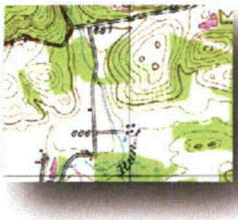
Bell Bend Nuclear Power Plant
Stream and Wetland Mitigation Design Report
Walker Run Site

Salem Township, Luzerne County, PA



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Rev 0, November 2010

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1 Introduction

The proposed stream and floodplain restoration includes approximately 3,440 linear feet of Walker Run located on the Bell Bend Nuclear Power Plant (BBNPP) development site, which is owned by PPL in Salem Township, Luzerne County, Pennsylvania (*see Figure 1-1*). The purpose of the project is to provide mitigation for proposed stream and wetland impacts associated with the BBNPP development. The proposed stream and wetland mitigation plan for the Walker Run site utilizes natural stream channel design (NSCD) techniques, which are consistent with the Keystone Stream Team's Guidelines for Natural Stream Channel Design for Pennsylvania Waterways, March 2007, to improve channel stability, water quality, and aquatic habitat along the project reach and to restore the functionality of the floodplain. The proposed design includes approximately 4,774 linear feet of restored stream channel, approximately 5.5 acres of enhanced wetlands, and approximately 8 acres of created wetlands creation.

As part of the restoration design effort, LandStudies completed a preliminary visual assessment and a detailed geomorphic assessment of Walker Run watershed to better understand the existing hydrology, hydraulics, and stream morphology of the project reach. The assessment also included a historic investigation of the watershed, which identified how past impacts to the stream/floodplain have influenced the current degradation and instability observed along the project reach. Understanding the causes of this instability is crucial for developing an effective solution/design. The proposed design was developed using information provided by the detailed geomorphic assessment of the Walker Run watershed as well as data collected at assessment reach locations within similar watersheds that exhibited signs of stability. This design report presents the design methodology and summarizes design calculations involved with the proposed restoration of Walker Run. The specific design objectives include:

1) Create a stable system using the principles of fluvial geomorphology to improve channel stability along the Walker Run Project Reach;
2) Create varying in-stream conditions that are ideal for both trout habitat and spawning.
3) Improve water quality by reducing bank erosion and by creating a vegetated floodplain with elevations closer to the seasonal water table that may store and treat surface runoff;
4) Provide flood flow storage and infiltration opportunities in the restored floodplain;
5) Improve aquatic and riparian habitat;
6) Reduce non-point source pollution, including sediment, nutrient and thermal pollution;
7) Provide a floodway that reduces the current flood flow elevations

These objectives have been achieved through the following tasks:

1) Analysis of the existing stream channel system and watershed and assessment of the influence of historical impacts on the current state of stream stability;
2) Obtaining and analyzing morphological data to characterize bankfull and flood flow conditions, determining boundary and critical shear stress limits, collecting sediment characteristics data including riffle particle texture and distribution, and computing stream morphological classifications; and
3) Development of a restoration design that integrates geomorphologic and hydraulic/sediment transport concepts to provide a stable channel and floodplain that enhances the riparian corridor.

The Walker Run project reach consists of two separate segments including: 1) Site A – beginning at the Beach Grove Road bridge and ending at the north Market Street bridge; and 2) Site B – beginning at the north Market Street bridge and ending near the existing treeline approximately 300 feet downstream from the existing farm pond on the BBNPP development site. Proposed design parameters were developed to accommodate existing valley characteristics at each site and to create varying in-stream conditions that favor both trout spawning (Site A) and trout habitat (Site B).

LEGEND

Existing Project Reach (Approximate)

Walker Run Site Boundary (Approximate)

FIGURE 1-1. PROJECT LOCATION MAP

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2 Physiographic Region, Hydrology, Geology, Sediment Supply and Existing Land Use

2.1 Physiographic Region

The project site is part of the Susquehanna Lowland Section of the Ridge and Valley physiographic province (*see Figure 2-1*), which is characterized by a distinctive series of linear ridges and valleys that are the result of differential erosion of folded sedimentary rocks with varying degrees of resistance to weathering and erosion. Valleys are composed of less resistant rocks such as limestone and shale, whereas ridges and uplands are composed of more resistant rocks, particularly sandstone and siltstone. The Susquehanna River has incised into and crosses these ridges as it flows generally from north to south, and its numerous tributaries form a trellis drainage network pattern as they flow along the valleys underlain by less resistant rocks.

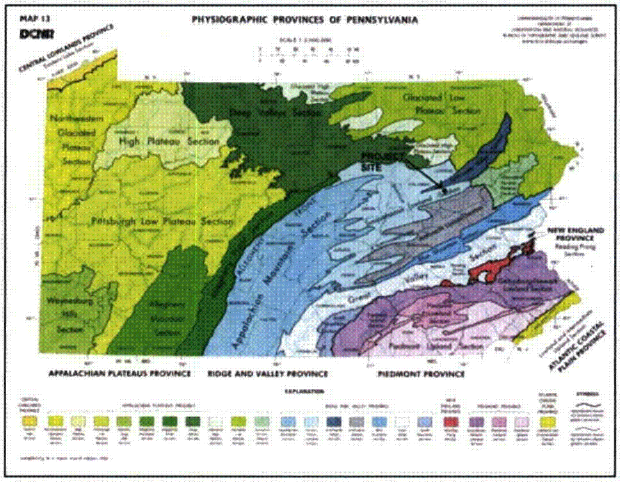
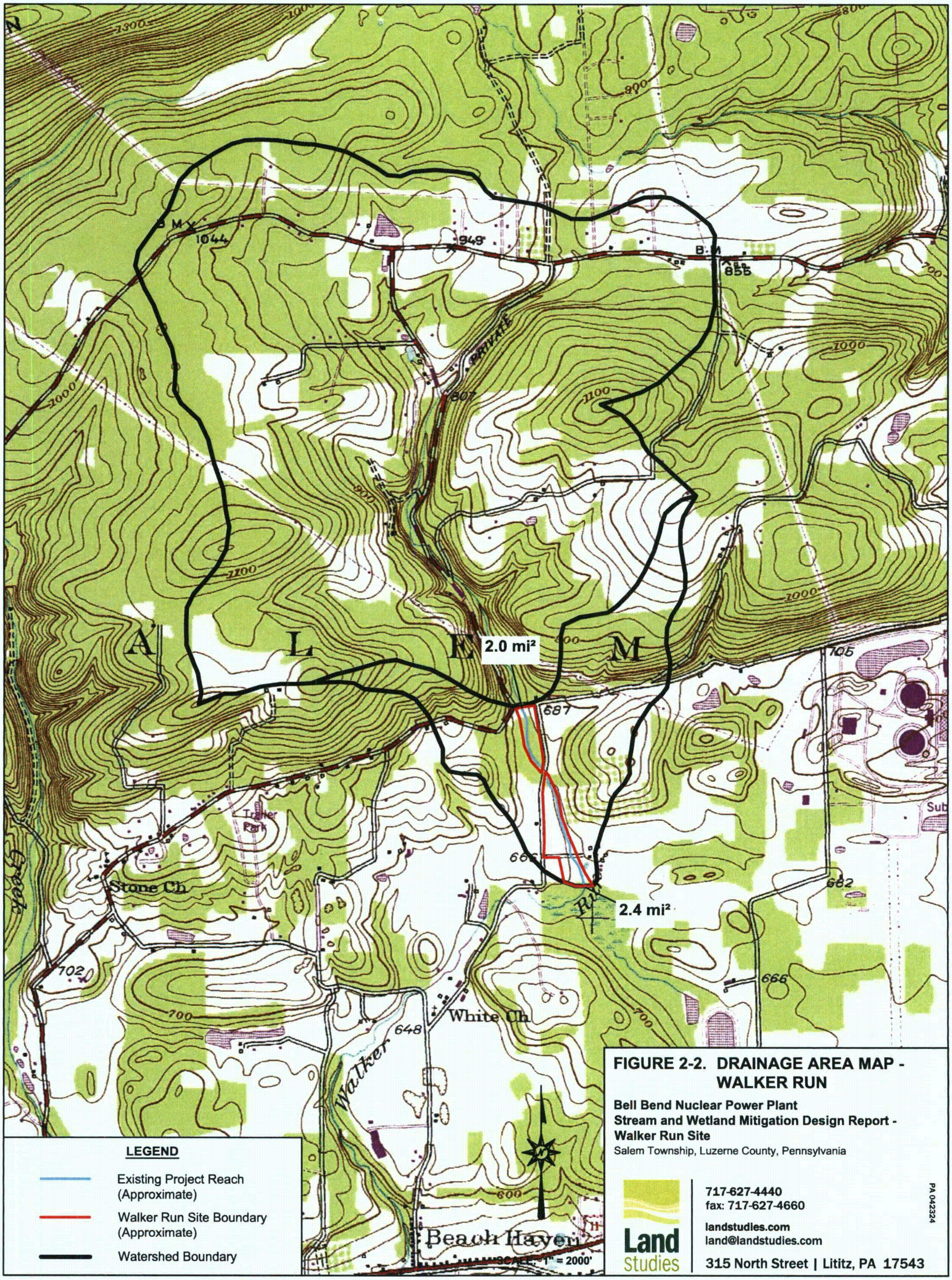


