase erosion process emerging as a common response to dam removal sediment releases, suggesting our results may have broad applicability (Major et al., 2012; O'Connor et al., 2015; Collins et al., 2017; Foley et al., 2017). Thus, we recommend that future DREAM model applications continue to employ simplified means for estimating active channel width and the longitudinal profile to minimize project cost. Given the channel width estimate errors in the Bloede impoundment (Reach 2), we also recommend field validating or collecting supplemental cross-section surveys in areas of special interest or reaches where remote data collection is difficult.

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Figure 1. Patapsco River watershed, Maryland (derived from The National Elevation Dataset, Gesch, D.B. 2007), showing existing and removed dams, USGS station #10289000 that was for forecast modeling, and the Fall Line that roughly separates the gravel- and sand-bedded reaches. Two additional USGS stations (#01589025 and #01589035) located approximately 0.5 km and 5.7 km, respectively, downstream of Simkins Dam are not shown in the map.

Figure 2. Longitudinal profile of the study reach of the Patapsco River, obtained by combining Interfluve August/September 2009 survey data (Ben Lee and Nick Nelson, per. comm., Sept. 2009) with 2005 Baltimore County LiDAR survey data (Garth Linder, per. comm., Nov. 2009). The pre-dam profile was estimated by connecting the bases of the dams and the upstream points where reservoir deposits appear negligible.

Figure 3. Estimated active channel width in the study reach.

Figure 4. Daily discharge record for three typical hydrological years at USGS #01589000: a wet year (WY 2004), an average year (WY 1983), and a dry year (WY 1965). The wet, average and dry years were selected from the available record with exceedance probabilities of approximately 0.1 for wet year, 0.5 for average year and 0.9 for dry year for both annual peak flow and annual runoff (Stillwater Sciences 2010). Combinations of these three years are used as model input to create variations in hydrologic conditions in the model.

Figure 5. Patapsco River, Maryland at Simkins Dam site before (top) and after (bottom) Simkins Dam removal.

Figure 6. Timeline of Patapsco River topographic surveys prior to and after Simkins Dam removal. The recorded daily discharge records at USGS #1589000 is also provided for references.

Figure 7. Surveyed channel cross-sections upstream of Simkins Dam before and after dam removal. The dashed lines (September 2010) represent pre-removal while all the other lines represent post-removal. More details of the survey data can be found in Collins et al. (2017).

Figure 8. Six of the twenty three surveyed channel cross-sections downstream of Simkins Dam before and after dam removal. The dashed lines (September 2010) represent pre-removal while all the other lines represent post-removal. More details of the survey data can be found in Collins et al. (2017).

Figure 9. Observed average thickness of sediment erosion or deposition downstream of Simkins Dam following its removal, showing less than 0.5 m of sediment deposition downstream of Bloede Dam. Here the average thickness for a particular cross-section used for thickness calculation was obtained by dividing the area of deposition by an active channel width interpolated from active channel width values used in DREAM-1 prediction shown in Figure 3.

Figure 10. Comparison of DREAM-1 model predictions with field data: cumulative change in average bed elevation. (a). Feb-2010; (b). Apr-2011; (c). Sep-2011; (d). Apr-2012; (e). Jun-2012; (f) Nov-2012; (g). Jan-2013.

Figure 11. Comparison of refined initial longitudinal profile with that used for Runs 1 through 4.

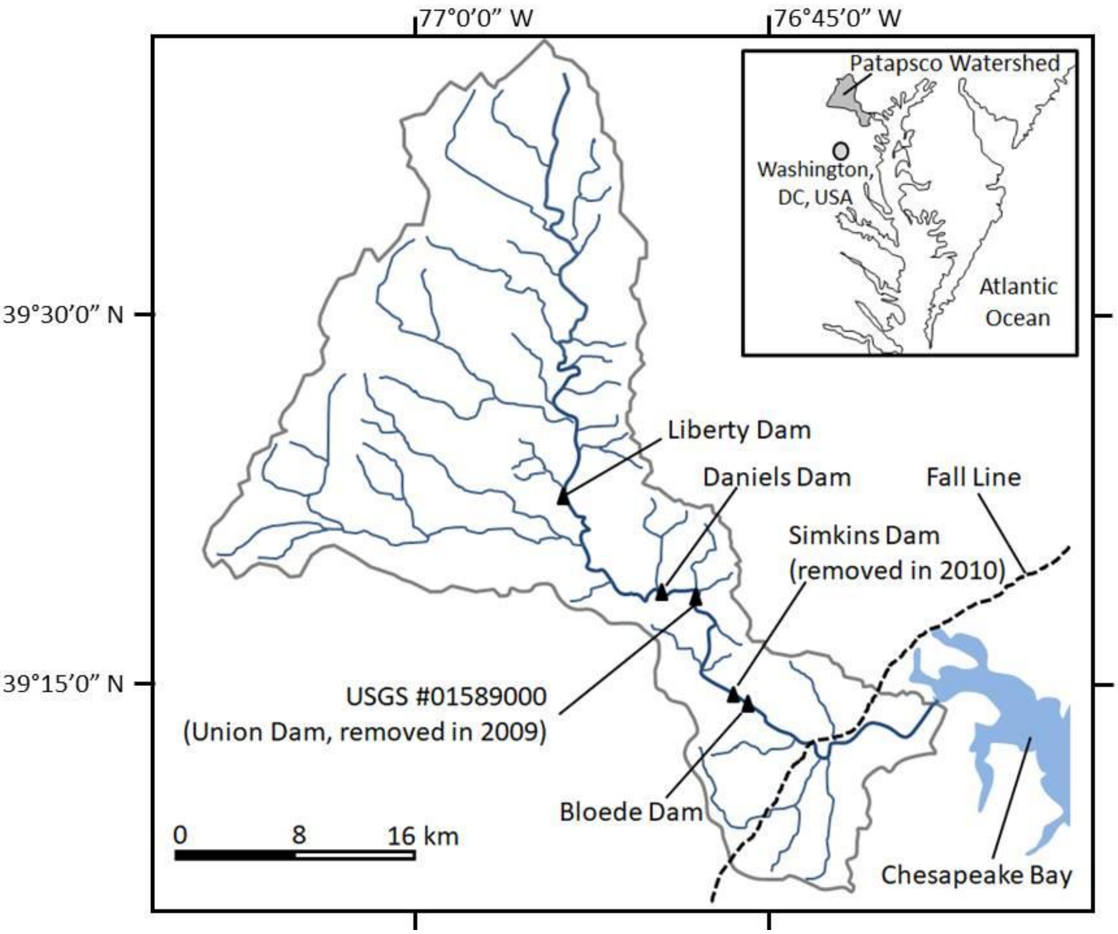
Figure 12. Comparison of Run 4 (pre-removal estimated channel geometry), Run 5 (refined channel geometry) and Run 6 (refined channel geometry and amount of sediment release) with field data: cumulative change in average bed elevation. (a). Feb-2010; (b). Apr-2011; (c). Sep-2011; (d). Apr-2012; (e). Jun-2012; (f) Nov-2012; (g). Jan-2013.

