Brandywine River Dams 4 and 6 Fish Passage Alternatives Analysis

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1.0 INTRODUCTION

The Brandywine River Restoration Trust, formerly known as Brandywine Shad 2020, intends to restore the region's most historic fish, the American Shad, to the Brandywine River. To accomplish this goal, the BRRT intends to create river passage at the 10 remaining dams on the Brandywine, thereby returning the river to its free-flowing, pre-colonial state or providing effective fish passage at dams that cannot be removed. This unique watershed approach has the potential to be the nation's most ambitious dam removal and fish passage project (by number of dams) across a single watershed with the purpose of providing passage for American Shad. This report builds on the earlier work completed on the Brandywine to restore American Shad and inform fish passage (University of Delaware, 2015; Brandywine Conservancy, 2005; Kleinschmidt 2021).

This alternatives analysis evaluates the provision of fish passage at Brandywine River Dam 4 (Alapocas Run Park / Bancroft Mills Dam) and Dam 6 (Dupont Dam). Dams are numbered sequentially from downstream to upstream and all are considered low head structures with heights ranging from approximately 3 ft to 13 ft (Table 1). Throughout this document, "river right" and "river left" will be used to describe components of the structures or locations of features. For consistency, these will always be viewed looking downstream.

1.1 Brandywine River

The river flows southeast from its headwaters, in the Piedmont of Southeastern Pennsylvania, to its confluence with the Christiana River at Wilmington, Delaware. The Brandywine has been designated as a "Water of Exceptional Recreational or Ecological Significance" (Brandywine Conservancy, 2005). The downstream section of the Brandywine has tidal influence below Dam 2. The dams are numbered along the Brandywine in Delaware from Dam 2 as the first fish passage barrier on the Brandywine, located 3 miles upstream of the confluence with the Christiana River, up to Dam 11 approximately 3.2 miles from the Pennsylvania-Delaware state line. Dams 2 - 11 span 7.2 miles of the Brandywine River with an elevation change from near tidewater to 120 feet above sea level. Due to the Brandywine's high head differential in Delaware, its waterpower was harnessed by mills in the colonial period and early America. It was estimated that there were over 130 mills and dams on the Brandywine during this time (Brandywine Conservancy, 2005). Most of these mills and dams are no longer operating, except for those preserved at the Hagley Museum.

The first barrier on the Brandywine is at Dam 2, below which it is free flowing to the ocean, where American Shad (*Alosa sapidissima*) spend part of their life. In Spring 2020, following the removal of Dam 1 in fall of 2019, Brandywine Shad 2020 and the University of Delaware collected over 150 young-of-the-year American Shad at the base of Dam 2 (Brandywine Park Dam), highlighting the reproduction potential of this River. Final design and construction of a full-width rock ramp nature-like fishway are being implemented for Dam 2 as part of Diamond State Port Corporation's Wilmington Harbor-Edgemoor Expansion project proposed mitigation plan (Verdantas, 2022). Once completed, the fishway and Dam 2 will provide fish passage up to Dam 4, as Dam 3 (Augustine Mill Dam) is partially breached (Brandywine Conservancy, 2005) and Dam 1 was removed in 2019.

As part of the permit consultation for this project to provide fish passage at Dams 4 and 6, BRRT initiated consultation with the USACE, DHCA, and the City of Wilmington relative to the potential archaeological and architectural resources at this site. As part of site investigations, a Phase II Architectural Report (CHAD, 2022) and Phase 1B Archaeological Report (RGA, 2022) have been prepared for the proposed work at Dams 4 and 6. The Phase II report found that Dam 4 and ancillary structures (e.g., abutting stone wall and fish ladder) are eligible for listing as an individual resource, in addition to being located within to the larger Bancroft and Sons Cotton Mills Historic District. The Phase II report found that Dam 6 is eligible for listing as an individual resource in the National Register, in addition to being located proximal to the Dupont Experimental Station buildings (which were not evaluated for individual listing in the National Register of Historic Places). The DHCA, and City of Wilmington concurred with these findings in their letters dated January 2022, and January 21, 2022, respectively. The Phase 1B Archaeological Report for Dams 4 and 6 found no intact archaeological resources and no archaeological sites at either dam and as such, recommended that no further survey of upland portions of the project area was required. DHCA concurred with these findings in their letter dated September 13, 2022.

This report outlines the alternatives considered in pursuit of the primary objective of providing fish passage at Brandywine Dams 4 and 6, considering existing natural resources and the historic nature of the dam. Providing fish passage at Dams 4 and 6 would add roughly 3,000 and 2,000 linear feet of spawning and rearing habitat, respectively.

Table 1. Brandywine River Dams in Delaware (Source: Brandywine Conservancy, 2005; Modified)

Dam No.	Dam Name(s)	River Mile	Latitude/ Longitude	Function	Height/ Width (ft.)	East Bank Parcel No. Owner (N/F)	West Bank Parcel No Owner (N/F)	Status?	Est. Shad Production Potential	Historic?
1	**West Street**	2.1	39.75142/ -75.54760	Protect water supply, enclose sewer pipes	3 ft. 176 ft.	2601340075 City of Wilmington	2601340075 City of Wilmington	Removed 2019	3,300	Wilmington Historic District
2	**Brandywine Park/ Broom Street**	2.9	39.75868/ -75.55502	City water intake; aesthetic (waterfall and mill race supply)	8 ft. 154 ft.	2601410006 City of Wilmington	2601340075 City of Wilmington	Intact	3,600	Yes, within Wilmington Historic District
3	**None**	3.35	39.76491/ -75.55695	None known; was for industrial water supply	7 ft. 135 ft.	0614300001 Augustine Mill Associates	2600640050 2/3 Mill Road LLC	Partially breached	4,600	Bancroft Mills Historic District
4	**Alapocas Run Park / Bancroft Mills**	3.6	39.76861/ -75.55922	None known; was for water supply	13 ft. 150 ft.	0612700002 State of Delaware	2600620041 Rockford Falls Partners LLC	Damaged	6,700	Yes, within Bancroft Mills Historic District
5	**Brandywine Falls**	4.2	39.77078/ -75.56919	Mill race supply; aesthetic; was for industrial water supply	3-10 ft. 200 ft.	0612700002 State of Delaware	2600230001 Brandy. Falls Condo Assoc.	Intact	7,700	Yes, within Bancroft Mills Historic District
6	**DuPont**	4.5	39.76959/ -75.57346	None known; possible backup water source	8 ft. 182 ft.	0612600002 E I DuPont Nemours & Co.	2600540002 City of Wilmington	Partially breached	9,000	Yes, individually eligible for listing
7	**Breck's Mill/ Walker's Mill**	4.8	39.77086/ -75.57903	Aesthetic, once fed two mill races	7 ft. 156 ft.	0612600001 Walkers Mill Associate LLC	703020017 Eleutherian Mills-Hagley	Intact	10,700	National Historic Landmark
8	**Henry Clay Mill/ Lower Hagley**	5.2	39.77636/ -75.57531	National Historic Landmark, Aesthetic (waterfall), mill race	6-8 ft. 215 ft.	061170001 Eleutherian Mills-Hagley	702700032 Eleutherian Mills-Hagley	Intact	12,100	National Historic Landmark
9	**Upper Hagley/ Birkenhead**	5.7	39.78270/ -75.57107	National Historic Landmark, Aesthetic (waterfall), mill race	7 ft. 205 ft.	0610800002 Black Gates LLC	0702700032 Eleutherian Mills-Hagley	Intact	13,000	National Historic Landmark
10	**Eleutherian Mills**	6.2	39.78556/ -75.57740	National Historic Landmark, Aesthetic (waterfall), mill race	3 ft. 126 ft.	0609800002 Black Gates LLC	0702700032 Eleutherian Mills-Hagley	Intact	16,400	National Historic Landmark
11	**Rockland Mills**	7.2	39.79757/ -75.57497	Part of Historic District. Once fed mill race. Aesthetic	7-8 ft. 135 ft.	0607500002 State of Delaware	0701900007 State of Delaware	Partially breached	26,600	National Historic Landmark

1.2 Dam 4 (Alapocas Run Park Dam/Bancroft Mills Dam)

Dam 4 is an approximately 13-foot-tall, 150-foot-wide dam located at river mile 3.6 on the Brandywine River. The GPS coordinates for the dam are: 39.76961, -75.55922. It is either referred to as the Alapocas Run Park Dam, Kentmere Dam, or the Bancroft Mills Dam. The land at the west abutment of the dam, river right, is owned by the Rockford Cap, LLC. The land at the east abutment of the dam, river left, and most of the dam, are owned by the State of Delaware. Historically the dam was used for water supply; however, there is no current use. There is no mill race with the dam in its current state. There is an existing fishway at the dam that was constructed in the 1970s; however, the fishway has not been operated or maintained since the 1980s and is in disrepair (CHAD, 2022). There is a sanitary sewer owned by New Castle County on the left shore, between the fishway and the riverbank. A section of the dam appears to be undermined, as evidenced from historic imagery showing cobble washing out of this area and the distortion of the dam face in the current condition (Figure 2). This dam is the tallest remaining dam in Delaware on the Brandywine (Table 1).

Figure 1. Dam 4 from River Right, Looking Upstream

Figure 2. Dam 4 Potentially Undermined Section, Looking Upstream at the Right Abutment (left photo) and area of instability (right photo)

From the 2022 Phase 2 Architectural Report (CHAD, 2022) for Dam 4:

> Dam 4, known as Kentmere Dam and Bancroft Dam, is a descending ramp, bowed, stone apron dam augmented by a later straight stone and concrete dam. Construction of the descending ramp, stone dam was completed in 1896 by the Joseph Bancroft & Sons Company, shortly after the company purchased the mill seat property. Bancroft & Sons added a straight stone and concrete dam c. 1940, immediately downstream of the curved dam. The extant dam structure today has the appearance of a double crest, with one created by the earlier 1896 descending ramp, stone dam and another running straight-across created by the straight stone and concrete dam. The overall dam structure extends across the Brandywine approximately 180 feet and has a fall of about 10 feet. A concrete fish ladder was built at the northern abutment of the dam c. 1970, the structure of which remains fairly intact.
>
> The 1896 descending ramp, stone dam arcs across the Brandywine, with an angled notch or carved channel on its northern side that is likely related to the dam's positioning at the mouth of Alapocas Run. Historical aerial photographs from the early-twentieth century show evidence of a rubble stone apron extending downstream from the 1896 dam (see figures 54 and 64). The c. 1940 straight stone and concrete dam sits a foot or two lower than the 1896 dam, with a reservoir created between their crests. Some large stones visibly protrude through the fall of water along the downstream face of the dam. There is also a large breach in the downstream face of the dam towards its southern end. The overall dam structure is supported on the southern bank at the point of an approximately 60-degree angle in a cut and quarried stone retaining wall. The retaining wall extends along the riverbank approximately 250 feet to the northwest and nearly 500 feet to the southeast and were the foundational walls for two large, non-extant mill buildings-built c. 1895 by

the Joseph Bancroft & Sons Company. The extant metal head gate for the southern mill race is situated immediately upstream (west) of the dam, though the mill race is no longer extant. The overall dam structure is buttressed on the northern bank by the natural bedrock of Brandywine Blue Gneiss. A poured concrete sanitary sewer line runs southeast from the northern side of the dam, with a poured concrete access hatch and metal cover, situated just east of the dam.

The fish ladder added to Dam 4 is a type of baffle fishway called a Denil fishway and constructed of poured rubble concrete with exterior walls measuring approximately 9.5 inches in width. The distance from the outer edge of one exterior wall to the other is 5 feet and 7 inches in width, making the interior runs of the ladder about 4 feet across. The fish ladder was designed with two runs, with a 45-foot-long lower run accessed by two entrance gates, rising southeast to a resting pool, followed by a second run in two sections, the first measuring 62.5 feet and rising to the northwest, then turning about 45 degrees and extending another 40 feet west-northwest to the top of the dam. Metal grating covers the runs between the ladder's concrete side walls, though some sections of grating are damaged or missing. The fish ladder was designed with wooden baffles that could be removed for repair or replacement, though none presently remain. The side slots or tracks into which the baffles were inserted are clearly visible. The wooden baffles were utilized to control water flow, turning the water back upon itself and slowing down the rate of flow to between about 2 and 4 feet per second, which is a manageable rate for shad to pass. The shad would swim in a stream created above the baffles in order to pass through the ladder. Housing for a sluice gate is located at the top of the ladder so that, outside of the period of the shad run, it could be closed to restore full water flow to the river; however, the sluice gate is no longer in place. The fish ladder is no longer in active use and shows signs of disrepair.