Figure 2-1. Physiographic Provinces Map of Pennsylvania

2.2 Hydrology

Walker Run is a perennial stream that flows into the North Branch Susquehanna River approximately 2 miles downstream from the project reach. The North Branch Susquehanna River confluences with the West Branch Susquehanna River near Sunbury, Pennsylvania to form the main branch of the Susquehanna River, which ultimately flows into the Chesapeake Bay. Multiple springs, rainfall, and snowmelt influence the stream flow of the project reach. Bankfull and higher flows may occur as a result of a variety of rain events, including rain or snow, frontal storm events, and occasional tropical storms. The project reach also receives stormwater runoff from some impervious surfaces adjacent to the project area. The drainage area to the upstream limit of the project reach is approximately 2.0 square miles. The drainage area to the downstream limit of the project reach is approximately 2.4 square miles (*see Figure 2-2*). Walker Run is listed as a Cold Water Fishery (CWF) and Migratory Fishes (MF) stream by the PADEP Water Quality Standards (25 Pa. Code Chapter 93, Drainage List K (25 § 93.9k)) and currently supports reproducing brown trout populations; therefore all wetlands that are hydrologically connected to Walker Run are considered to be exceptional value wetlands.



LEGEND

🟦	Existing Project Reach (Approximate)
🟥	Walker Run Site Boundary (Approximate)
⬛	Watershed Boundary

FIGURE 2-2. DRAINAGE AREA MAP - WALKER RUN

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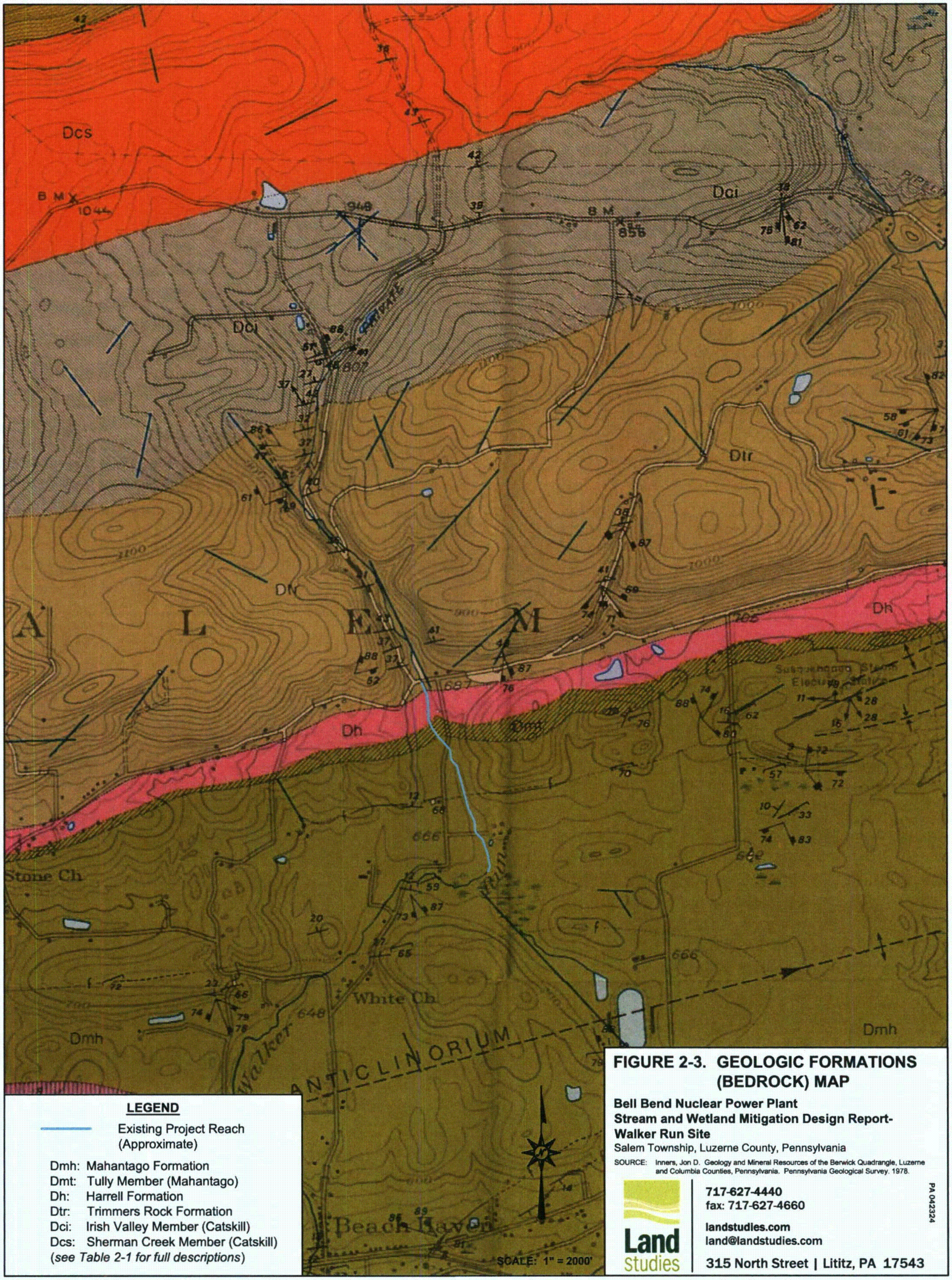
2.3 Geology and Sediment Supply