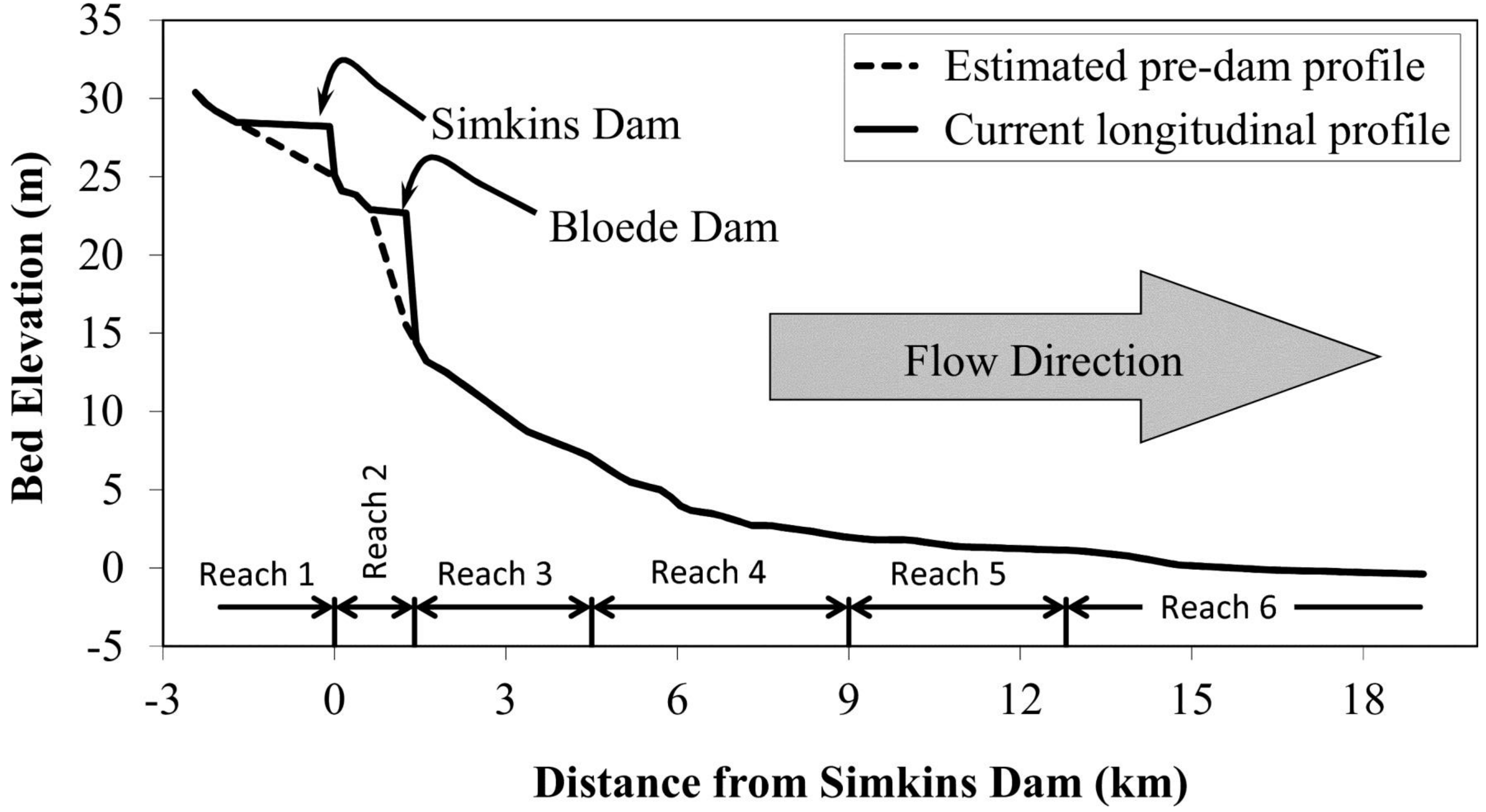
Figure 13. Comparison of Reach 2 (between Simkins and Bloede dams) sediment deposition between Run 4 (original channel geometry, recorded discharge) and Run 5 (refined channel geometry, recorded discharge, with estimated volume of impoundment deposit identical to that of Run 4).