1.3 Dam 6 (Dupont Dam)

Dam 6 is an approximately 8-foot tall, 182-foot-wide dam located at River Mile 4.5 on the Brandywine River. The GPS coordinates for the dam are: 39.76959, -75.57346. It is referred to as either the DuPont Experimental Station Dam, Dupont Dam, Lower Hagley Yard Dam, or the Rockford Park Dam. The land at the west abutment of the dam, river right, is owned by the City of Wilmington. The land at the east abutment of the dam, river left, is owned by the E I DuPont Nemours & Co. Historically the dam was used for water supply by the DuPont Company; however, it is no longer used for water supply and the water intake at river left has been sealed up. The DuPont Company currently receives water from the City of Wilmington. There is no mill race with the dam, in its current state. New Castle County has a concrete encased sewer line that crosses the river approximately 200 feet downstream of the dam. The sewer line does protrude up from the bottom of the waterway, creating a barrier to fish passage at lower flows. There is also a sewer line running along the right abutment and shoreline that is also owned by New Castle County, as well as a connecting sewer line on river right as well.

Figure 3. Dam 6 Viewed from the Right Bank

From the 2022 Phase 2 Architectural Report (CHAD, 2022) for Dam 6:

> Dam 6, known as the Lower Hagley Yard Dam, is the earliest extant dam on the lower Brandywine. It was constructed c. 1839 as an ascending ramp, curved, stone dam. The dam arcs across the Brandywine approximately 180 feet and has a fall of approximately 5 feet. It is supported on the southern bank by the natural bedrock of Rockford Park Gneiss, with scattered large boulders and rubble stones along the bank. The north side of the dam is tied into a mortared stone and poured concrete retaining wall. Just north of the stone retaining wall is an extant mill race, which runs under Buildings 269, 256 and 236 of the DuPont Experimental Station. The space formerly housing the mill race's head gate is filled in with concrete. The retaining wall continues running northeast of the dam. A sanitary sewer line crosses the Brandywine approximately 140 feet east of the crest of the dam, running from the southern bank to the northern bank. The line is buttressed at regular intervals by poured concrete and continues running northeast along the northern bank.

The dam features a wooden plank ramp on its upstream side, with wooden planking, or lagging, covering its downstream face, and is constructed or back-filled with stone. The upstream ramp, which begins about 20 feet and 6 inches from the southern bank, is comprised of wooden planks laid perpendicular (west to east) to the crest of the dam. The planks, measuring about 6 to 8 inches in width, abut one another and evidence some deterioration towards the crest of the dam. A string piece (a long piece of timber creating a margin or edge of construction) appears to run along the eastern edge of the plank ramp. An approximately 6-foot-wide concrete cap is visible between the eastern edge of the plank ramp/string piece and the crest of the dam, with metal I-beams abutting and reinforcing it. Some of the central planks situated along the apex of the dam's upstream curve are shorter than those towards the northern and southern sides of the ramp, with what appears to be concrete in-filling this area, which may have served to better reinforce the overall structure of the dam. Some small stones are also visible along the crest of the dam. It is unknown when the concrete additions and/or repairs were completed but may date to the early-twentieth century when the DuPont Experimental Station was under initial development.

1.4 Dams 4 and 6 Fish Passage Design Criteria

In consultation with BRRT, Kleinschmidt developed the following design criteria for the proposed fish passage projects at Dams 4 and 6. Many of these design criteria are the same as the design criteria developed in consultation with the Brandywine NLF Technical Subcommittee (BNTS) for the design of the NLF at Dam 2. The Dam 2 NLF Design criteria are described in more detail in Kleinschmidt's Preliminary Brandywine NLF Design Criteria Memorandum dated December 23, 2021. The design criteria that are the same for both sites are presented first, with site specific criteria for Dams 4 and 6 detailed in the sections below.

<u>Primary Design Criteria</u>

1. Target Species: American Shad, Blueback Herring, and Alewife Herring, with goal of allowing year-round upstream and downstream passage for resident species
2. Upstream Fish Passage Season for Target Species: March 15 through June 15 each year
3. Design Flows: The fishway will provide suitable passage from the 95% exceedance to the 5% exceedance flows during the fish passage season, as based on the USGS Gage 01481500 on the Brandywine River at Wilmington for the past 20 years of data.

Percent Exceedance Flow (fish passage season)	Corresponding River Flow (cfs)*
5	1,326
50	470
95	233

* *Flow is from USGS Gage 01481500. The flow was not adjusted due to the small difference in drainage areas from the gage to the project site.*

4. The 2019 USFWS Region 5 Fish Passage Engineering Design Criteria will be used to guide the design (see Table 2).
5. Design Flood/Stability Event: dam and fishway structures will be designed to resist major structural failures during a reasonably anticipated 100-year return period flood event (33,000 cfs flow).
6. Minimize, to the extent feasible, the overall project footprint, and the duration of construction.
7. Minimize any impacts to existing utilities.
8. No upstream or downstream rise in flood water elevations compared to existing conditions, with a lowering of the flood water elevations as highly desirable.
9. Minimize risk to the public at any remaining dam components.
10. Minimize or eliminate maintenance of the fishway.
11. Minimize construction and maintenance costs.

Table 2. Summary of Federal Interagency Nature-like Fishway Design Guidelines and Maximum Velocity Criterion for American Shad, Blueback Herring, and Alewife Herring

	Minimum Pool/Channel Width (ft)	Minimum Pool/Channel Depth (ft)	Minimum Pool/Channel Length (ft)	Minimum Weir Opening Width (ft)	Minimum Weir Opening Depth (ft)	Maximum Weir Opening Water Velocity (ft/sec)	Maximum Fishway Channel Slope
Species	W_p	d_p	L_p	W_N	d_N	V_{max}	S_O
American shad (*Alosa sapidissima*)	20.0	4.00	30.0	5.00	2.25	8.25	1:30
Blueback herring (*Alosa aestivalis*)	5.0	2.00	10.0	2.25	1.00	6.00	1:20
Alewife (*Alosa pseudoharengus*)	5.0	2.25	10.0	2.50	1.00	6.00	1:20

At this level of the review of the alternatives, there are many uncertainties, assumptions, and risks that must be considered, and it is not advisable to take all alternatives to 30% design to better determine which ones will or will not work. Therefore, this report acknowledges these uncertainties and generally noted them below for each alternative. Overall, uncertainties are tied to the existence of various unknowns - some of which are known at the design stage and others that only become apparent at some point in the future. In general, the sources of uncertainty and risk are:

- **Design.** Uncertainties are associated with how closely various design assumptions mirror actual conditions. This includes parameters such as depth to bedrock, headpond and tailwater depths, range of flows in future years, and stability of existing structures. Consequences include additional investigations during design, potential re-design if assumptions are invalidated late in the design stage, or complicated permitting if conflicting objectives are present.
- **Construction.** During construction there can be floods that require demobilization or damage to the project. The conditions can vary from those anticipated during design, requiring redesign or additional funding to resolve any issues.
- **Project Performance.** A certain degree of uncertainty is associated with how well the project performs as compared to its projected performance level at the time of design. Performance can be influenced by impacts of climate change and other unforeseen habitat stressors on suitable spawning and rearing habitat. These effects could significantly alter anticipated project outputs. Performance uncertainty can be partially mitigated by ensuring there is adequate depth and velocity for the target species and by minimizing velocities as much as possible to improve passage success.

Based on Kleinschmidt's review of the existing conditions at Dams 4 and 6, a literature review, experience with fishways across the United States, the project design criteria, and the goal of improving fish passage on the Brandywine River at Dams 4 and 6, a recommended alternative is identified for implementation for each site.

1.4.1 Dam 4 Specific Fish Passage Design Criteria

In addition to the primary design criteria listed above, Kleinschmidt developed the following design criteria specific to the proposed fish passage project at Dam 4.

<u>Dam 4 Additional Primary Design Criteria</u>

1. Location: Brandywine Dam 4 and immediate vicinity
2. Protection of dam abutments and downstream area below the dam.
3. Protection of New Castle County sewer line on river left.
4. Leave portion of West and East abutment intact (to document location of the dam), including a stable angle on any breach of the dam.
5. Maintain structural stability of abutting structures on river right after the installation of fish passage.

1.4.2 Dam 6 Specific Fish Passage Design Criteria

In addition to the primary design criteria listed above, Kleinschmidt developed the following design criteria specific to the proposed fish passage project at Dam 6.

Dam 6 Additional Primary Design Criteria

1. Location: Brandywine Dam 6
2. Regrade channel over the downstream sewer line to protect sewer line and provide fish passage over the sewer line, which is currently a blockage to passage.
3. Leave portion of east and west abutments intact (to document location of dam), including a stable angle on any breach of the dam.
4. Maintain structural stability of abutting structures on river right after the installation of fish passage.

1.5 Fish Passage Alternatives

This alternatives analysis focuses on fish passage at Dams 4 and 6 in consideration of Brandywine River Restoration Trust's plans to provide passage at these sites as part of their larger objective to restore American shad runs to the Pennsylvania portion of the Brandywine River. After reviewing BRRT's design criteria and the sites, the following fish passage options were considered in this analysis include:

1. no action,
2. dam removal, or
3. installation of fish passage structures:
    a. nature-like fishways, and
    b. technical fishway.

1.5.1 No Action

This option would not involve any impacts to historic architectural or archaeologic resources, but it would also not meet the goals of the project to provide fish passage at Dams 4 and 6. This option would continue to limit access for anadromous species to the upstream reaches of the Brandywine, where they have historically been able to forage and spawn, prior to the installation of the dams. Therefore, this option was not considered as a viable option for these sites as it would continue to adversely affect the access of anadromous and resident fish species to the habitat above Dams 4 and 6.

1.5.2 Dam Removal

The most effective and widely preferred means of passage for American Shad and other migratory fish, particularly at a low head dam, is dam removal. Dam removal, when done correctly, results in close to 100% passage effectiveness for fish motivated to migrate past the location of the dam. For a relative comparison of fish passage options, we consider dam removal to be the "benchmark" to compare all other options against and therefore we ranked full dam removal as a

“10” on a scale of 1 to 10 (Table 3). Removal also helps restore natural ecological function of the stream by providing unhindered upstream and downstream passage of other aquatic species, improving water quality, transfer of biomass, and transport of organisms that require a transfer host such as mussel glochidia. The immediate effects of dam removal’s effect on American Shad passage were seen at Dam 1, which was removed in 2019 and in 2020 juvenile American shad were found spawning upstream of the former dam. Effective dam removal includes reconstruction of at least a portion of the stream channel to ensure a zone of passage for migratory fish (suitable depth and velocity) is available at river flow conditions anticipated during the migration season. Although dam removal is a preferred means to provide passage, the function of many dams is still needed, or the dam may have significant historic value, precluding removal as a feasible option. In these circumstances, other alternatives are routinely considered.

Under some circumstances, a partial dam removal might be possible when full removal is not feasible. One common approach to partial dam removal is breaching or notching, which involves removing a full height section of a dam to provide suitable fish passage conditions but leaving the rest of the dam intact. This partial width approach directs most of the stream base flow through the removed section as opposed to over the remaining portion of the dam. Another approach to partial dam removal includes lowering a dam to a height that allows fish passage yet maintains water elevation upstream for specific needs, such as a water intake. This will be called the partial depth approach later in this analysis. Partial width removals and partial width removals can create high velocity areas or hydraulic drops that are difficult for some fish species to negotiate and in general provide less suitable upstream passage than a full removal. Generally, it can be expected that a well-designed partial dam removal would result in upstream passage effectiveness of 80 to 95 percent for American shad and river herring at ideal or “normal” flows during fish passage season. While partial removals can be effective under “normal” flow conditions, partial removals may not provide optimal passage velocities for target species at either high and/or low flow conditions, thereby lowering expected effectiveness relative to a full dam removal (Table 3) to a rank of 9. Further, partial removals can leave a portion of the former dam accessible to the public, which may leave an unacceptable public safety risk. A partial depth removal also requires substantial placement of fill to create a “rock ramp” below the dam, increasing project impacts to the river and further complicating upstream passage for the target species.