The underlying bedrock of the Walker Run project reach watershed consists of five distinct geologic formations that are composed of Devonian-age sedimentary rocks including various types of sandstone, siltstone, shale, and claystone (*see Figure 2-3*). These formations trend generally in a northeast to southwest direction from southern Luzerne County towards Harrisburg. Also, there are five Quaternary-age surficial geologic formations that exist throughout the watershed (*see Figure 2-4*), which were deposited more recently as a result of glacial and fluvio-glacial activity. *Table 2-1* briefly describes both bedrock and surficial geologic formations. Bed materials within the Walker Run may be derived from any of these formations as well as any fine-grained sediment that have accumulated in the valley bottoms as a result of more recent human influences such as clear-cutting, dams, and farming.

During the past 2 million years (approximate), the landscape has been modified by cyclical erosion and deposition associated with advancing and retreating ice sheets, up to several kilometers thick in places, which flowed southward from the northern polar regions. The most recent ice advance, known as the Wisconsinan, occurred about 45,000 to 15,000 years ago. The most recent part of this advance is referred to in this region as the Woodfordian, which is responsible for creating the most prominent glacial features in the Walker Run watershed and the surrounding region. These features include a northwest-southeast trending Woodfordian terminal moraine complex that consists of boulder, poorly sorted sediment, and Woodfordian glaciofluvial (including kame) terraces along the Susquehanna River that consist of stratified sands and gravels. "Kame terraces are frequently found along the side of a glacial valley and are the deposits of meltwater streams flowing between the ice and the adjacent valley side. These kame terraces tend to look like long flat benches, with a lot of pits on the surface made by kettles. They tend to slope down-valley with gradients similar to the glacier surface along which they formed, and can sometimes be found paired on opposite sides of a valley" (definition provided by www.wikipedia.org). The terminal (end) and ground moraines deposited at the front of and beneath the ice sheet, respectively, are much coarser than the outwash sediments, and also are marked by kettles. Kettles are depressions on the ground surface that resulted from melting of ice blocks within the glacial deposits during deglaciation. After deglaciation, which ended approximately 10,000 yrs ago, the landscape of the Walker Run watershed was mantled with fresh glacial and near-glacial deposits, which consisted of kame terrace sediments that were deposited along the sides of river valleys adjacent to ice margins, and of various types of till and outwash that formed at the leading edge of the Woodfordian ice sheet. Drainage was poor as a result of the near-glacial and glacial deposits, which typically consist of sediment that ranges from clay- to boulder-size, and resulted in widespread swampy conditions as streams adjusted to deglacial conditions.



LEGEND

Existing Project Reach (Approximate)

Dmh: Mahantago Formation
Dmt: Tully Member (Mahantago)
Dh: Harrell Formation
Dtr: Trimmers Rock Formation
Dci: Irish Valley Member (Catskill)
Dcs: Sherman Creek Member (Catskill)
(see Table 2-1 for full descriptions)

FIGURE 2-3. GEOLOGIC FORMATIONS (BEDROCK) MAP

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SOURCE: Inners, Jon D. Geology and Mineral Resources of the Berwick Quadrangle, Luzerne and Columbia Counties, Pennsylvania. Pennsylvania Geological Survey. 1978.

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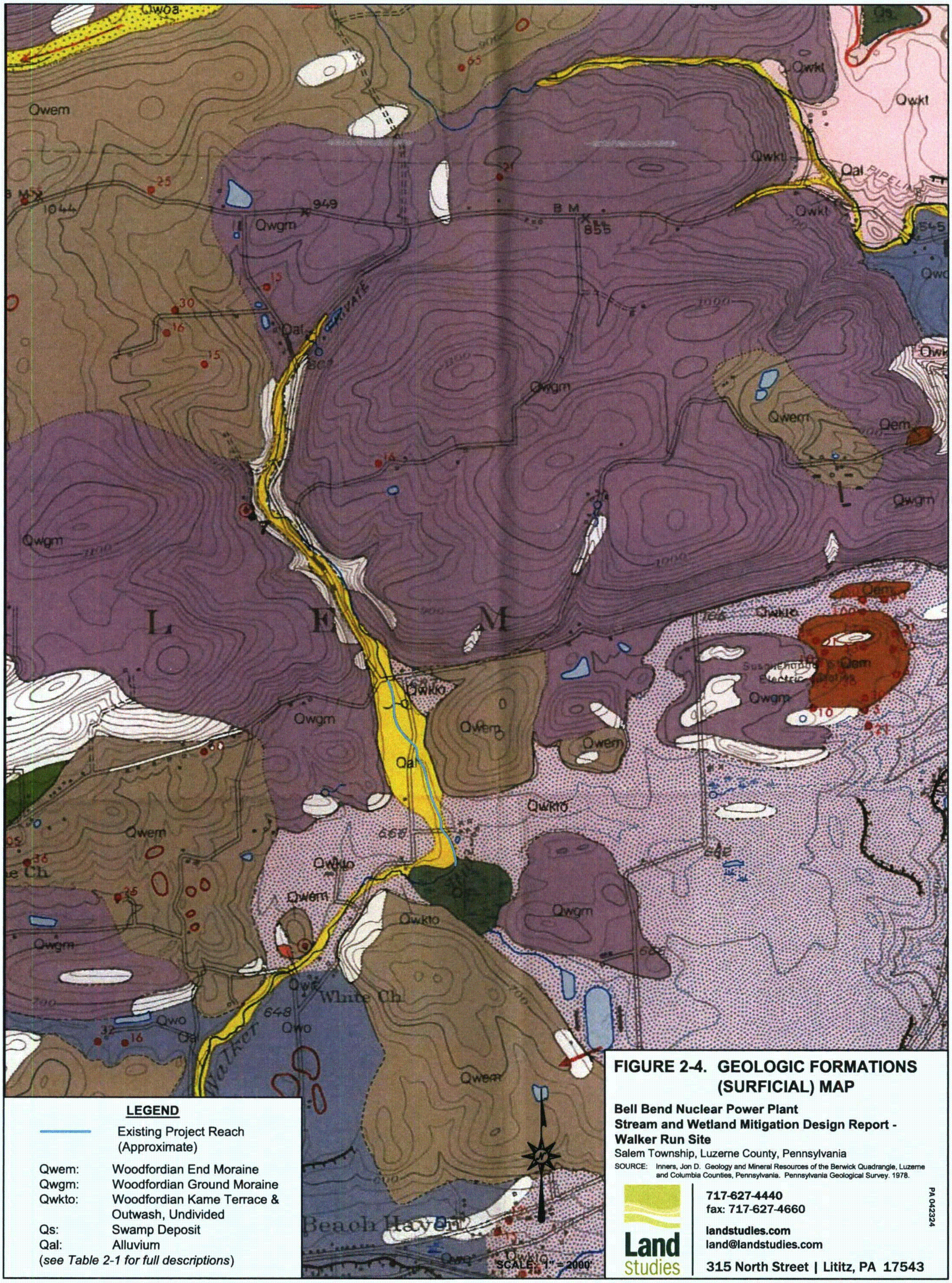