List of Tables

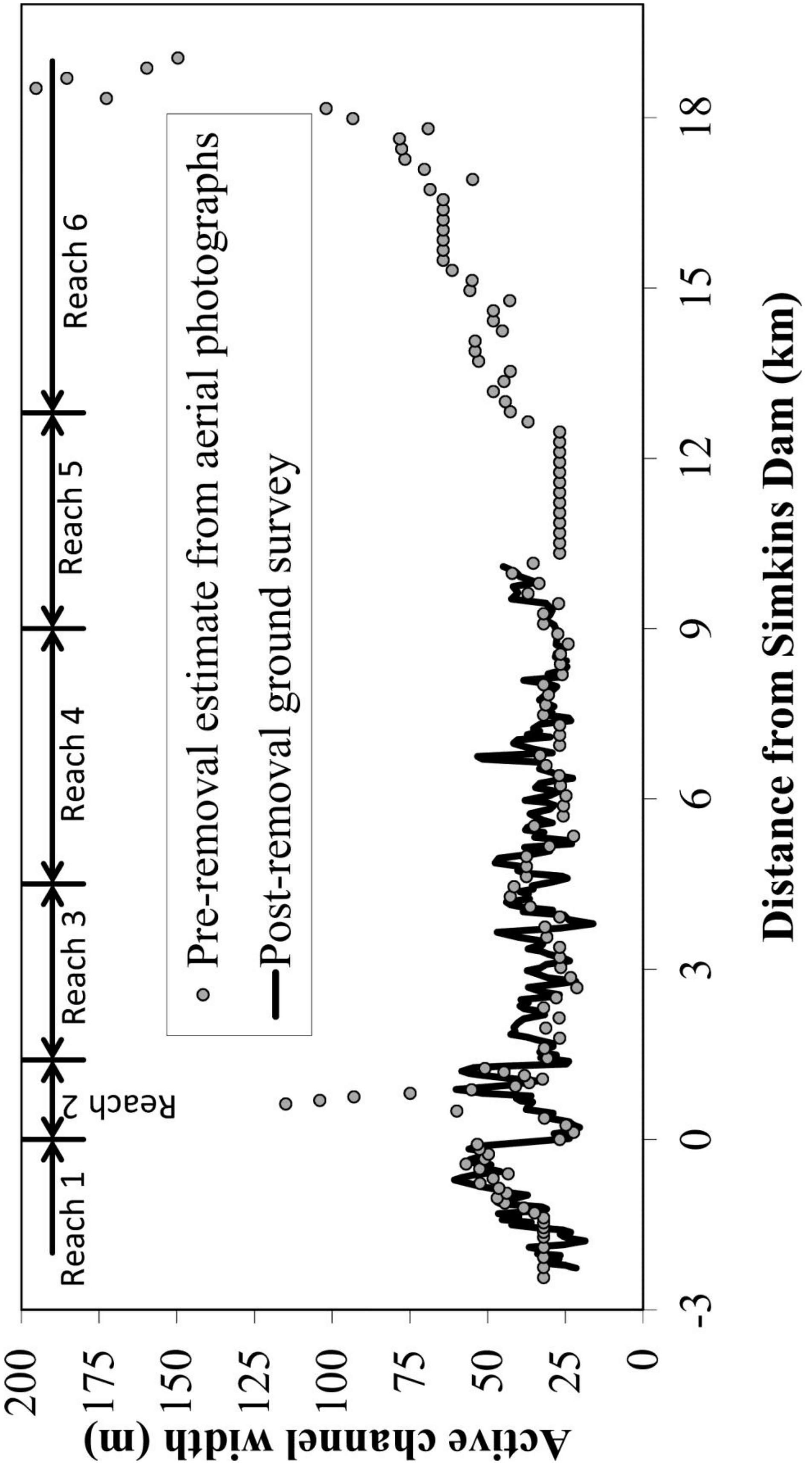
Table 1. Summary of all runs

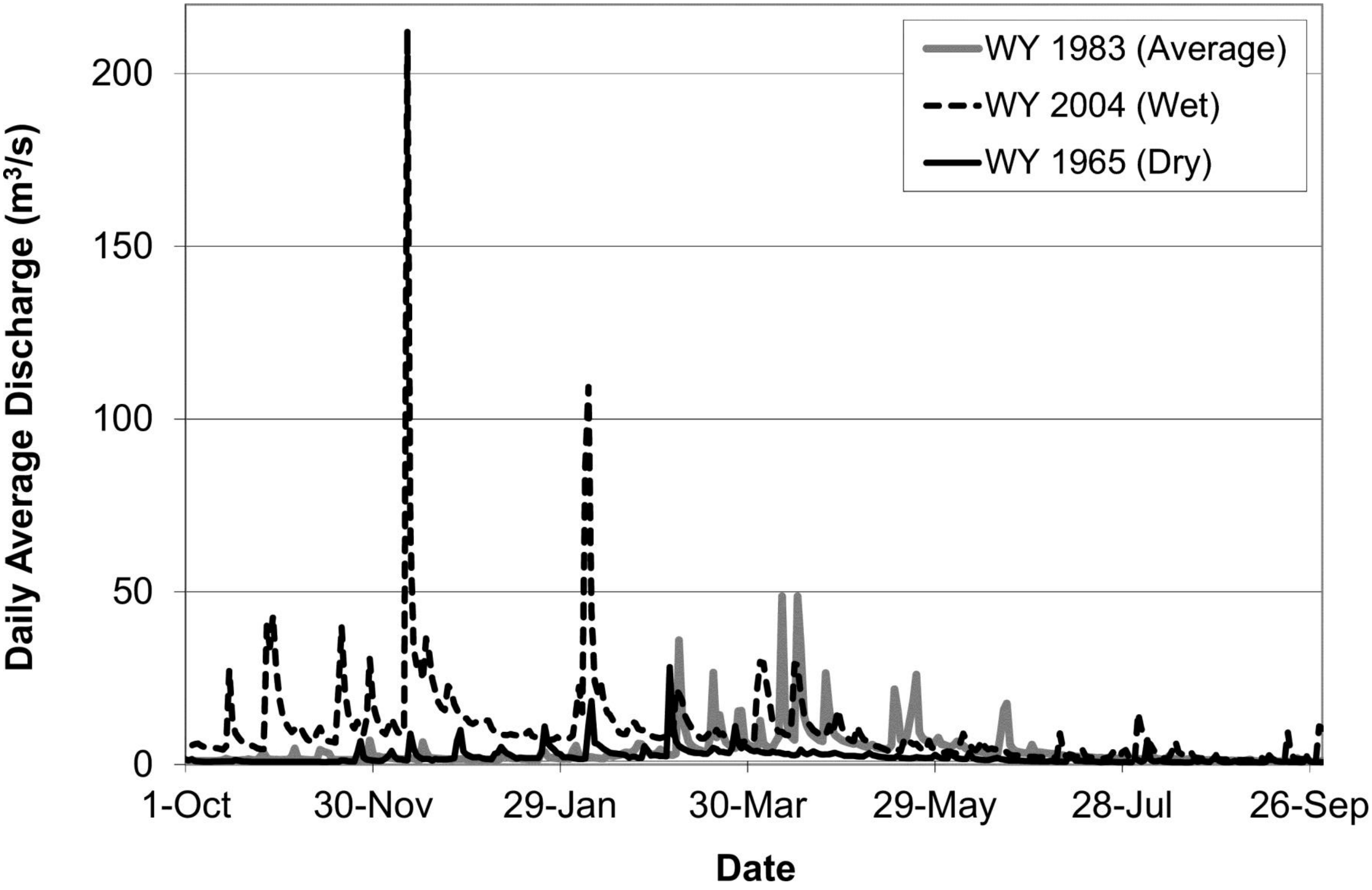
Runs	Discharge/Hydrology	Downstream Profile	Upstream Profile
Run 1	Wet – Average – Dry	Derived based on thalweg and water surface surveys	Derived based on thalweg surveys
Run 2	Average – Average – Wet		
Run 3	Dry – Average – Wet		
Run 4	Recorded post-removal discharge		
Run 5	Same as Run 4	Refined with detailed cross section surveys	
Run 6	Same as Runs 4 and 5		Adjusted based on observed volume of sediment erosion


77°0′0″ W
76°45′0″ W
39°30′0″ N
39°15′0″ N
Patapsco Watershed
Washington, DC, USA
Atlantic Ocean
Liberty Dam
Daniels Dam
Fall Line
Simkins Dam (removed in 2010)
USGS #01589000 (Union Dam, removed in 2009)
Bloede Dam
Chesapeake Bay
0
8
16 km