Figure 4. Example Partial Dam Removal by Kleinschmidt - Lombard Dam; Vassalboro, Maine

1.5.3 Nature-Like Fishway

Nature-like fishways (NLFs) are man-made instream or near-stream structures that essentially convert a low-head dam into a long riffle/pool sequence that mimics natural conditions migrating fish can navigate or provides a bypass around the dam that replicates a natural stream channel. NLFs are usually constructed using natural material (gravel, rocks, boulders, and soil) and result in hydraulic conditions and stream gradient that dissipate energy and provide efficient passage for migratory and resident fish assemblages. The United States Fish & Wildlife Service (USFWS, 2019) has published guidance on design of NLFs, including acceptable slopes, velocities, and depths by anticipated species of interest. Each nature-like fishway should have as much variability as feasible to provide multiple zones of passage for the target species, including multiple width/depths at key locations in the upstream passage, such as over the dam crest. There are two basic types of NLFs: Rock Ramp and Bypass Channel.

1.5.3.1 Rock Ramp Fishway

Generally, Rock Ramps consist of well-graded rock fill and/or rock weirs that create a series of pools and riffles with velocities suitable for fish passage across the full width of the river or area below the dam (Figure 5). Rock Ramp foundations are routinely set on a stable riverbed, or bedrock. They typically include a low flow channel that conveys the 95% exceedance flow, as well as a multi-stage channel, or sloping channel bottom, to provide suitable passage velocities under the range of flow conditions at the specific site. At higher flows, the full channel width (dam breadth) is incorporated, and suitable fish passage velocities exist at the shoreline extents of the channel or designed zones of passage, rather than in the center of the channel. Under some circumstances, a partial Rock Ramp that includes only a portion of the width of a dam can be constructed to provide effective passage if the entrance can be properly located to intercept migrating fish before they reach the dam; however, these types of fishways can have a problem with fish finding the entrance.

Material size and configuration of instream structures are critical design elements to ensure both longevity and passage effectiveness of rock ramps. The design of a Rock Ramp incorporates data regarding flood frequency and magnitude to select boulder size and to design channel features that will be stable during high flow events and durable over time. Material size can range from boulders larger than 4 feet (to set the grade) to pea gravel (used to fill interstitial spaces between larger material) and often requires notching of the dam in multiple locations to accommodate fish passage over the dam.

The design of Rock Ramps for American Shad and River Herring typically follow the fish passage criteria in the Federal Interagency Guidelines for NLFs (Turek et al., 2016), including velocities less than 6 feet per second (fps), pool depths of at least 4 feet, pool widths of at least 20 feet, and pool lengths of 30 feet for these species. The slope is typically set to 1:30 (or shallower; agencies prefer less than 2% slope) to minimize hydraulic drops and maintain the recommended hydraulics in the channel. Rock Ramp fishways are expected to result in upstream passage effectiveness of 70 to 95 percent of American Shad and River Herring that approach the structure, and proper design and construction of the structure is essential to ensure hydraulics in the Rock Ramp meet the design criteria and provide effective hydraulic zones of passage. A recent telemetry study by Raabe et al., (2019) on effectiveness of American Shad in a large Rock Ramp constructed on the Cape Fear River in 2012, reported 53% to 65% of tagged shad passed upstream. This facility was the first Rock Ramp constructed on the East Coast for American Shad. Since that time, design standards have been modified and USFWS anticipates passage effectiveness for shad will be improved in new installations that follow the published design guidance. Full-Width Rock Ramps received a relative ranking of 8 (Table 3).

Figure 5. Example Rock Ramp Fishway – Rock Arch Rapids Fishway at the Cape Fear River Lock and Dam No.1; Cape Fear River, North Carolina
(https://www.fisheries.noaa.gov/feature-story/reopening-cape-fear-river-migration-benefits-both-fish-and-people)

Given the proximity of the recently constructed condominiums at Dam 4, flooding experienced in the garages below this building in Hurricane Ida, and the anticipated rise in flooding locally if a rock ramp were installed, a rock ramp is not determined to be feasible at Dam 4.

1.5.3.2 Bypass Channel

A Bypass Channel is a man-made channel that usually has an entrance for upstream migrating fish to enter near the base of a dam, passes around an abutment, and proceeds upstream to a location where it rejoins the stream or river (Figure 6). Although the entrance and exit of a Bypass Channel are connected to the mainstream channel, the Bypass Channel itself is constructed outside the existing river channel and therefore requires a suitable area along the stream margin for installation. Like Rock Ramps, Bypass Channels for American Shad and River Herring are designed in accordance with the USFWS guidelines, including a slope less than 1:30 (with preference by agencies of less than 2% slope), a minimum pool depth of 4 feet, a minimum weir width of 5 feet, and a minimum weir depth of 2.25 feet. They typically have a hydraulic drop of less than 0.7 feet per pool and for River Herring, a target maximum velocity of 6 fps. To provide downstream passage of juveniles, a notch (or notches, perhaps one on each side of dam) would be required to allow downstream swimming juveniles to pass over the dam. This route of downstream passage is not ideal but is required as juveniles cannot be expected to find the fishway exit above the dam and swim downstream though the fishway. This would likely require impacts to the dam to provide a notch several feet wide and over a foot deep, with final sizing dependent on further design.

Entrance location, the efficiency of attracting fish to the entrance from both near and far field, hydraulic design within the channel, and the design of the floodplain channel for high flows are important components to Bypass Channel design. The anticipated passage effectiveness of a well-designed Bypass Channel for American Shad and River Herring is expected to vary from 65% to 85%. Decreases in passage efficiency compared to dam removal occur due to improper entrance location, insufficient attraction to the entrance, and/or areas of high velocity and shallow depth within the channel. These uncertainties result in a relative ranking of 7 (Table 3).

Figure 6. Example Natural Bypass NLF on the Penobscot River in - Howland, Maine

1.5.4 Technical Fishway

Technical fishways, often referred to fish ladders, employ engineering designs with concrete, metal, polymer, and/or wood, with standardized dimensions, using common construction techniques (USFWS 2019). Technical fishways include pool and weir fishways, vertical slot fishways, Denil fishways, eel ladders, fish locks, and fish lifts. Fish locks and fish lifts are mechanical in design and are generally used at larger and higher head dams than those on the Brandywine and are not considered here.

The effectiveness of technical fishways is highly dependent on siting the entrance in the proper location and providing hydraulics within the fishway that enable migrating fish to pass through the fishway relatively unimpeded. Either of these major elements will reduce overall passage effectiveness if not designed appropriately, as the fish have to find a small entrance among the water pouring over the entire dam. Additionally, the ability of a technical fishway entrance to attract migrating fish is often reduced as river flow increases because increasing discharge of the river can “drown out” attraction discharge of the fishway. Given these uncertainties, technical fishways were given a relative rank of 7 (Table 3).

A Denil fishway is a type of technical fishway that consists of a linear channel, with baffles arranged at regular and relatively short intervals, angled upstream against the flow (Figure 8). Each baffle has a cut-out section in the middle that creates a “tongue” of current that fish swim through. Backflows formed between the baffles dissipate energy and allow relatively low flow velocity through the cut-out section in the baffles where fish can pass. This configuration allows a Denil ladder to be set at steeper slopes relative to other types of technical fishways, and to overcome small to medium height differences over relatively short distances. Normally, Denil fishways are constructed of concrete or aluminum and have V-shaped wooden or metal baffles set at a 45-degree angle to the fishway floor. Generally, the slope of a Denil ladder designed to pass American Shad and River Herring varies from 8% to 12%. These ladders usually have flat resting and/or turn pools that are typically 3 to 4 feet wide. Recently, the USFWS has started moving away from recommending Denil ladders to pass American Shad and prefer that they only be considered at sites where design populations are appropriate, or cost and/or site constraints prohibit other fishways.

A technical fishway requires substantially more upkeep to maintain an effective fishway, as there is only one route of passage (compared to multiple options in a dam removal or NLF) and a single large tree or piece of debris can clog the fishway. Typically, the most effective fishways are located next to a staffed operation (such as a powerhouse), where staff can quickly notice a debris jam or disturbance to the fishway. The sites along the Brandywine are generally unmanned, and especially so at Dams 4 and 6, so maintenance of a technical fishway at either of these locations would be a more substantial effort.

Figure 7. Example Denil Fishway in South Berwick, Maine

1.5.5 Summary and Comparison

This review and ranking of fishways is provided as general guidance and it should be noted that fishway passage effectiveness, cost, and in turn, the selection of a fish passage alternative is highly site dependent. From a design perspective, entrance location and fishway hydraulics are the most critical design elements to effectively pass fish for any fish passage alternative. However, sometimes cost constraints and site-specific circumstances such as historical significance of structures, landowner permission, and existing infrastructure, are essential considerations in selection of the alternative. In these cases, the design effort must strive to balance all interests while maintaining the primary goal of maximizing fish passage effectiveness.

Table 3. Relative Ranking, Anticipated Effectiveness and Relative Cost of Fish Passage Alternatives under Consideration for the Brandywine Dam 2

Fish Passage Alternatives	Relative Rank of Passage Effectiveness	Anticipated Effectiveness Based on Literature and Professional Opinion under Ideal Design Conditions	Relative Cost
No Action	0	0%	0
Dam Removal	10	95% - 100%	$ - $$
Nature-Like Fishways			
Full-Width Rock Ramp	8	70% - 95%	$$$
Bypass Channel	7	65% - 85%	$$$
Technical Fishways			
Denil Fishway	7	65% - 85%	$ - $$

2.0 DAM 4 ALTERNATIVES

Prior to evaluating the potential alternatives for improving fish passage at Dams 4 and 6, Kleinschmidt completed a site visit and literature review. In addition to this literature review, Kleinschmidt engaged their in-house experts on fish passage to review each of the alternatives. As part of this review, Kleinschmidt first evaluated each alternative independently and then provided a recommendation for the best alternative to improve fish passage at each site. The alternatives evaluated were:

1. No Action
2. Technical Fishway
3. Dam Removal
    a. Full Removal
    b. Partial Removal
        i. Partial Width Removal
        ii. Partial Depth Removal
4. Nature-like Fishways
    a. Bypass Channel (both sites)
    b. Note: A Rock Ramp was not considered at Dam 4, due to known flood concerns with placing additional fill in the river below Dam 4 and the high cost of installing a rock ramp.

2.1 No Action

This alternative would leave the dam as it exists currently. During several field visits to Dam 4 to gather data for the fish passage feasibility assessment, we have observed what appears to be a cavity that has eroded into a portion of the downstream face of the Dam. Although, we have not collected any empirical data or conducted a formal dam safety inspection, we have observed the cavity at low-flow river conditions when it is most readily visible.

As shown in below Photo 1 and Photo 2, the cavity is large, approximately 20 ft. long, extending vertically from below the concrete cap/crest to below the water level. While we have no formal drawings or construction photos of this dam, it appears as if the original Dam has been modified to have a concrete cap/crest that was poured on top of a stacked masonry wall installed downstream of the original Dam. It is possible that this wall and cap could have been part of the original construction. From the downstream side of the dam (and under low flow conditions), it can be seen that a number of the dam construction elements have been displaced from underneath the concrete cap. The crest of the Dam in this area also has a noticeable upward tilt not seen in sections of the Dam to either side of the damaged area. It is unknown if this condition has existed from the time it was constructed, or if it is a result of the crest settling into the void created from the displaced rocks. Aerial imagery from approximately 2016 shows a pile of cobble/boulder immediately below the Dam. The source of that material is potentially fill from the center of the Dam, redistributed after the downstream face of the Dam was breached from undermining activity. That material is no longer present, evidently washed downstream and indicating active erosion in this area.