LEGEND

━ Existing Project Reach (Approximate)

Qwem: Woodfordian End Moraine
Qwgm: Woodfordian Ground Moraine
Qwkto: Woodfordian Kame Terrace & Outwash, Undivided
Qs: Swamp Deposit
Qal: Alluvium
(see Table 2-1 for full descriptions)

FIGURE 2-4. GEOLOGIC FORMATIONS (SURFICIAL) MAP

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	Formation Name	Abbrev.	Age	Description
Bedrock Formations	Mahantago Formation (includes Tully Member)	Dmh Dmt (Tully)	Devonian (360-408 million yrs.)	Dark-gray silty claystone (95%) with some argillaceous, fine-grained limestone (5%) in uppermost part.
	Harrell Formation	Dh	Devonian (360-408 million yrs.)	Dark-gray to grayish-black clay shale and silty clay shale.
	Trimmers Rock Formation	Dtr	Devonian (360-408 million yrs.)	Dark-gray, fine-grained sandstone (25%), dark-gray siltstone and silt shale (60%), and dark-gray silty clay shale (15%).
	Irish Valley Member (Catskill Formation)	Dci	Devonian (360-408 million yrs.)	Grayish, fine-grained sandstone (30%), greenish-gray and grayish-red siltstone (20%), grayish-red silty claystone (30%), and greenish-gray silty clay shale (20%).
	Sherman Creek Member (Catskill Formation)	Dcs	Devonian (360-408 million yrs.)	Greenish-gray and grayish-red fine- to medium-grained sandstone (50%) and grayish-red siltstone and silty claystone (50%).
Surficial Formations	Woodfordian End Moraine	Qwem	Pleistocene (10,000 yrs.–1.6 million yrs.)	Till (unsorted mixture of clay, silt, sand, gravel, cobbles, and boulders); well-developed depositional topography; surface is hummocky with many closed depressions (kettles); up to 100' thickness.
	Woodfordian Ground Moraine	Qwgm	Pleistocene (10,000 yrs.–1.6 million yrs.)	Till (unsorted mixture of clay, silt, sand, and gravel, with many cobbles and boulders); vague depositional topography; 10-15' average thickness.
	Woodfordian Kame Terrace and Outwash, Undivided	Qwkto	Pleistocene (10,000 yrs.–1.6 million yrs.)	Predominantly sand, gravel, and cobbles with some boulders; kame terrace and outwash deposits are undifferentiated; thickness ranges is 10-100'.
	Swamp Deposit	Qs	Holocene (present–10,000 yrs.)	Organic silty clay with some peat; water-saturated; surface of deposits flat to slightly hummocky; thickness unknown; located in undrained or poorly drained depressions in glaciated terrain.
	Alluvium	Qal	Holocene (present–10,000 yrs.)	Mostly sand, silt, and gravel, with some cobbles and boulders; typically less than 6' thick in tributary valleys.

Table 2-1. Bedrock and surficial geologic formations located within the Walker Run watershed.

2.4 Existing Land Use

The project reach is located entirely within the proposed BBNPP development site owned by PPL. The valley bottom consists of mostly agricultural fields (both active and fallow) with some forested areas at the upstream portion of the project reach. Dominant land cover on the existing side slopes includes forest, scrub-shrub, open meadow, and agricultural fields. A road (Market Street) and some small residential homes are adjacent to the west boundary of the project area. The Walker Run restoration site will be left as a natural open space area after construction.

3 Historical Land Use and Potential Sources of Stream Instability

3.1 Pre-Settlement Conditions

Before European settlers arrived in the Middle Atlantic Region of the United States, the landscape was dominated by forests of mixed hardwoods, conifers, and a variety of woody and herbaceous flora, from mountain peaks down to the valleys and streams and rivers. The characteristics of pre-settlement soils suggest that the valley bottoms were broad, forested wetlands with small, shallow and anabranching and chain-of-pool streams that experienced frequent overbank flow (Walter and Merritts, 2008). These conclusions are consistent with accounts by early explorers that found swampy meadows and marshes, fed by springs at the base of valley side-slopes (Kalm, 1987). In stream and river valleys, floodplains were wide and fairly flat. Floodplain soils were thin, peaty, and loamy – rich with organic material and highly porous, allowing abundant infiltration of surface water, which then percolated down to groundwater supplies. In these valleys, groundwater flowed near the floodplain surface, contributing to the base flow of the streams. The floodplain surface typically rose only slightly above the stream channel base flow water surface elevation. The typical pre-settlement scenario, then, looked something like the conditions shown in *Figure 3-1* – relatively narrow stream channels meandering through the lower elevations of the valleys.

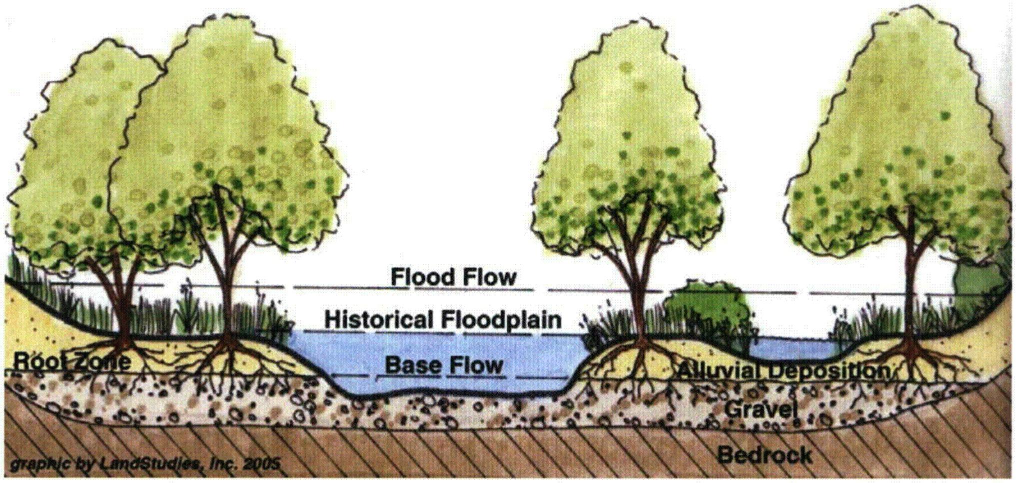


Figure 3-1. Stable, pre-settlement stream and floodplain systems were characterized by: a low floodplain in close contact with surface water in the stream channel, allowing for frequent inundation of the floodplain during high flows; riparian vegetation with root zones in contact with ground water that enabled groundwater denitrification through root uptake; and a channel bed composed of cobble and gravel, which helped protect the bed from erosive flow forces.