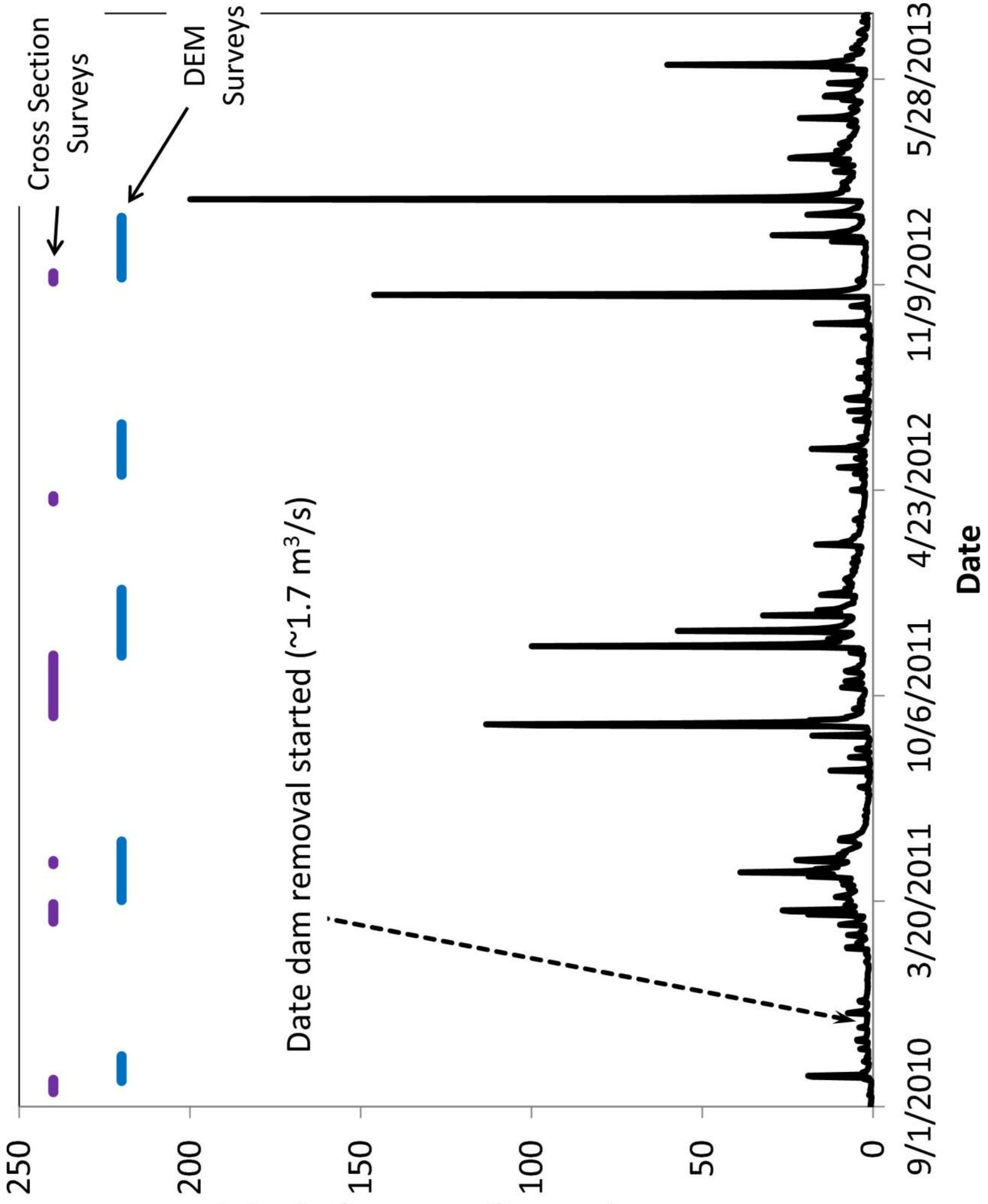


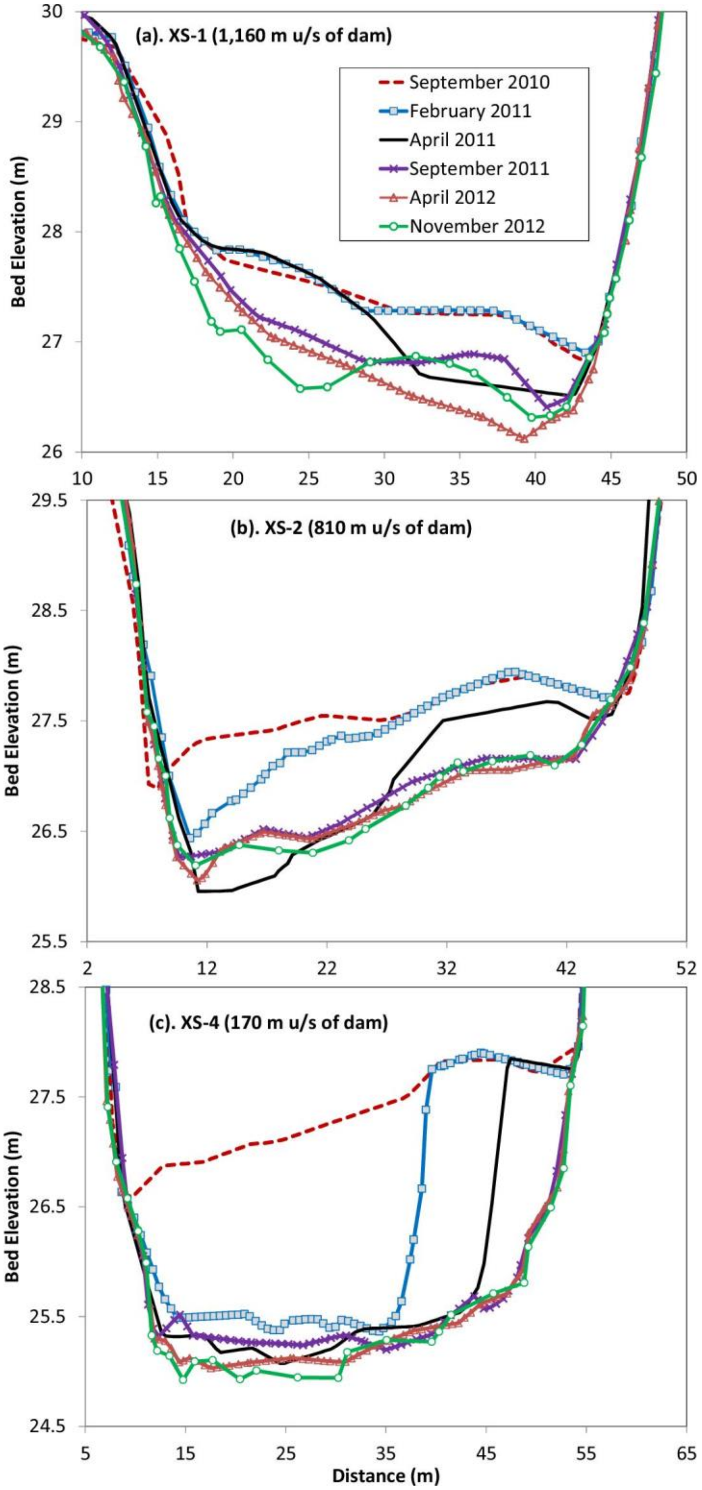
Estimated pre-dam profile
Current longitudinal profile
Simkins Dam
Bloede Dam
Flow Direction
Reach 1
Reach 2
Reach 3
Reach 4
Reach 5
Reach 6
Bed Elevation (m)
35
30
25
20
15
10
5
0
-5
-3
0
3
6
9
12
15
18
Distance from Simkins Dam (km)