Without significant maintenance being undertaken, the dam may eventually fail in the section that appears to be damaged. Predicting the timeline at which this would occur is very difficult without a detailed structural evaluation of the dam. Furthermore, the initial failure of the dam is not likely to result in conditions that are passable for migratory fish. Further deterioration could be necessary, beyond a potential dam failure, for the dam to be passable for migratory fish. A dam failure could lead to an uncontrolled release of impounded water and sediment, the effects of which cannot be easily quantified.

This alternative would have the least amount of impact on the historical resource of the dam, but also leaves the resource at risk of loss if the dam were to continue to incur damage. Finally, this alternative would not achieve the primary objectives of providing fish passage at this dam and reducing flooding near the dam.

Photo 1. Aerial View of Dam 4 from Drone Showing Void on Left Side, Dated 9/25/2020

Photo 2. Downstream Face of Dam 4 Showing Void, Dated 8/04/2020

2.2 Technical Fishway

A technical fishway was previously constructed at Dam 4 on the left abutment but has since been abandoned in place with portions of the control structures and site protections missing or damaged. This alternative provides a relatively small entrance for fish to find amid the larger flow of water over the dam, so as discussed above, it is not as effective as dam removal or a full-width rock ramp. Additionally, a technical fishway would require notching through the dam to a depth of at least 3 feet for the outlet of the fishway, as well as a downstream passage notch, resulting in two separate impacts to a historic resource. Given the lack of staff to operate this fishway to ensure that it remains unclogged and available for fish passage during the upstream migrating period, this alternative would have substantial maintenance costs. A technical fishway on either the right or left banks at this dam would also be subject to debris loading from the river, which could clog the fishway during critical upstream migration periods. Finally, a technical fishway would not likely provide year-round passage for resident species, unless it was maintained and operated year-round, further increasing the maintenance burden. The flood impacts of a technical fishway at Dam 4 may be minimal, if it were put in a similar footprint as that of the current fishway, but it is possible that portions or all of the current fishway would need to be modified or removed to allow for the best available technology to be installed. If pursued, this alternative would require additional investigation to further assess the condition and design of the current fishway. Given the lower anticipated passage of anadromous and resident species, as well as the high maintenance burden for a technical fishway, Kleinschmidt does not recommend a technical fishway for this location.

2.3 Dam Removal

This alternative seeks to improve fish passage by removal of a majority or portion of the dam. A drawing of the full-removal alternative is included in Appendix A. It would leave a section of the west and east abutment intact and would include a stable angle on the sides of the breach. Dam material would be redistributed from the breach to armor the abutments and shoreline areas near the dam. The sediment behind the dam has been tested and was found to be similar to other sediment within the river and "based upon the evaluations conducted, risk associated with dam modification, removal and/or failure is not likely to increase the risk of toxicity as compared to its current state (with dams in place)" (Cargill et al., 2020). Further, the DNREC report found less sediment than expected behind these dams. Either dam removal option (e.g., full or partial removal) would have substantial impact on the historic resource that is Dam 4; however, portions of the dam would be preserved in place in both cases to document the existence of a dam at this location, as well as to stabilize the abutment walls that are to remain in place.

At this time Kleinschmidt does not have substantial information regarding the structural design of the buildings for the abutting property owners to the south of Dam 4, or any information relative to the structural loading/stability calculations that were performed as part of the construction of the condominiums near this dam and impoundment. It was anticipated by the state (majority owner of the dam) that this dam was to be removed, so it may be that the developers have accounted for removal of the dam in the design of their buildings, but that should be evaluated as part of further consultation during final design of fish passage at Dam 4. The following is a review of what a full removal or partial removal of this dam could entail.

2.3.1 Full Dam Removal

The full dam removal scenario lowers 70-foot section of the dam center to the natural (pre-dam) elevation and grades a 3:1 slope from the breach invert up to the remaining abutments on either side of the channel (Figure 8). The 70-foot-wide breach is proposed to preserve a portion of the abutments in place, but also to maximize the breach size to achieve the design criteria of minimizing velocity at the dam to improve fish passage.

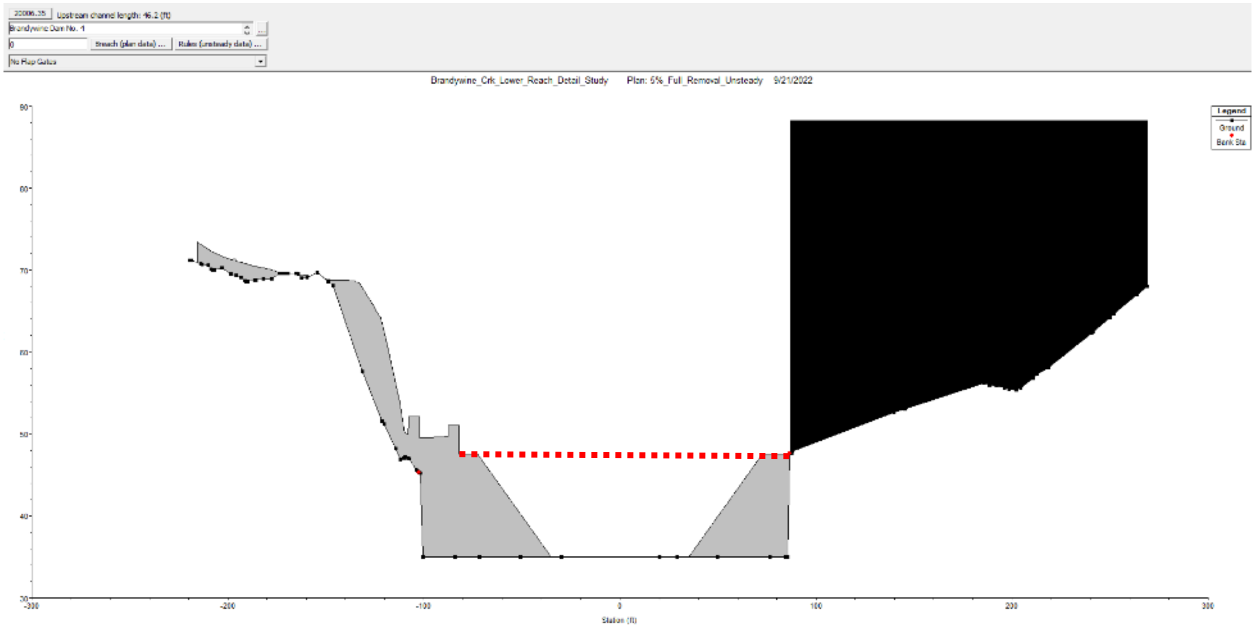

Figure 8. Full Removal Geometry for Dam 4 in HEC-RAS (red line is existing dam crest, grey is dam/banks to remain)

2.3.2 Partial Dam Removal

Two partial removal scenarios were considered. The partial depth scenario, which involves removal of the upper portion of the dam and adding a rock ramp below the dam (to provide fish passage over the remaining dam) with a 2% slope was deemed not feasible as it would have to extend roughly 750 feet downstream, would require a large amount of rock fill in the channel, and is anticipated to increase flooding locally at the rock ramp (which could impact the condominiums).

A partial width dam removal scenario was evaluated that involved a 35-foot-wide breach (half of the full-removal scenario) that lowers the dam to grade and grading a 3:1 slope from the breach up to the remaining abutments on either side of the channel (Figure 9). This would leave the current dam crest exposed and visible to the public, which could provide a public safety hazard for users of the Alapocas Run State Park and allow the breach to be plugged (jeopardizing fish passage) by a large tree during a storm event.

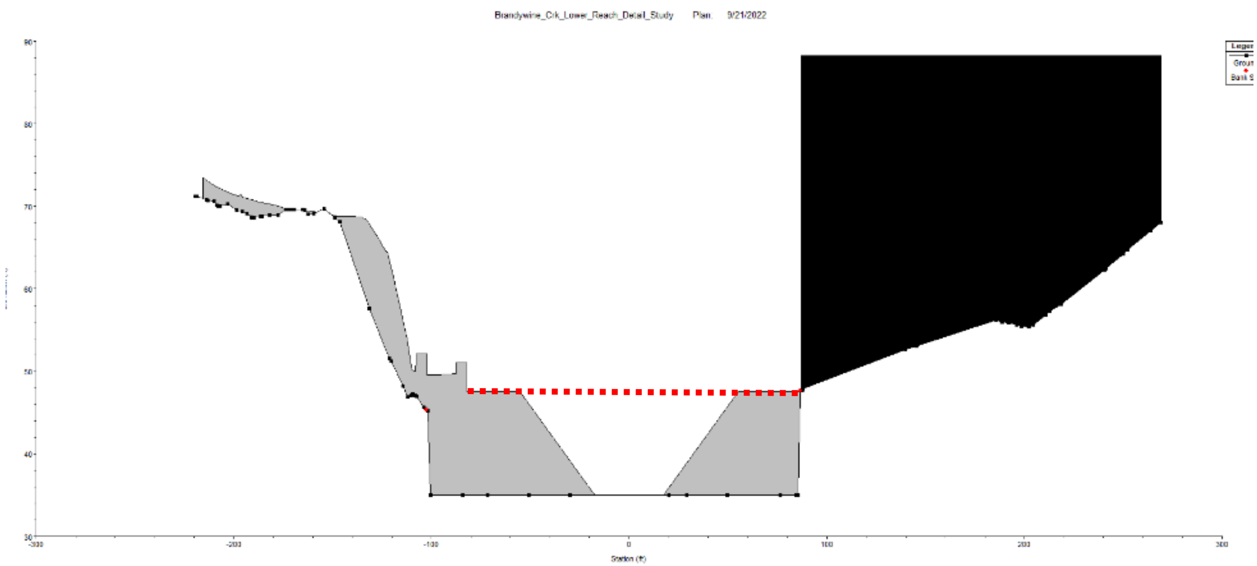

Figure 9. Partial-width Removal Geometry Visualization for Dam 4 in HEC-RAS Modeling Software (red line is existing dam crest, grey is dam/banks to remain)

2.4 Nature-like Bypass Channel

This alternative would seek to improve fish passage at Dam 4 by constructing a natural bypass channel around the dam. To pass fish around this approximately 13-foot-tall dam, a natural bypass channel would need to be at least 20 feet wide and over 650 feet long (at 2% slope), with adequate side slopes, or a concrete retaining wall, on either side of the bypass. Both sides of the river were considered as potential locations for the natural bypass channel. River right, the site of the historic Bancroft Mills, has been recently redeveloped, and as such is not a viable option for a natural bypass channel. On river left, there are several conflicts include the existing fishway and large sewer line, which would need to be demolished, moved, and/or protected to allow for the fishway entrance. There is also a tributary (Alapocas Run) that enters just downstream of Dam 4 on the left bank, which would complicate the installation of a bypass NLF on this bank. Notching of the existing dam would likely be required to provide supplemental attraction water at the fishway entrance and suitable downstream fish passage., impacting this historic resource. Additionally, steep riverbanks and the significant cost to relocate the New Castle County Sewer along the riverbank make locating the natural bypass channel on river left a difficult-to implement alternative at this site.

Impacts to historic resources of this alternative include notching the dam and modification of the left abutment, particularly demolition of the crest to create the notch(es) to provide enough water at the fishway entrance below the dam to attract fish to this area. The upland area identified in the Phase 1B Archaeology report did not identify any archaeological sites near the dam, but the survey did not cover the full extent of the upstream extent where a bypass would need to be located.

3.0 DAM 4 ALTERNATIVE SUMMARY AND RECOMMENDED ALTERNATIVE

Based on the information available at the time of this report, Kleinschmidt provides the following summary of benefits and challenges for the identified alternatives and a recommendation for the preferred alternative given the design criteria for the Dam 4 fish passage project (as presented in Section 1.4).