Channel flows intersected with groundwater during times of high base flows and recharged groundwater during drought or normal base flow conditions. Low, frequently inundated floodplains consisted of porous, well-vegetated soils. Root systems throughout the floodplain reached down to the groundwater and streambed elevations, the root zone providing a large surface area for pollutant removal from groundwater and surface water. Floodplains also served as a major recharge area for surface flow because of their porous material that held and gradually infiltrated flood flows from the channel as well as overland flows.

This scenario is nature's design for a fully functioning stream system that holds its stability while helping control storm flow and purifying water supplies. The constant interaction among the various components – surface water, groundwater, soil, and vegetation – is what is required to allow a stream channel, its floodplain, and the attendant wetland pockets to provide the benefits of a fully functional system. And this is how stream channels and floodplains in the Walker Run watershed probably looked like and functioned before European settlers arrived and began to alter the landscape.

3.2 Early Historical Impacts

The Walker Run watershed exhibits effects of colonial and post-colonial (early 1700s to 1930s) land-use practices that are commonly found throughout the Eastern United States. Wholesale land clearing and poor farming practices led to widespread erosion of uplands and massive deposition of soils in the stream valleys (Caverns 1925, Costa 1975, Jacobson and Coleman 1986) (*see Figure 3-2*).

Figure 3-2. Indiscriminate land clearing caused massive erosion from hillsides.

Stream channel beds and floodplains, including tributaries, grew artificially high, perched on the fine-grained eroded materials. Elevated channel beds and floodplains were no longer closely connected to groundwater supplies; therefore, flows were composed predominantly of surface water runoff, with temperatures far exceeding that of the groundwater. Over time, the channels vertically degraded through the accumulation of fine-grained sediments leaving abandoned floodplain terraces with elevations well above the channel bed. Additionally, to make it easier for farming and/or other human activities, meandering stream channels were moved from the lowest elevations in the valley centers to the higher elevations at valley edges, and in the process were typically straightened. It was common Vegetation changed because of the disconnection of the newly elevated floodplain in relation to the elevation of the stream channel. Wetland systems were created not because of their proximity to groundwater but because they sat on dense, fine, nearly impervious sediments perched high above the streambed and groundwater. No longer could those wetland plants extend their root systems into the groundwater to remove the nitrogen compounds.

As a result, many floodplains in the Eastern United States do not actually function as floodplains are intended to in stable, natural channel environments. Rather, these current surfaces are at elevations that are too high above the stream's ordinary high water mark to provide effective and frequent flood-flow conveyance and attenuation. Streams are typically deeply incised, or entrenched, with high vertical streambanks composed of fine-grained, easily-erodible sediments (*see Figure 3-3*).

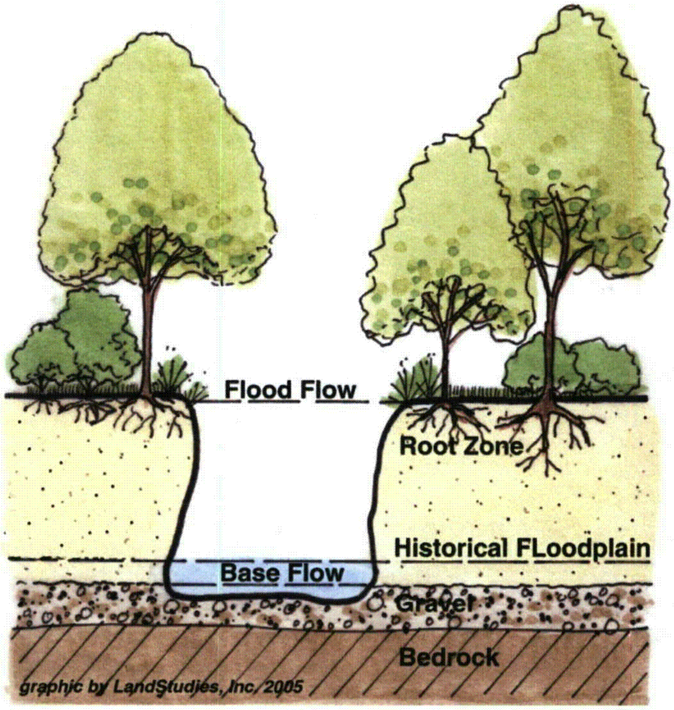


Figure 3-3. Stream channels are eroding or have eroded down through post-settlement sediments, leaving their alluvial floodplains high above the current base flow water elevation, and disconnecting riparian root systems from groundwater flows. The processes of frequent floodplain inundation, relieving in-channel stresses; groundwater infiltration through porous floodplain material; and nitrogen removal from groundwater through root systems are lost under these conditions that are prevalent today throughout the northeast United States.

Most high flows are contained within the channel, which creates high shear stresses along the bed and banks and subsequently, high bank erosion rates. As a result of this channel instability, large accumulations of fine-grained sediment are introduced into the stream channel during high flow events, which lowers water quality and, in turn, negatively affects the existing aquatic habitat.

3.3 Existing Conditions

In many cases, the causes of channel instability are directed related to past human impacts such as clear-cutting, poor farming practices, construction of mill dams/ponds, ditching or channelization, and road or railroad development. In the case of Walker Run, several of these impacts may have influenced the present instability along the project reach. However, it is likely that the most significant influence was the relocation of the channel to man-made ditches along the edges of the valley to improve farming accessibility and/or to increase farmable acreage. As a result, the channel is disconnected from its floodplain and bank failure is common during high flows. As the stream migrates laterally, gravel imbedded in the banks is displaced and deposited locally forming point bars along the opposite banks from the degrading cut banks or mid-channel bars in the stream. The point bars become vegetated because they are low enough in elevation to convey flood flows without degrading. This process would continue until the stream channel has eroded enough sediment to create a low-lying wide stable floodplain. However, until this stability is achieved, the eroded fine-grained sediments will continue to be washed into the stream and pollute the downstream watershed.

To better understand the soil stratigraphy and surficial deposits of the project site, trenches were excavated perpendicular to the stream channel to depths up to 6 feet. While the trenches were open, a soil stratigraphy analysis and geomorphic investigation was performed by Dr. Dorothy Merritts of Franklin & Marshall College. During the field analysis, a series of elevations were surveyed including the ground surface, the bottom of the historic sediments (post-settlement deposition beginning in early 1700's), and the top of the pre-settlement gravelly bed material. Based on these field measurements, it is estimated that approximately 1-4 feet of historic sediments exist along the floodplain of the project reach (*refer to Geomorphic Assessment of Sediment and Soils along Walker Run, Berwick in Appendix A*). Based on the results of this analysis, the existing bed elevations of the project reach are lower than the top of the pre-settlement gravels, which indicates that the present stream channel either downcut or was artificially ditched to elevations well below the bottom of historic deposits and into unsorted glacial deposits and post-glacial alluvium. The glacial and post-glacial deposits vary dramatically in size from sandy clays to boulders. The geomorphic assessment of the soil stratigraphy is important for the restoration design because the proposed bed elevations of the project reach were correlated to the pre-settlement stream bed elevations.