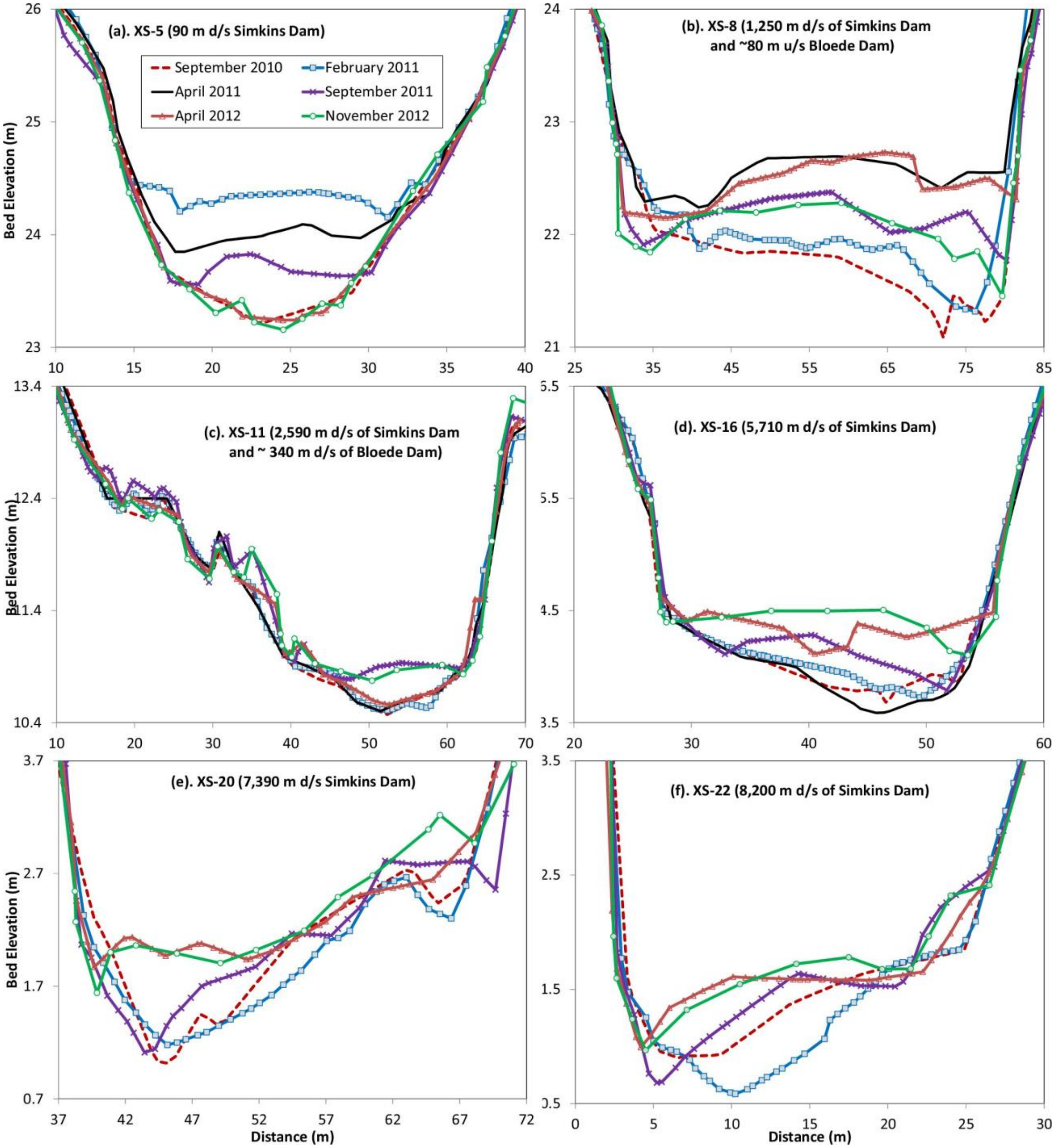

Active channel width (m)
200
175
150
125
100
75
50
25
0
Distance from Simkins Dam (km)
-3
0
3
6
9
12
15
18
Reach 1
Reach 2
Reach 3
Reach 4
Reach 5
Reach 6
Pre-removal estimate from aerial photographs
Post-removal ground survey