Table 4. Dam 4: Summary of Alternative Benefits and Challenges

Alternative Option	Benefits	Challenges
No Action	- No cost - Continued deterioration could result in passage of migratory fish after the dam has completely failed - No immediate impacts to the historic resource of Dam 4	- Dam not passable for migratory fish - Risk of dam failure remains, including risk to public safety - Risk of loss of historic resource due to deterioration - No reduction in flood water levels anticipated
Technical Fishway	- Potentially lower cost than bypass, but depends on design and fishway location - Smaller footprint than rock ramp or bypass - Existing technical fishway could be evaluated for modification/re-use	- Requires two notches in the historic dam for the fishway exit and supplemental attraction water/downstream fish passage - Less effective upstream passage as compared to full width rock ramp or dam removal - High maintenance burden for debris removal and staffing during upstream migration period to open/close fishway and keep clean of sediment/debris - limited conveyance of attraction water could limit effective fish passage at higher flows - No year-round passage of resident species unless operated year-round. - Limited to no reduction in flood water levels anticipated
Dam Removal	- Provides ecological connectivity - Provides the best fish passage effectiveness. - Potential for shorter construction period than natural bypass channel - Anticipated reduction in flood levels local to dam and impoundment - Opens the Brandywine to recreation use by boaters	- Causes a release of sediment from the impoundment - Impacts to historic resource that is Dam 4 - Need to consult with right abutter regarding structural design on buildings and infrastructure that was recently constructed

Alternative Option	Benefits	Challenges
Natural Bypass Channel	- Provides the acceptable fish passage effectiveness. - Results in minimal fill within the waterway - Construction may be able to be done partially in the dry (out of water) - Preservation of most of the historic resource in place, (but still have risk of further deterioration of the dam)	- Not a viable solution due to infrastructure constraints - Does not address necessary dam maintenance - Likely requires a concrete diversion wall along the length of the fishway to separate it from the river - Significant excavation required and disposal of spoils would be required - Anticipated to be the highest cost alternative - Increased maintenance as compared to dam removal or no action alternative - Still requires impacts to historic resource to provide downstream passage

Since a full-width rock weir nature-like fishway is in the process of being developed at Dam 2, and Dam 3 is partially breached and considered passable in its current state, the next barrier to passage on the Brandywine would be Dam 4. Given that Dam 4 is already deteriorating and no longer serves to provide water for the historic mills, or other consumptive uses, this dam is a prime candidate for removal. The height of the dam, surrounding infrastructure and the confined space it is in makes any other alternative cost-prohibitive or unfeasible to pursue. Thus, Kleinschmidt recommends Dam Removal for Dam 4. In a March 23, 2017 article published in the local news, state officials concurred that this was their intent as owners of the dam, indicating that the removal of this dam would "allow passage of American shad during their spring spawning run" (Wilson, 2017). The following is an analysis of both the full and partial dam removals.

3.1 Dam 4 Comparison between Full and Partial Width Dam Removal

A 1D HEC-RAS model was created to compare the full and the partial width dam removal scenarios for fish passage at the 95%, 50%, and 5% exceedance flows during the fish passage season when it is critical to provide suitable depths and velocities for upstream fish passage. A partial depth removal was not modeled due to the amount of material and space a rock ramp would take up in the river, which would be anticipated to lead to localized flooding, which would not be acceptable to local communities. A 1D model cannot give maximum velocity (due to model constraints, it only provides an average velocity at each cross section), thus an average velocity is shown in the following table. Within each cross section there will be some areas of higher velocity and some areas of lower velocity, as is typical for a natural stream channel; however, given this averaging, it would be ideal to strive to minimize velocity in the breach to maximize fish passage potential.

Table 5. Full and Partial-Width Velocities by Exceedance Flow at Dam 4

Percent Exceedance (during fish passage season)	River Flow above Dam 6 (cfs)*	Full Breach Avg. Velocity at Dam 4 (ft/s)	Partial-width Breach Avg. Velocity at Dam 4 (ft/s)
5	1,326	2.5	4.1
50	470	1.0	1.7
95	233	0.6	0.9

The average velocities for all cases are lower than the maximum velocity values listed in the Summary of Federal Interagency Nature-like Fishway Design Guidelines and Maximum Velocity Criterion for American Shad, Blueback Herring, Alewife, and Hickory Shad (Table 2). The reported velocities are averages, and there will be certain cases and locations where the velocity could be higher. A more detailed, 2D analysis would be required to see local maximums in velocity. At the 5% flow, there is a 1.6 ft/s reduction in velocity with the full removal, as compared to the partial width removal. Weaker swimmers, such as resident species would be more likely to pass in this full removal option, as the slower water allows them to better traverse the former dam area.

Another aspect of the modeling was to compare existing conditions were compared with the proposed conditions to see if there was any reduction in flooding at the 100-yr flood (33,200 cfs). The full removal is estimated to lower the 100-year flood water surface elevation near the dam by approximately 4.0 ft, while the partial-width removal is estimated to reduce the same flood water elevation by approximately 2.7 ft (Table 6). This means that the full removal will further reduce the flood risk in the vicinity of the dam.

Table 6. Dam 4 Comparison of Existing and Proposed Conditions at the 100-Year Flood Flow

Condition	Estimated 100-Year WSE Upstream of Dam (ft NAVD 88)	Estimated Difference (ft)
Existing Conditions	61.5	N/A
Full Removal	57.6	4.0
Partial Removal	58.8	2.7

Another safety consideration is public access. For the partial removal, more of the spillway will remain in place, but be dewatered and dried out (due to upstream water surface elevations being lowered). The public could want to walk on the remaining parts of the dam, which could potentially lead to loss of life or injury due to fall hazards or diving into shallow water from this structure. The risk can be mitigated by adding in fencing and signage, but risks will still be present as there is no way to permanently remove access to the dam in a partial removal scenario and any fencing could reasonably be anticipated to be damaged in any substantial flooding. The full removal will have less of the dam remaining and the abutments can be more closely graded into the shoreline, thereby reducing this risk.

The full removal shows more of a long-term benefit compared to the partial width removal. While it would be more costly and have greater historic resource impacts; fish passage, flooding, and public safety would be all improved by a full removal. Thus, Kleinschmidt recommends a full removal at the Dam 4 site, given the design objectives for this project.

4.0 DAM 6 ALTERNATIVES

Prior to evaluating the potential alternatives for improving fish passage at this site, Kleinschmidt visited the site and completed a literature review. In addition to this literature review, Kleinschmidt engaged their in-house experts on fish passage to review each of the alternatives. As part of this review, Kleinschmidt first evaluated each alternative independently and then provided a recommendation for the best alternative to improve fish passage at the site. The alternatives evaluated were:

1. No Action
2. Technical Fishway
3. Natural Bypass Channel
4. Full-Width Rock Ramp Fishway
5. Dam Removal
    a. Full Removal
    b. Partial Removal
        i. Partial Width Removal
        ii. Partial Depth Removal

4.1 No Action

This alternative would leave the dam as it exists currently. There are some anomalies in the downstream toe of the dam that appear to indicate a few stones of the dam apron have been eroded out of the dam (Figure 10). If nothing is done at this dam, that loss of dam material may continue, potentially requiring future maintenance of the dam. While this alternative would preserve the historic resource in place, it would not achieve the primary objectives of providing fish passage at this dam and would also not provide any reduction in flooding locally at the dam.

Figure 10. Dam 6 at Low Flow, Showing Potential Loss of Stones at Toe (Inside Red Circle) along Non-Linear Toe of the Dam

4.2 Technical Fishway

This alternative provides a relatively small entrance for fish to find amid the larger flow of water over the dam, so as discussed above, it is not as effective as dam removal or a full-width rock ramp. Additionally, a technical fishway would require notching through the dam to a depth of at least 3 feet for the outlet of the fishway, as well as a downstream passage notch, resulting in two separate impacts to a historic resource. Given the lack of staff to operate this fishway to ensure that it remains unclogged and available for fish passage during the upstream migrating period, this alternative would have substantial maintenance costs. A technical fishway on either the right or left banks at this dam would also be subject to debris loading from the river, which could clog the fishway during critical upstream migration periods. Finally, a technical fishway would not likely provide year-round passage for resident species, unless it was maintained and operated year-round, further increasing the maintenance burden. The flood impacts of a technical fishway at Dam 6 would need to be evaluated, but if it is to be able to be serviced, it may need to have infrastructure that rises above the existing ground elevation, potentially increasing flooding near the fishway. If pursued, this alternative would require additional investigation to further assess the right bank of the river (the most likely location for this fishway) and develop a detailed design of the fishway. Given the lower anticipated passage of anadromous and resident species, as well as the high maintenance burden for a technical fishway, Kleinschmidt does not recommend a technical fishway for this location.

4.3 Nature-like Bypass Channel

This alternative would seek to improve fish passage at Dam 6 by constructing a natural bypass channel around the dam. To pass fish around this approximately 8-foot-tall dam, a natural bypass channel would need to be at least 20 feet wide and over 400 feet long (at 2% slope), with adequate side slopes, or a concrete retaining wall, on either side of the bypass to separate the flow in the bypass from the river flow during normal fish passage flows. Both sides of the river were considered as potential locations for the natural bypass channel. On river right, the area contains a sewer line that parallels the Brandywine, making the project costs increase significantly to relocate this sewer line. The bypass would likely need to relocate the sewer line up the hill for the full length of the bypass, as it would cross the bypass twice. Additionally, there is an old USGS stream gage on this right bank. It is our understanding that the stream gage is no longer in use, a new stream gage was constructed upstream around the New Bridge Road bridge. This USGS stream gage was determined not to be eligible for listing on the national historic register (CHAD 2022). Any construction at this location would require approval by USGS and New Castle County. For this reason, river right is not a viable option for the location of the natural bypass channel. On river left, there are buildings and infrastructure for the DuPont Experimental Station. As a result, river left is not a viable option for a natural bypass channel. Therefore, a nature-like bypass channel was not deemed feasible at Dam 6, based on the design criteria for this project as it would impact substantial infrastructure.

4.4 Full-width Rock Ramp Fishway

This option would utilize the full-width of the river below Dam 6 to create a nature-like rock ramp up to several notches in Dam 6 to provide passage over the dam. The alternative has similar details as previously discussed under Dam 4 but would extend over 500 feet downstream of the dam (at slope of 2%), due to the height of the dam and quickly dropping stream slope below the dam. This option would require at least two new 5-foot wide by 2.25-foot deep notches in the dam for low flow conveyance, thereby impacting this historic resource.

The rock ramp for the three-target species would generally follow the USFWS guidelines, including target velocities of less than 6 fps, pool depths of at least 4-ft., pool widths of 20-ft., and pool lengths of 30-ft. The slope would be set to a minimum of 2% slope to minimize vertical drop barriers, reduce velocities, and maintain the recommended hydraulics in the channel, including considerations for maintaining desirable energy dissipation factors. To minimize impacts to flooding, the fill for the rock ramp would need to be placed at, or below, the crest of Dam 6, or as required during hydraulic modeling performed as part of later design. However, the placement of fill below Dam 6 and the approximately 500 feet downstream of the dam required to build the rock ramp would likely raise flood water elevation in the vicinity of the fishway. This raise would likely impact three buildings on the Dupont Experimental Station The advantages and disadvantages of a full-width rock ramp fishway have been stated previously under Dam 4 above. The placement of fill in the river would be anticipated to cause more frequent flooding of the Dupont buildings, as the water levels would be higher in this area of the fishway, as compared to current water elevations. This option would also require fill over the New Castle County sewer lines (potentially on both sides of the river), thus consultation and approval by New Castle County would be necessary as this would limit access to this infrastructure and potentially increase groundwater levels local to that utility. Given the increase in local flood water elevations and corresponding impacts to Dupont infrastructure and New Castle County utilities, this alternative is not deemed feasible.

4.5 Dam Removal

This alternative seeks to improve fish passage at Dam 6 by a majority or portion of the dam. This dam is also showing some signs of instability with evidence of some displacement of stones within the spillway, as shown in Figure 10. Dam material would be redistributed from the breach to armor the abutments and shoreline/riverbed areas near the dam. To protect the sewer line crossing below the dam, the rubble from the dam would be used to re-grade the channel over the sewer line and up through the existing dam, thereby eliminating the potential fish passage barrier that currently exists at the sewer line crossing as part of this dam removal. This would also provide additional protection for the sewer line that is currently encased in concrete but exposed to trees and debris that flow down the Brandywine.