4 Visual Assessment of Watershed and Project Reach.

A visual assessment of the project reach and the surrounding watershed was performed between winter/spring 2009 and provides information for this report regarding the in-channel stream morphology for Walker Run. The visual assessment of Walker Run has been divided into three "visual assessment" reaches consisting of: 1) the Base Level Control Reach; 2) the Project Reach; and 3) the Supply Reach. The base level control reach is located immediately downstream from the end of the project reach and includes any natural or man-made features that currently affect the flow regime of the project reach and/or provide an artificial or natural grade control, which would maintain the existing stream bed elevation through the project reach. The project reach includes a segment of Walker Run beginning at Beach Grove Road and ending approximately 3,700 feet downstream. The supply reach is located upstream of the project reach and under current conditions contributes to the sediment load that is being transported downstream into the project reach. Each visual assessment reach is described below in a downstream to upstream direction.

4.1 Downstream Base Level Control Reach

The base level control reach (hereafter BLCR) includes approximately 1,400 feet between the south Market Street bridge crossing and the downstream limit of the proposed restoration project site. The bridge crossing at Market Street is an open-bottomed stone arch bridge culvert (*see Figure 4-1*). Even though this bridge crossing does not appear to provide any natural or artificial grade control, it identifies the lower end of the base level control assessment. At the bridge, there appears to be some level of scour that has occurred as a result of higher flow events; however, there are no visible head-cuts downstream of the Market Street bridge that would affect the base level elevation of the streambed within the BLCR. The BLCR is slightly incised, or entrenched, which means there is a disconnection between the channel and its floodplain, from Market Street to an existing 36-inch pipe culvert crossing along a farm access road approximately 860 feet upstream (*see Figure 4-2*). With no obvious downstream base level control, it would be expected that the stream channel is only beginning to vertically degrade and lose its connection with its floodplain as it becomes more entrenched. However, the bed is composed of larger-sized (large gravel and cobble) substrate throughout this segment, which is helping to sustain current bed elevations and reducing the potential for future bed degradation.

Figure 4-1. View of the south Market Street bridge crossing (facing downstream).

Figure 4-2. Typical conditions upstream of the south Market Street bridge showing moderately entrenched stream with minor bank erosion.

Approximately 800 feet upstream from Market Street is a 36-inch corrugated metal pipe culvert crossing, which conveys the base level flow of Walker Run under an existing farm access road (*see Figure 4-3*). It was determined that this culvert is the primary base level control for the project reach. The farm access road is at elevation higher than the existing floodplain, which obstructs flood flows. Flood flows that do not exceed the elevation of the road are forced through the undersized pipe culvert. This obstruction slows the velocities of flood flows and creates a backwater condition upstream that causes sediment to deposit within the channel.

Figure 4-3. View of the culvert crossing along an existing farm access road, which provides the primary upstream base level control. This control structure prevents long-term vertical bed degradation upstream because of the fixed bed elevation of the culvert.

Upstream of the culvert crossing, Walker Run is more significantly entrenched and incised. The stream flows through a mature forest for approximately 850 feet between the farm access road and the existing tree-line near the downstream limit of the project reach. It appears that this forested segment of the BLCR has degraded vertically to match the invert elevation of the 36-inch pipe culvert located downstream. The channel is relatively straight and over-wide with a bed substrate dominated by very dense sandy clay (*see Figure 4-4*). The stream banks are 2-4 feet high and are composed of fine alluvial silts and sandy material. As with other described reaches of Walker Run, this reach appears to have been manipulated by human activities in the past, most likely ditching to drain surrounding swamp and wetland areas in an effort to generate more usable land. A beaver dam approximately 3-4 feet higher than channel bed existed near the transition between the BLCR and the project reach, which created a backwater condition that extended upstream well into the project reach. However, this beaver dam was removed in April 2010, which lowered upstream water surface elevations to match water surface along most of the BLCR.

Figure 4-4. Typical conditions within forested segment of the BLCR upstream of the farm access road.

Based on the visual assessment of the BLCR between the farm access road and the project reach, there are no significant head-cuts, steep riffles, or other man-made drop structures that would allow or promote vertical channel adjustment upstream of the base level control because it is likely that vertical degradation has already occurred. Therefore, by providing base level control, the pipe culvert along the existing farm access road creates a condition that will likely prevent further bed degradation upstream and through most of the project reach. Even if the culvert was to fail or is removed, the bed elevation difference upstream and downstream of the culvert crossing is not significant enough to create vertical instabilities that would affect conditions upstream within the BLCR and project reach. However, as long as the culvert crossing exists, it serves as a fail-safe for limiting the long-term potential for vertical channel degradation upstream.

In addition to the base level control provided by the culvert crossing, a well-defined riffle composed of gravel and some cobble-sized bed material exists at the approximate location where the beaver dam had been removed from Walker Run. This riffle sets a uniform grade across the entire stream channel and provides some degree of a localized base level control. This is also the approximate elevation where the proposed channel will tie into existing conditions.

4.2 Project Reach

The project reach begins near the location of the previously existing beaver dam approximately 850 feet upstream of the 36-inch pipe culvert crossing. An existing access road for the BBNPP site intersects the reach approximately 1,670 feet upstream from the culvert crossing and the north Market Street crossing is 1,430 feet further upstream. The upstream limit of the project reach is the Beach Grove Road bridge crossing. The downstream-most 150 feet of the project reach is within mature forest. As discussed earlier, a well-defined riffle exists where the beaver dam had been near the downstream limit of the project reach (*see Figure 4-5*). A deep, wide pool exists near the forest boundary just upstream of the former beaver dam location where an unnamed tributary flows into Walker Run.

Figure 4-5. Approximate location of previously existing beaver dam where a well-defined riffle now exists. Note the establishment of vegetation on the low-lying bankfull bench (lower left quadrant of photo). This bench is a feature that is being incorporated into the restoration design.

Beyond the tree-line, the project reach is severely entrenched and surrounded by abandoned agricultural fields for approximately 1,430 feet before entering another stand of existing forest up to Market Street. Banks range between 4 and 5 feet in height and the channel is relatively straight from artificial channelization. There are 2 sets of truncated meanders just downstream of the BBNPP access road where Walker Run has undergone some natural lateral adjustment since being historically channelized (*see Figure 4-6*). The segment of channel downstream from the BBNPP access road generates significant volumes of sediment into the stream during high flows, which creates poor conditions for aquatic habitat.

Figure 4-6. View of lateral migration just downstream of the existing BBNPP site access road.