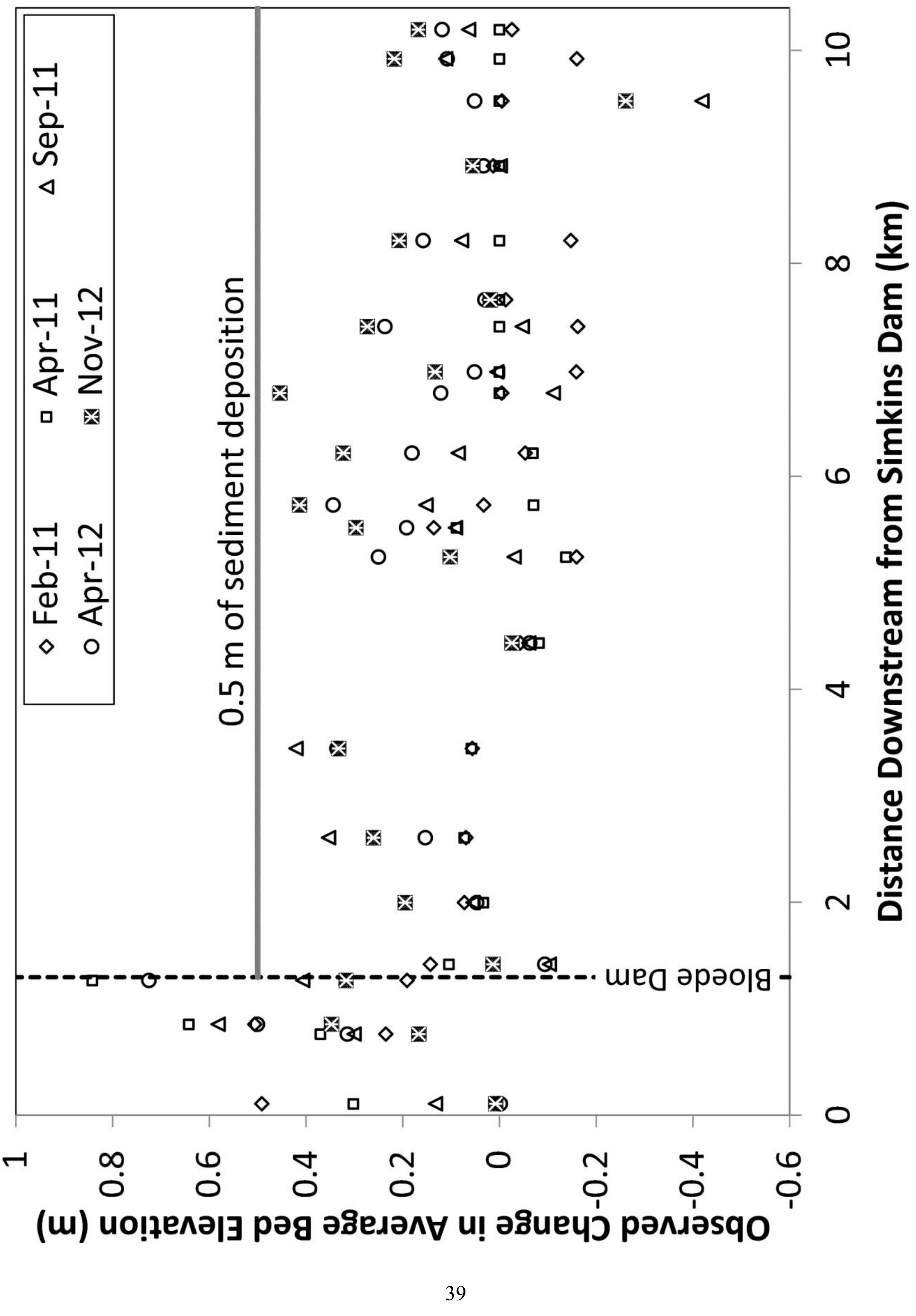


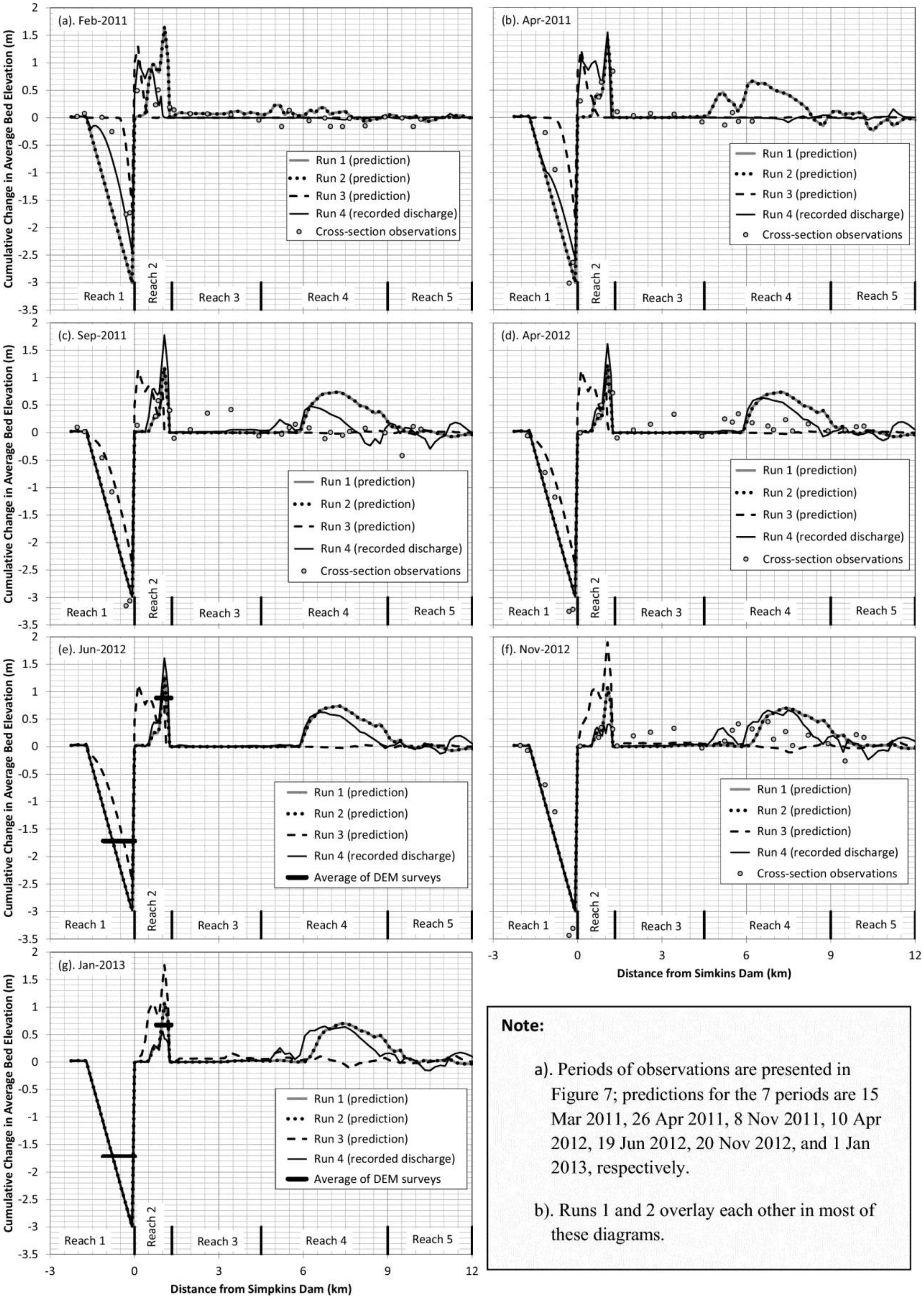
WY 1983 (Average)
WY 2004 (Wet)
WY 1965 (Dry)
Daily Average Discharge (m³/s)
200
150
100
50
0
1-Oct
30-Nov
29-Jan
30-Mar
29-May
28-Jul
26-Sep
Date


Daily Average Discharge (m³/s)
250
200
150
100
50
0
9/1/2010
3/20/2011
10/6/2011
4/23/2012
11/9/2012
5/28/2013
Date
Cross Section Surveys
DEM Surveys
Date dam removal started (~1.7 m³/s)


(a). XS-1 (1,160 m u/s of dam)
September 2010
February 2011
April 2011
September 2011
April 2012
November 2012
Bed Elevation (m)
30
29
28
27
26
10
15
20
25
30
35
40
45
50
(b). XS-2 (810 m u/s of dam)
Bed Elevation (m)
29.5
28.5
27.5
26.5
25.5
2
12
22
32
42
52
(c). XS-4 (170 m u/s of dam)
Bed Elevation (m)
28.5
27.5
26.5
25.5
24.5
5
15
25
35
45
55
65
Distance (m)