The sediment behind the dam has been tested and was found to be similar to other sediment within the river and "based upon the evaluations conducted, risk associated with dam modification, removal and/or failure is not likely to increase the risk of toxicity as compared to its current state (with dams in place)" (Cargill et al., 2020). Further, the DNREC report found less sediment than expected behind these dams. This implies that there would be less adjusting of grades in the current impoundment post-dam removal. In preliminary consultation with Delaware DOT, who owns Rising Sun Bridge, just upstream of the dam (which is eligible for listing on the National Register for Historic Places), they ask that they be consulted regarding any changes in hydraulics near the bridge to ensure there is not a structural impact to that bridge. Kleinschmidt understands the unique component of this bridge to be the approximately 25-foot-wide stone arch on the river right side of the bridge that was over a former mill race that has been filled in. This portion of the bridge is not currently near the river and is not anticipated to be impacted by a dam removal. Additional analysis of the hydraulics at the ashlar abutments will be required, in addition to consultation with Delaware DOT.

To protect the sewer line crossing below the dam, the rubble from the dam would be used to re-grade the channel over the sewer line and up through the existing dam, thereby eliminating the potential fish passage barrier that currently exists at the sewer line crossing. A design drawing of the full removal alternative is included in Appendix B. The full removal alternative would leave the west and east abutment intact and would include a stable angle on the sides of the breach of the remaining dam. Kleinschmidt's analysis shows that the proposed full-width breach is sized to allow passage of migratory fish across the full range (95 % to 5% Exceedance Probability) of flow during fish-passage season, with low enough velocities that it is likely to pass resident species as well.

Either dam removal option (e.g., full or partial removal) would have substantial impact on the historic resource that is Dam 6; however, portions of the dam would be preserved in place in both cases to documents the existence of a dam at this location, to protect the riverbanks, and to stabilize the abutment sections that are to remain in place.

4.5.1 Full Dam Removal

The full removal scenario lowers an approximately 90-foot section of the dam center to the natural (pre-dam) elevation and grades a 3:1 slope from the breach invert up to the remaining abutments on either side of the channel (Figure 11). The breach is proposed to preserve a portion of the abutments in place (approximately 25 feet on each abutment), but also to maximize the breach size to achieve the design criteria of minimizing velocity at the dam to improve fish passage.

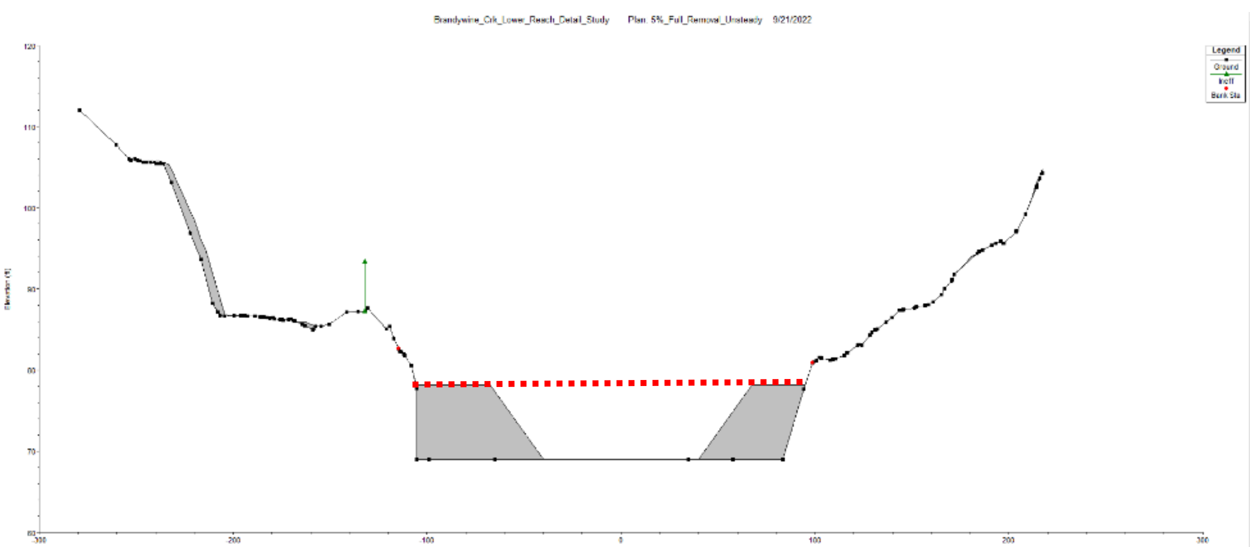

Figure 11. Full Removal Geometry Visualization for Dam 6 in HEC-RAS Modeling Software (red line is existing dam crest, grey is dam/banks to remain)

4.5.2 Partial Dam Removal

Two partial dam scenarios were considered, both of which would preserve more of the historic resource in place than a full removal. The partial depth scenario, which involves removal of the top portion of the dam and adding a rock ramp with a 2% slope would have to extend roughly 500 feet downstream and would require a large amount of rock fill in the channel, increasing local flood elevations at the Dupont buildings, as well as incurring similar challenges as identified in the full-width rock ramp section above. Therefore, the partial depth dam removal was not deemed feasible at Dam 6.

A partial width removal scenario involved a 40-foot-wide breach that lowers the dam to the estimated pre-removal stream grade and grading a 3:1 slope from the breach up to the remaining abutments on either side of the channel (Figure 12). This would leave the current dam crest exposed and visible to the public, which could provide a public safety hazard for users of the City's Rockford Park (no public access from north side of the dam) or recreational users of the river. Further, this smaller breach is more likely to be plugged (jeopardizing fish passage) by a large tree during a storm event. Finally, the structural stability of the remaining sections of the dam would need to be evaluated for long-term stability, in addition to reviewing the composition of the dam during dam breaching to evaluate if the remaining sections of the dam would even persist long term. Wood planking on the upstream face and the stone dam itself may degrade over time, as they would be exposed to additional weathering and freeze/thaw cycles with the lowered water levels post-dam decommissioning.

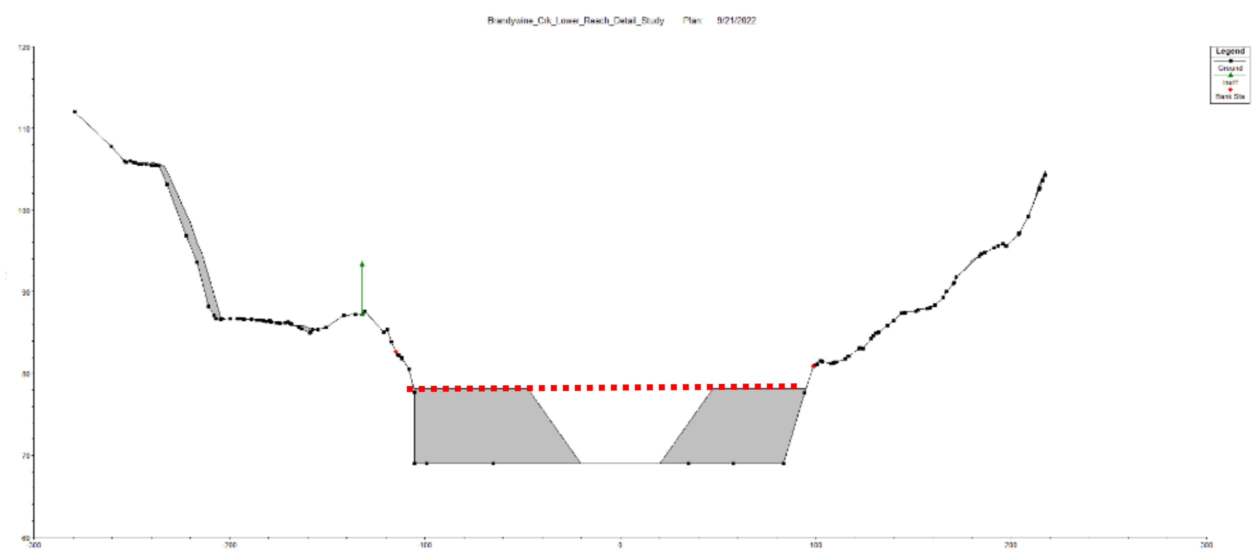

Figure 12. Partial-width Removal Geometry Visualization for Dam 6 in HEC-RAS Modeling Software (red line is dam crest, grey is dam/banks to remain)

5.0 DAM 6 ALTERNATIVE SUMMARY AND RECOMMENDED ALTERNATIVE

Based on the information available at the time of this report, Kleinschmidt provides the following summary of benefits and challenges for the identified alternatives and a recommendation for the preferred alternative, given the design criteria for the Dam 6 fish passage project (as presented in Section 1.4).

Table 7. Dam 6: Summary of Alternative Benefits and Challenges

Alternative Option	Benefits	Challenges
No Action	- Low cost - No immediate archaeologic or architectural impacts	- No reduction in flood water levels anticipated (continued flooding of Dupont property) Dam 6 remains a barrier for anadromous and resident fish passage - Potential for continued loss of stone at toe of dam
Technical Fishway	- Potentially lower cost than bypass, but more expensive than dam removal - Smaller footprint than rock ramp or bypass	- Requires two notches in the historic dam for the fishway exit and supplemental attraction water/downstream fish passage - Less effective upstream passage as compared to full width rock ramp or dam removal - High maintenance burden for debris removal and staffing during upstream migration period to open/close fishway and keep clean of sediment/debris - limited conveyance of attraction water could limit effective fish passage at higher flows - No year-round passage of resident species unless operated year-round. - Anticipate potential increase in flood water levels
Bypass Channel on River Right (Nature-like fishway)	- Provides the acceptable fish passage effectiveness. - Preservation of most of the historic resource in place, - Results in minimal fill within the waterway - Lower maintenance - Construction can be completed mostly in the dry - May have less flood water level impacts	- Not a viable solution due to infrastructure constraints - Significant excavation required and disposal of spoils would be required - Likely requires a concrete diversion wall along the fishway to separate it from the river - Requires the construction of a flow control structure at the fishway exit and notching of the dam for supplemental attraction flow - conflicts with existing utilities and requires relocation of ~400 feet of sewer line - Anticipated to be the highest cost alternative - Increased maintenance as compared to dam removal or no action alternative - Still requires impacts to historic resource to provide downstream passage

Alternative Option	Benefits	Challenges
Full-Width Rock Ramp (Nature-like Fishway)	- Provides variable velocity across all flows to increase fish passage - More natural looking - Minimal shading to deter shad passage - Lower maintenance than technical fishway or bypass fishway - Sediment and debris generally pass through, minimizing clogging - Anticipated to be the most effective fish passage other than dam removal	- Complicated hydraulics require modeling - Potentially higher construction cost - Impacts to existing aquatic resources by more fill in river - Long construction period with potential for short-term impacts to downstream water quality - Likely increase in flood water elevations near the fishway - Requires at least two notches in historic dam for passage - Archaeological & Architectural Resource Impacts
Dam Removal	- Offers greatest improvement in fish passage - Restores full connectivity from below impoundment to above Dam 6 - Provides additional protection of sewer line below Dam 6 - Potential for shorter construction period than natural bypass channel - Anticipated reduction in flood levels local to dam and impoundment - Opens the Brandywine to recreation use by boaters	- Small release of sediment from impoundment - Impacts to historic resource that is Dam 4 - Preservation of existing sewer lines during construction and site stabilization - Need to consult with Delaware DOT regarding changes in hydraulics at upstream bridge

Dam 6 is in a relatively tight space between the Dupont buildings and an active sewer line on both sides of the river, as well as below the dam. Thus, any shore-based fish passage would require substantial impacts to existing utilizes, likely requiring substantial relocation of these utilities. A rock ramp may be feasible, but given the height of the dam, this ramp would extend well downstream and may increase flooding locally right at the rock ramp, which would impact Dupont's property. A technical fishway, while feasible to construct, would have a large maintenance burden and the lowest anticipated fish passage effectiveness of all options other than the "no action" alternative. All of the alternatives have at least one direct impact to the historic resource of Dam 6 in order to provide suitable attraction flow for fish to find the fishway or to provide downstream fish passage. Based on the prior discussion of benefits and challenges for each alternative, Kleinschmidt recommends that dam removal be pursed, based on the design objectives for this project.