Prior to the removal of the beaver dam, there was an artificially elevated water surface profile that extended upstream approximately 800 feet upstream and through the existing BBNPP access road located in the middle portion of the project site. This reduced the average water surface slope and therefore reduced the shear stress within the channel, which, in turn, limited the potential for vertical and lateral channel degradation. Now that the beaver dam no longer exists, the average stream slope is steeper and the existing shear stresses have increased. This will eventually lead to additional lateral extension and potential upstream vertical degradation as the sediment that had been stored upstream of the beaver dam will continue to be flushed downstream. This sediment load will be further increased by erosion associated with renewed lateral migration of the channel and further degrade the already poor existing biological community.

The project reach continues to be significantly incised and entrenched upstream of the BBNPP access road (see *Figure 4-7)*, where Walker Run has been historically channelized and moved to the eastern edge of the valley in order to maximize usable agricultural land. This in effect has reduced stream lengths and therefore steepened stream slopes and increased shear stresses in the channel during the more frequent high flow events. This adjustment in profile and plan form has significantly impacted channel stability of the reach. Even though the stream banks appear to be fairly well vegetated, the channel is not connected with a functional floodplain. This channel incision promotes vertical and lateral adjustment during high flows. The streambed substrate consists mainly of silts and sands with the occasional large cobble and or boulder, most likely from being exposed as a result of the channel being moved to the eastern fringe of the valley. As a result of the highly entrenched conditions and the abundance of fine-grained sediments along the channel bed, conditions are less than ideal for sustaining diverse in-stream biological habitat for fish and macroinvertebrates.

Figure 4-7. Typical conditions upstream of the BBNPP access road with 4- to 5-foot streambanks.

The project reach is surrounded by forest again beginning approximately 770 feet upstream from the BBNPP access road. The channel bends sharply to the northwest after about 350 feet into the forest before continuing relatively straight towards Market Street. Along this forested segment, the channel is still pinned against the eastern valley wall. There are short, steep riffles where the bed appears to be perched on the larger colluvial material at the base of the valley slope that was likely exposed as a result of the historical channelization. This perched streambed condition creates a long backwater condition immediately downstream of the Market Street bridge crossing (see *Figure 4-8*). Here, the streambed substrate consists of silts and sands, most likely deposited as a result of the flattened stream slope.

Figure 4-8. View of the project reach from the northern Market Street bridge crossing (facing downstream). The channel is an incised F5 stream type consisting of long flat pool.

North of the Market Street bridge, Walker Run flows parallel with Market Street for approximately 100 feet before turning west. During high flows, the Market Street crossing is a constriction to the floodplain forcing all flows to be conveyed through the bridge culvert. Because it is an open bottom culvert, it does not appear to provide upstream base level control. However, along the first 150 feet upstream of the bridge crossing the bed is composed of large-sized gravels, cobbles, and even some boulders, which does control the grade. This large bed material is somewhat of an anomaly along the project reach and may be remnants from past human activity, such as roadway or bridge improvements or from intentionally placed bank armoring to stabilize the banks. This large bed material creates a series of few short, steep riffles and has prevented the channel from downcutting any further; however, upon reaching vertically stability, the channel now exhibits signs of moderate lateral migration as it approaches the bridge crossing. With that said, this portion of the project reach is only slightly entrenched and a low-lying vegetated bench feature has developed adjacent to a well-defined riffle surface as a result of the lateral migration. The development of this bench feature indicates that the channel is progressing towards a more stable condition by creating a new floodplain at lower elevations (*see Figure 4-9*). This bench feature is an important geomorphic feature that was helpful in determining proposed bankfull elevations and served as an appropriate tie-in location for the restored project reach (*refer to Chapter 7 – Restoration Design for more information*).

Figure 4-9. View of the project reach just upstream of the north Market Street crossing (facing downstream). Note large boulder material in foreground, which is also present in streambed immediately downstream. Through lateral migration, the channel has developed a low-lying bench feature (right side of photo), which is indicative of the stream's progression towards stability.

Continuing upstream, the channel slope flattens and stream becomes significantly entrenched as it turns west for approximately 200 feet across the valley bottom and becomes pinned along the western valley wall for another 200 feet. The channel then turns back toward the center of the valley and follows a series of meanders for approximately 450 feet. The existing stream banks range between 3 and 5 feet in height and are composed of silts and sands. The existing valley bottom consists of a fairly mature forest. However, trees and shrubs along the banks have minimal rooting depths and provide little bank stabilization due to the incised condition of the channel (*see Figures 4-10, 4-11, and 4-12)*. This condition of high banks composed of easily-erodible fine sediments and elevated root systems does not provide adequate protection for long-term stream stability during frequent and higher flow events. As a result, this portion of the existing project reach is experiencing accelerated bank erosion during high flows. Trees are being undermined and are falling into the stream, which creates debris jams that further accelerated bank erosion and promote vertical bed scouring. Throughout this reach, the bed consists of primarily fine-grained alluvial sediments (silts and sands), which most likely originate from local stream bank erosion. These fines deposit along the channel bed as high flows recede due to the low average water surface slope along this segment. The abundance of these fines within the channel creates poor trout spawning potential and poor in-stream habitat for macroinvertebrates despite having adequate overhead cover provided by the forest.

Figure 4-10. Typical conditions upstream of the well-defined riffle complex near the north Market Street bridge crossing. Low channel slopes create flat water that extends upstream through most of the project reach south of Beach Grove Road.

Figure 4-11. View of *typical stream conditions showing bank erosion between Market Street and Beach Grove Road.*

Figure 4-12. View of typical stream conditions showing bank erosion approximately 400 downstream of Beach Grove Road.

The conditions described above are representative of typical conditions throughout the majority of the project reach segment between Market Street and Beach Grove Road. However, approximately 300 feet downstream of Beach Grove Road where the channel is no longer surrounded by forest, there is a well-defined riffle segment where the stream bed consists of small- to medium- sized gravels and a distinct low-lying bench feature has developed along the west bank (*see Figure 4-13*). Even though this reach is moderately entrenched, the bench feature indicates some stability and the streambed substrate appears to be sustainable in the long-term and provides suitable habitat for aquatic organisms. This is the approximate location where the proposed channel profile will tie into the existing profile of Walker Run and proposed floodplain elevations will tie into the elevation of the existing bench feature.

Figure 4-13. View of well-defined riffle with an adjacent low-lying bankfull bench feature located approximately 300 feet downstream of Beach Grove Road that resembles some degree of stability This segment serves as an appropriate location to begin the proposed channel relocation.

Approximately 150 feet downstream of the Beach Grove Road bridge crossing, the project reach makes 2 truncated 90-degree bends before continuing relatively straight towards the bridge crossing. At the upstream 90-degree bend, the outside meander bank is approximately 5 feet in height and consists of silts and sands (*see Figure 4-14*). The bank erosion at this meander bend is a significant source of the sediment being contributed to the downstream channel segments. The straight segment between this meander and the Beach Grove Road bridge crossing in entrenched with banks ranging between 3 to 4 feet in height. A deep plunge pool exists immediately downstream of the Beach Grove Road bridge crossing where an elevated high-pressure gas line crosses the project reach (*see Figure 4-15*).