(a). XS-5 (90 m d/s Simkins Dam)
September 2010
February 2011
April 2011
September 2011
April 2012
November 2012
Bed Elevation (m)
26
25
24
23
10
15
20
25
30
35
40
(b). XS-8 (1,250 m d/s of Simkins Dam and ~80 m u/s Bloede Dam)
24
23
22
21
25
35
45
55
65
75
85
(c). XS-11 (2,590 m d/s of Simkins Dam and ~ 340 m d/s of Bloede Dam)
Bed Elevation (m)
13.4
12.4
11.4
10.4
10
20
30
40
50
60
70
(d). XS-16 (5,710 m d/s of Simkins Dam)
.5
.5
4.5
3.5
20
30
40
50
60
(e). XS-20 (7,390 m d/s Simkins Dam)
Bed Elevation (m)
3.7
2.7
1.7
0.7
37
42
47
52
57
62
67
72
Distance (m)
(f). XS-22 (8,200 m d/s of Simkins Dam)
3.5
2.5
1.5
.5
0
5
10
15
20
25
30
Distance (m)

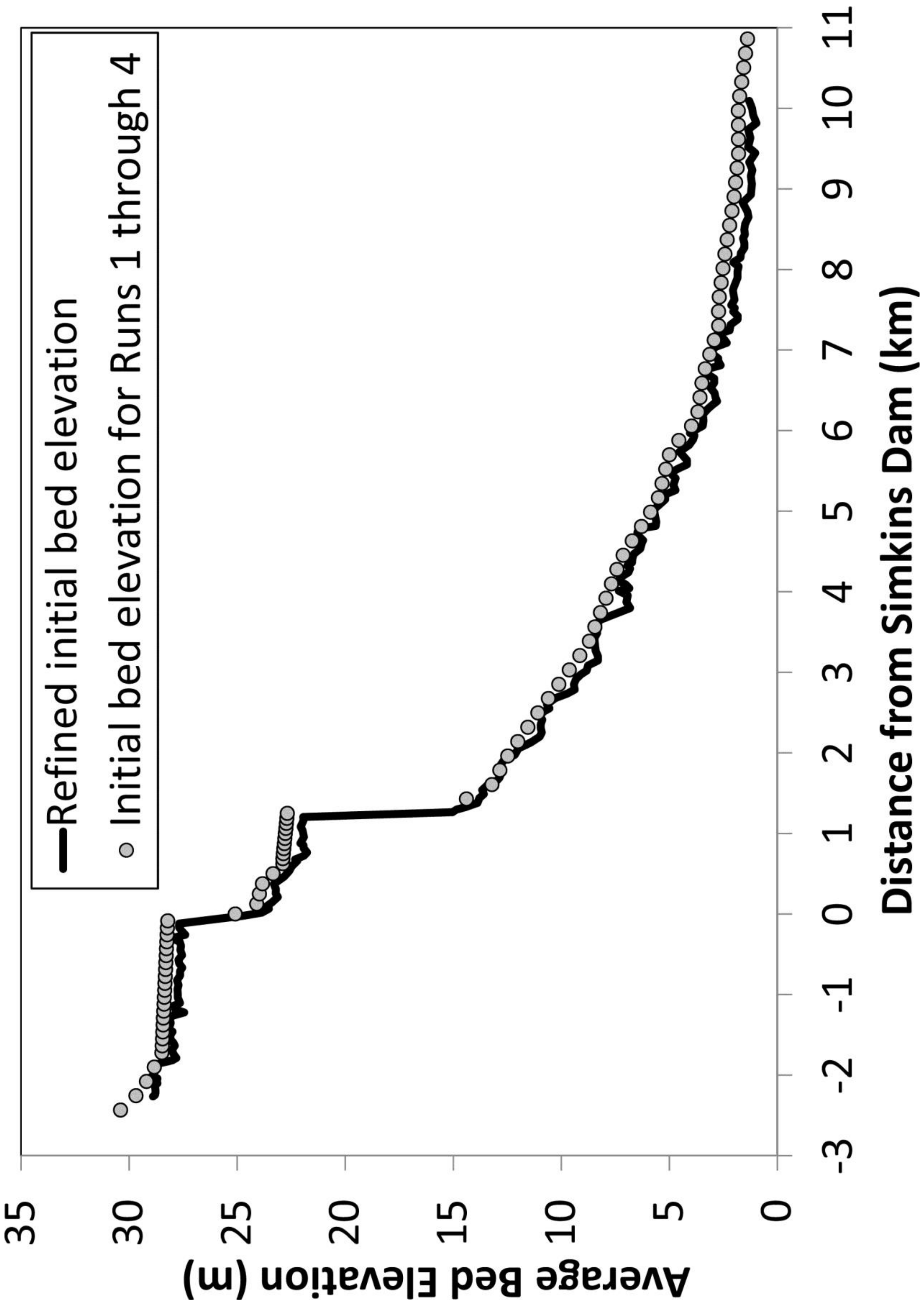

Feb-11
Apr-11
Sep-11
Apr-12
Nov-12
0.5 m of sediment deposition
Bloede Dam
Observed Change in Average Bed Elevation (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
Distance Downstream from Simkins Dam (km)
0
2
4
6
8
10