5.1 Dam 6 Comparison between Full and Partial Width Dam Removal

A 1D HEC-RAS model was created to compare the full and the partial width dam removals scenarios for fish passage at the 95%, 50%, and 5% exceedance flows during the fish passage season when it is critical to provide suitable depths and velocities for upstream fish passage. A partial depth removal was not modeled due to the amount of material and space a rock ramp would take up in the river, which would be anticipated to lead to localized flooding, which would not be acceptable to dam abutters. A 1D model cannot give maximum velocity (due to model constraints, it only provides an average velocity at each cross section), thus an average velocity is shown in the following table. Within each cross section there will be some areas of higher velocity and some areas of lower velocity, as is typical for a natural stream channel; however, given this averaging, it would be ideal to strive to minimize velocity in the breach to maximize fish passage potential.

Table 8. Full and Partial-width Velocities by Exceedance Flow at Dam 6

Percent Exceedance (during fish passage season)	River Flow above Dam 6 (cfs)*	Full Breach Avg Velocity at Dam 6 (ft/s)	Partial-width Breach Avg Velocity at Dam 6 (ft/s)
5	1,326	3.7	5.2
50	470	2.1	3.8
95	233	1.3	2.4

The 5% velocity at the partial-width breach is approaching the 6 ft/s criteria listed in the Summary of Federal Interagency Nature-like Fishway Design Guidelines and Maximum Velocity Criterion for American Shad, Blueback Herring, Alewife, and Hickory Shad (Table 2). This means that smaller migratory species such as Alewife and Blueback herring would have a challenging time passing at higher flows, as this is an average, so it is likely a portion of the cross section at the dam would be unpassable at this flow. The reported velocities are averages, and there will be certain cases and locations where the velocity could be higher. A more detailed, 2D analysis would be required to see local maximums in velocity and better evaluate passage by target species. Resident species, such as sunfish would move easily be able to pass in the full-breach option with its average velocities at the 50% exceedance flow anticipated to be 1.7 fps less than the breach velocities in the partial-width condition.

Another aspect of the modeling was to compare existing conditions with the proposed conditions to see if there was any reduction in flooding at the 100-yr flood (33,200 cfs). The full removal is estimated to lower the 100-year flood water surface elevation near the dam by approximately 3 ft, while the partial-width removal is estimated to reduce the same flood water elevation by approximately 2.2 ft (Table 8). This means that the full removal will further reduce the flood risk in the vicinity of the dam.

Table 9. Dam 6 Comparison of Existing and Proposed Conditions at the 100-Year Flood

Condition	100-yr WSE upstream of Dam (ft NAVD 88)	Difference (ft)
Existing Conditions	91.4	-
Full Removal	88.4	3.0
Partial Removal	89.2	2.2

Just like at Dam 4, Dam 6 would also have public access risks that vary between partial and full-width removals. For the partial removal, more of the spillway will remain in place, but be dewatered and dried out (due to upstream water surface elevations being lowered). The public could want to walk on the remaining parts of the dam, which could potentially lead to loss of life or injury due to fall hazards or diving into shallow water from this structure. The risk can be mitigated by adding in fencing and signage, but risks will still be present as there is no way to permanently remove access to the dam in a partial removal scenario and any fencing could reasonably be anticipated to be damaged in any substantial flooding. The full removal will have less of the dam remaining and the abutments can be more closely graded into the shoreline, thereby reducing this risk.

The full removal shows more of a long-term benefit compared to the partial width removal. While it would be more costly and have greater historic resource impacts; fish passage, flooding, and public safety would be all improved by a full removal. Thus, Kleinschmidt recommends a full removal at the Dam 6 site, given the design objectives for this project.

6.0 REFERENCES

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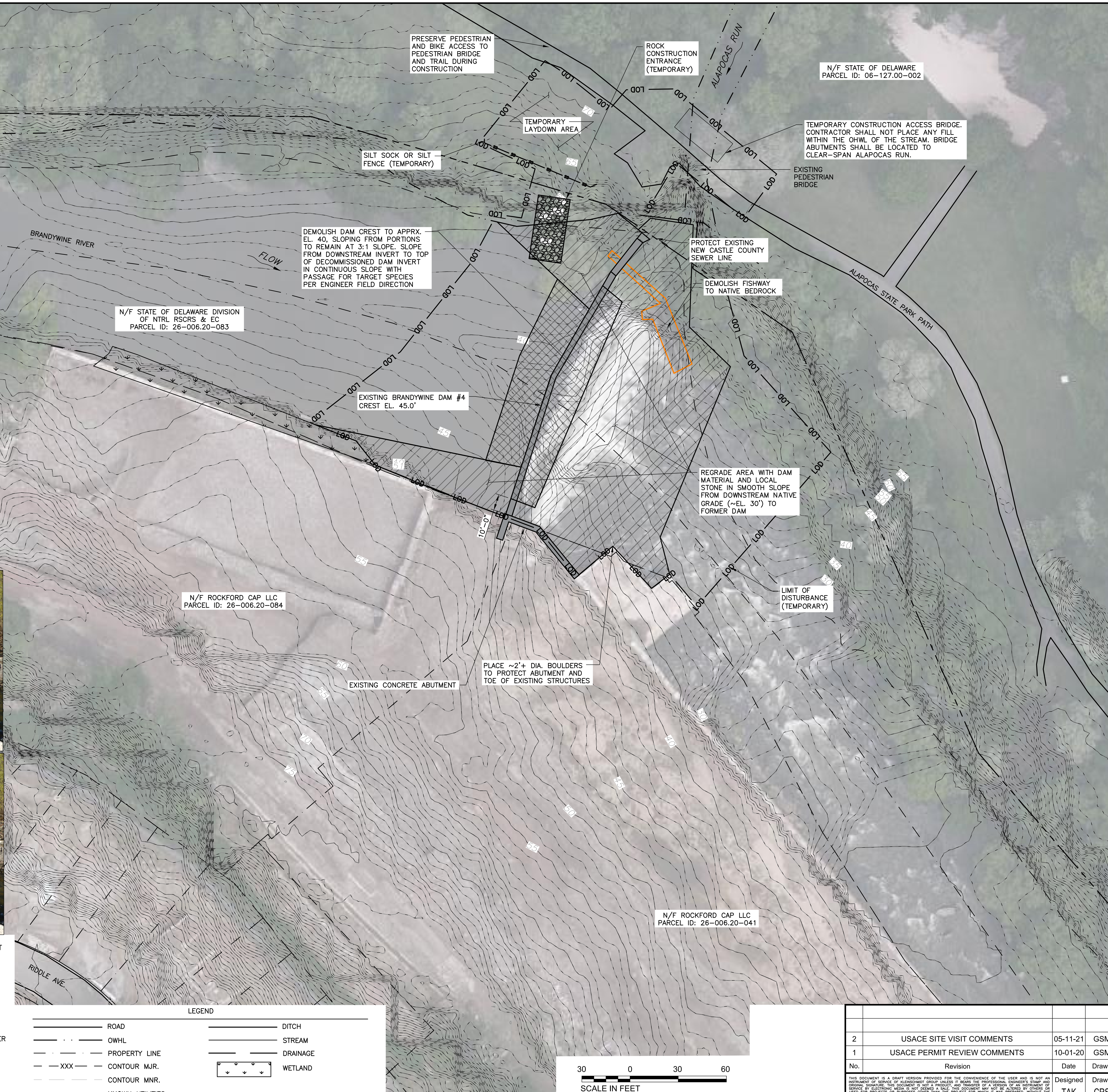
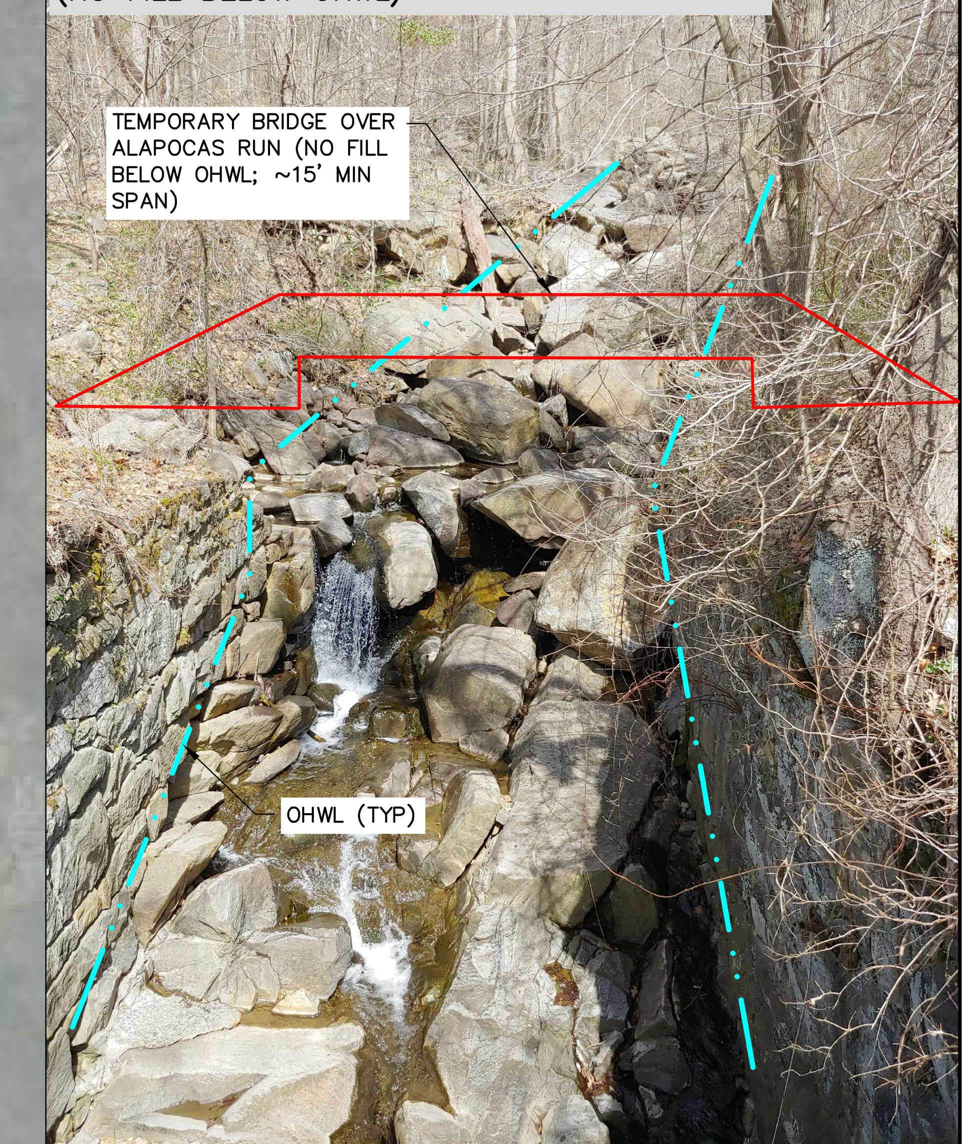
Wilson, Xerxes. 2017. Delaware Oks rare land swap of historic mill property. Published in The News Journal, shared on Delaware Online. March 23, 2017. https://www.delawareonline.com/story/news/2017/03/23/delaware-oks-rare-land-swap-historic-property/99545372/.

APPENDIX A

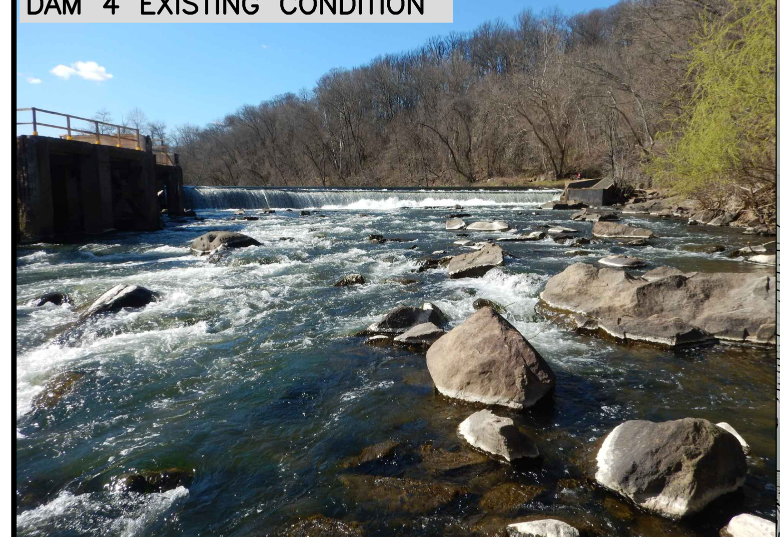
BRANDYWINE DAM 4: FULL DAM REMOVAL DESIGN



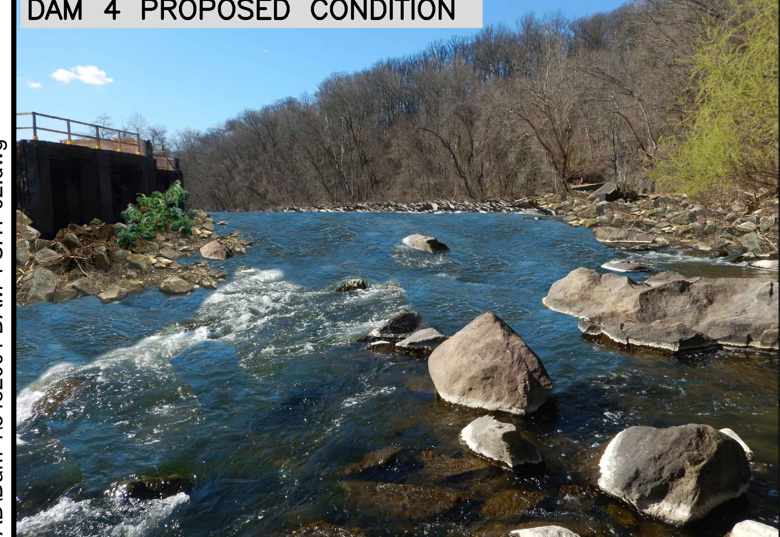
SECTION AT ALAPOCAS RUN TEMPORARY BRIDGE (NO FILL BELOW OHWL)



DAM 4 EXISTING CONDITION



DAM 4 PROPOSED CONDITION



PROPOSED CONSTRUCTION SEQUENCE:

1. INSTALL EROSION AND SEDIMENT CONTROLS AND DEFINE LIMIT OF DISTURBANCE.
2. PROTECT AND MARK OUT PORTIONS OF DAM AND SITE TO REMAIN FOR HISTORICAL PURPOSES OR ABUTTING OWNER'S REQUIREMENTS.
3. REMOVE AND RESHAPE DAM IN ACCORDANCE WITH PROJECT DRAWINGS AND PER ENGINEER FIELD DIRECTION.
4. REMOVE ANY TRASH ENCOUNTERED DURING DAM REMOVAL.
5. OBSERVE SEDIMENT FLUSHING AND INFORM PROJECT ENGINEER IF CONDITIONS DEVIATE FROM ANTICIPATED CONDITIONS.
6. ENGINEER TO VERIFY DAM REMOVAL AND RESHAPING ARE ADEQUATE TO PROVIDE FISH PASSAGE.
7. RESTORE UPLAND PORTION OF SITE TO PRE-CONSTRUCTION CONDITIONS.

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LEGEND

———	ROAD	———	DITCH
— · · —	OWHL	———	STREAM
— · —	PROPERTY LINE	———	DRAINAGE
— XXX —	CONTOUR MJR.		WETLAND
— — —	CONTOUR MNR.		
— — —	KNOWN UTILITIES		

NOTES:

1. TOPOGRAPHY FROM USGS NATIONAL MAP 3DEP ELEVATION PROGRAM, ORIGINAL SOURCE NOAA, DOWNLOADED ON MARCH 31, 2020, WITH 1 SQUARE METER RESOLUTION.
2. BATHYMETRY INTERPOLATED FROM FEMA HEC-RAS MODEL CROSS SECTIONS RECEIVED FROM THE UNIVERSITY OF DELAWARE IN MARCH 2020. HYDRAULIC CALCULATIONS FOR THIS DESIGN COMPLETED BY DR. GERALD KAUFFMAN, P.E. (UNIVERSITY OF DELAWARE). CONTRACTOR SHALL VERIFY GRADES (BATHYMETRIC AND UPLAND) PRIOR TO CONSTRUCTION AND NOTIFY THE ENGINEER OF ANY DISCREPANCIES.
3. ALL ELEVATIONS IN NAVD88 DATUM.
4. UTILITIES LOCATED BASED ON GIS DATA PROVIDED BY NEW CASTLE COUNTY DELAWARE SEWER DEPARTMENT. WETLANDS WERE DELINEATED BY KLEINSCHMIDT. ADDITIONAL INFRASTRUCTURE HAS BEEN DIGITIZED FROM PUBLICLY AVAILABLE AERIAL PHOTOGRAPHY. ADDITIONAL FIELD SURVEY WILL BE REQUIRED TO CONFIRM LOCATIONS PRIOR TO CONSTRUCTION.
5. EXTRA DAM MATERIAL NOT USED FOR ON-SITE REGRADING AREAS SHALL BE DISPOSED OF AT AN APPROVED OFF-SITE LOCATION. NO ADDITIONAL/NEW FILL SHALL BE LEFT IN THE RIVER.
6. MANMADE MATERIAL (TIMBERS, CONCRETE, TRASH, ETC.) SHALL BE REMOVED FROM THE SITE TO THE EXTENT FEASIBLE. ANY CONCRETE RE-USED ON SITE SHALL HAVE ALL EXPOSED REINFORCING METAL REMOVED.
7. ALL TEMPORARY FILL PLACED BELOW THE WATERLINE SHALL BE REMOVED PRIOR TO CONTRACTOR COMMENCING SITE STABILIZATION.
8. REPLANT UPLAND PORTIONS OF SITE TO PRE-CONSTRUCTION CONDITION, INCLUDING GRASS ESTABLISHMENT AND REPLANTING NATIVE SHRUBS AND TREES IN AREAS THAT WERE FORESTED PRIOR TO CONSTRUCTION (PLANT AT 10' O.C.)
9. BEDROCK REMOVAL IS NOT ANTICIPATED, BUT MAY BE REQUIRED BASED UPON FIELD DIRECTION BY ENGINEER.
10. UPLAND WORK SHALL BE PERFORMED IN ACCORDANCE WITH THE DELAWARE EROSION & SEDIMENT CONTROL HANDBOOK, MOST RECENT EDITION.

PRELIMINARY DESIGN

NOT FOR CONSTRUCTION

BRANDYWINE SHAD 2020
WILMINGTON, DE

DAM 4 REMOVAL

BRANDYWINE DAM #4 PLAN
OVERALL PROPOSED CONDITIONS

No.	Revision	Date	Drawn	Checked
2	USACE SITE VISIT COMMENTS	05-11-21	GSM	TAK
1	USACE PERMIT REVIEW COMMENTS	10-01-20	GSM	TAK

Designed	Drawn	Checked	Project No.	Date Revised	Drawing No.
TAK	CRS	TAK	3452001	05-26-20	D4-02

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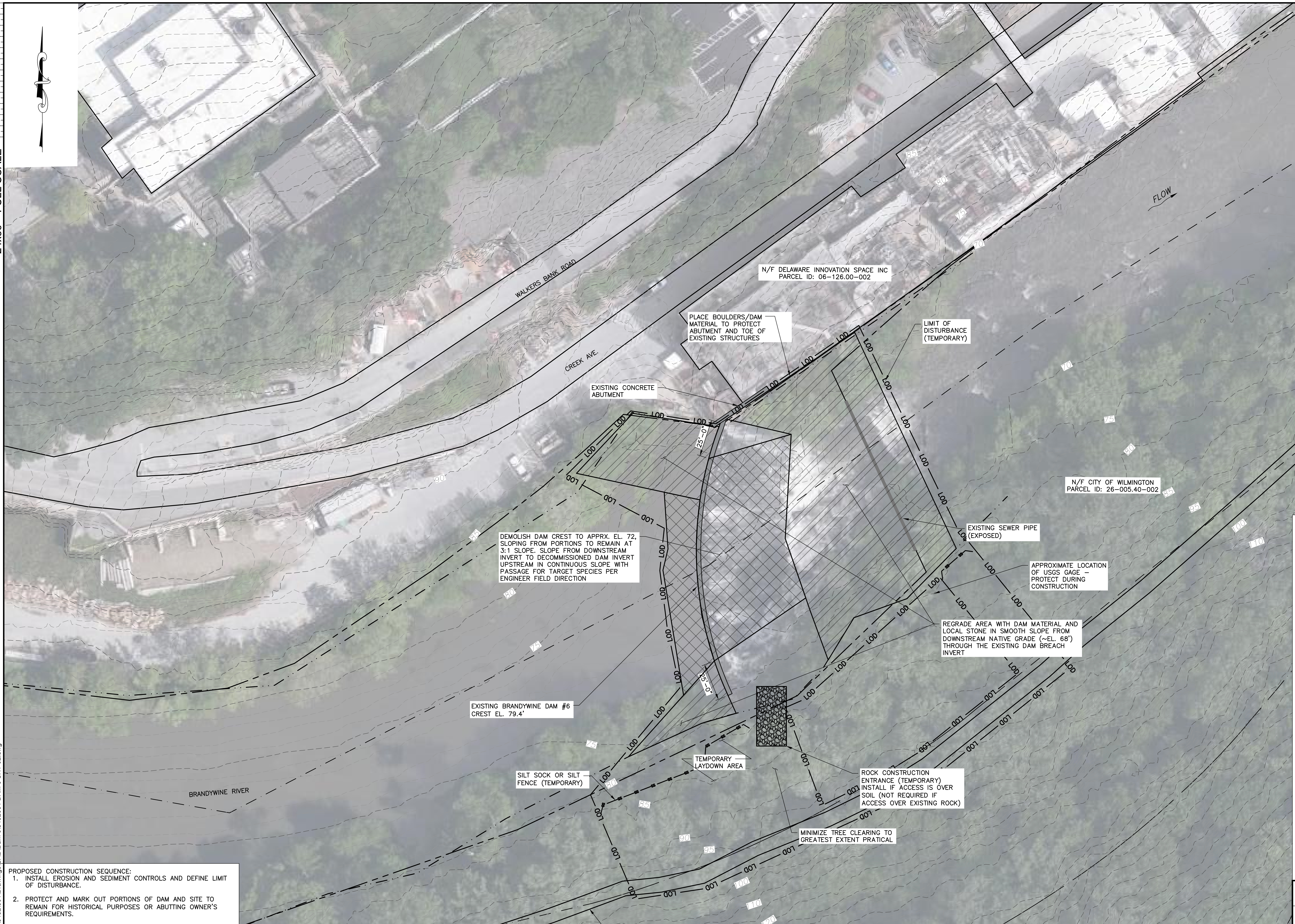
APPENDIX B

Brandywine Dam 6: Full Dam Removal Design



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LEGEND

ROAD	DITCH
OHWL	STREAM
PROPERTY LINE	DRAINAGE
CONTOUR MJR.	WETLAND
CONTOUR MNR.	
KNOWN UTILITIES	

30 0 30 60
SCALE IN FEET

No.	Revision	Date	Drawn	Checked
2	USACE SITE VISIT COMMENTS	05-11-21	GSM	TAK
1	USACE PERMIT REVIEW COMMENTS	10-01-20	GSM	TAK

Designed	Drawn	Checked	Project No.	Date Revised	Drawing No.
TAK	CRS	TAK	3452001	05-26-20	D6-02

BRANDYWINE SHAD 2020
WILMINGTON, DE

DAM 6 REMOVAL

BRANDYWINE DAM #6 PLAN
OVERALL PROPOSED CONDITIONS

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