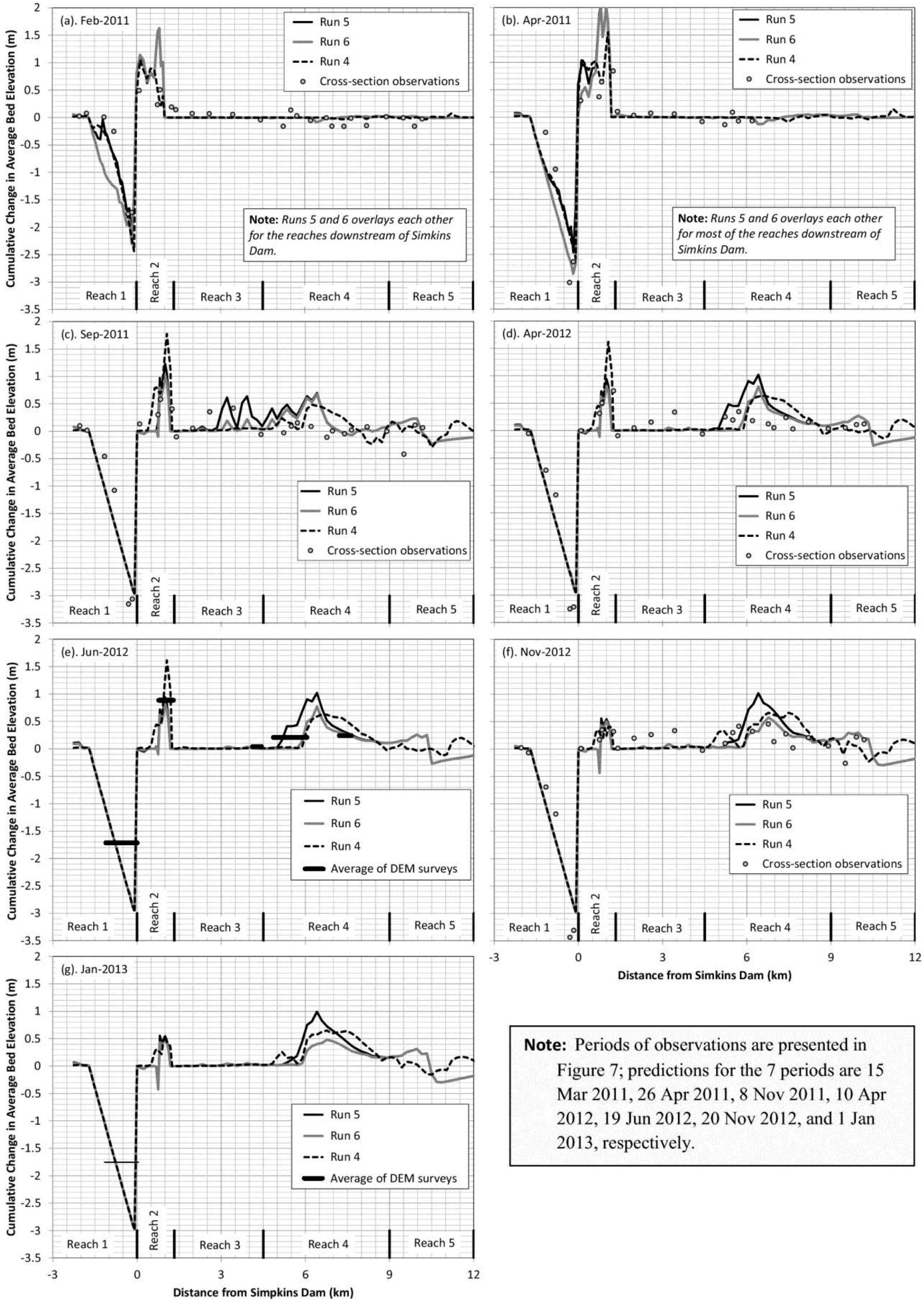


Note:

a). Periods of observations are presented in Figure 7; predictions for the 7 periods are 15 Mar 2011, 26 Apr 2011, 8 Nov 2011, 10 Apr 2012, 19 Jun 2012, 20 Nov 2012, and 1 Jan 2013, respectively.

b). Runs 1 and 2 overlay each other in most of these diagrams.

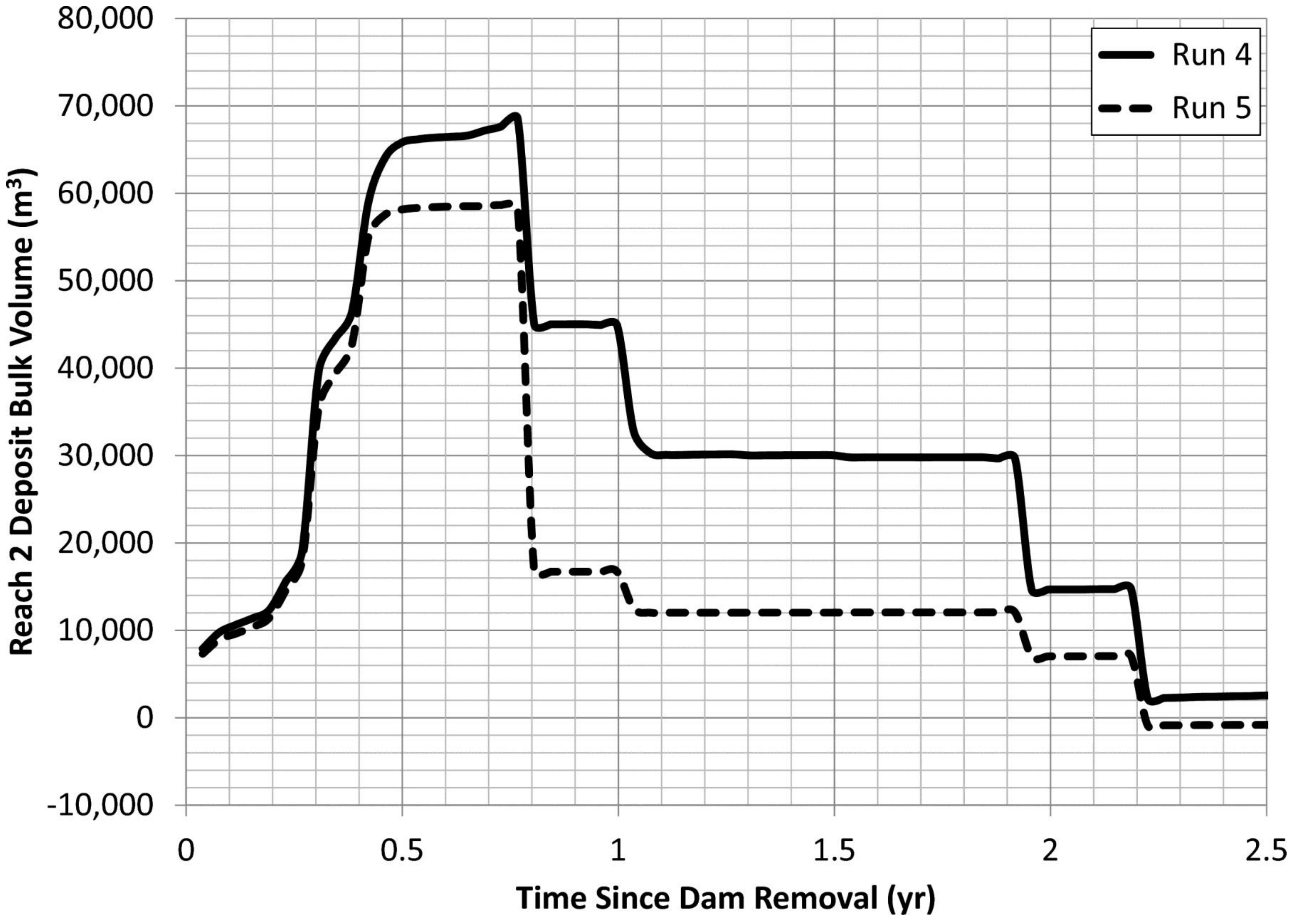

Refined initial bed elevation
Initial bed elevation for Runs 1 through 4
Average Bed Elevation (m)
0
5
10
15
20
25
30
35
Distance from Simkins Dam (km)
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11



Note: *Runs 5 and 6 overlays each other for the reaches downstream of Simkins Dam.*

Note: *Runs 5 and 6 overlays each other for most of the reaches downstream of Simkins Dam.*

Note: Periods of observations are presented in Figure 7; predictions for the 7 periods are 15 Mar 2011, 26 Apr 2011, 8 Nov 2011, 10 Apr 2012, 19 Jun 2012, 20 Nov 2012, and 1 Jan 2013, respectively.



Run 4
Run 5
Reach 2 Deposit Bulk Volume (m³)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
-10,000
0
0.5
1
1.5
2
2.5
Time Since Dam Removal (yr)