Figure 4-14. View of severely-eroded vertical bank immediately downstream of Beach Grove Road at a 90-degree bend to the left (facing downstream).

Figure 4-15. View of *Beach Grove Road bridge crossing with elevated high-pressure gas line.*

4.3 Supply Reach

The Supply Reach includes a segment of Walker Run that begins at the Beach Grove Road bridge and ends approximately 1,500 feet upstream. The visual assessment was performed along this reach to: 1) characterize existing conditions of Walker Run upstream of the project reach; 2) identify any indicators of channel stability such as low-lying vegetated bench (bankfull) features and/or good connection between the channel and its floodplain; 3) determine sources of sediment and bedload material that are being contributed to and mobilized within the project reach downstream; and 4) identify any hydraulic conditions that may prevent or reduce the available bedload from being transported into the project reach.

The Beach Grove Road bridge crossing is a stone mortared closed-bottom culvert, which provides upstream base level control (*see Figure 4-16*). During high flows, the road obstructs the floodplain and forces all flows through the undersized bridge opening, which creates a backwater condition upstream. The backwater condition flattens out the water surface slope and reduces sediment transport through the culvert. As a result of this backwater condition, it is likely that most sediments mobilized during high flows are deposited upstream of the bridge crossing.

Figure 4-16. View of the Beach Grove Road bridge culvert (facing downstream). The undersized opening creates an upstream backwater condition during high flows, which limits sediment transport.

The first 400 feet of Walker Run upstream of the Beach Grove Road bridge crossing is a relatively straight riffle-dominated segment that flows northwest to southeast (*see Figure 4-17*). It is pinned against a steep valley wall that rises up to Stone Church Road on the west, while mowed residential lawn exists along the east side of the channel. This segment is only slightly steeper than the upper portion of the project reach.

Figure 4-17. View of supply reach approximately 200 feet upstream of the Beach Grove Road bridge crossing (facing downstream). The channel flows relatively straight between a residential lawn to the east (left side in photo) and a steep slope up to Stone Church Road to the west (right side in photo).

Then Walker Run bends north into a forest dominated by a mix of coniferous and deciduous trees and the valley begins to exhibit characteristics typical of an upper watershed (headwater) stream system with a narrow valley width, steep side slopes, and steeper valley slope. This upper watershed portion of Walker Run appears to be in a relatively stable condition. Stream banks are fairly low and there is a good connection between the channel and its floodplain, or floodprone area (*see Figure 4-18*). With steeper slopes, the reach flows relatively straight with large colluvial bed materials providing channel roughness that limits flow velocities and shear stress (*see Figure 4-19*). In addition, the reach exhibits minor lateral extension as it occasionally branches into a series of channels, a condition that could be considered anabranching. As a result of this anabranching condition, shear stress energies are minimized further. For these reasons, it was determined that this reach does not provide a significant source of large-sized bed material to the downstream sections of Walker Run including the project reach. In addition to the low sediment supply being contributed from the upstream condition, the backwater condition associated with the Beach Grove Road bridge during higher flows causes more deposition of mobilized sediments and further limits sediment transport. Therefore, the sediment being contributed by the supply reach and transported into to the project reach would consist mainly of silts, sands, and small gravels.

Figure 4-18. View of supply reach (facing downstream). The channel is well-connected to its floodplain (right side in photo) despite having a steep side slope to the east (left side in photo).

Figure 4-19. View of supply reach (facing downstream). The bed is armored with large colluvial material (gravels, cobbles, and small boulders). Low shear stresses and low bankfull discharge velocities limit the mobilization of these materials. It is likely that only small gravels, sands, and silts are transported downstream into the project reach.

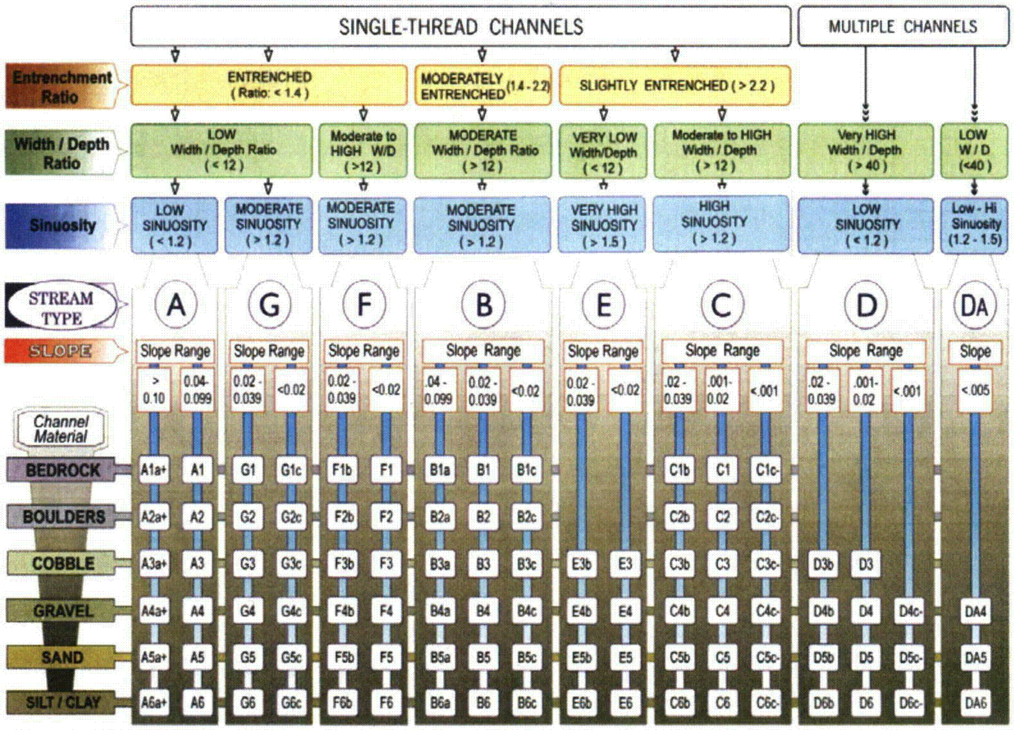
5 Detailed Geomorphic Assessment

5.1 Bankfull Indicators and Channel Stability Determination

In addition to identifying unstable conditions and potential causes of instability within the watershed, the visual assessment involved the identification of stable stream segments within the Walker Run watershed as well as adjacent watersheds exhibiting similar characteristics (drainage area size, valley slope, stream slope, stream type, geology, sediment supply, etc.). Signs of stability are typically identified based on the presence of bankfull indicators along representative riffles along a particular stream reach. These bankfull indicators, or channel forming features, consist of vegetated benches or terraces that have formed within the existing channel at consistent elevations along a reach that is not greatly influenced by backwater from culvert crossings, debris jams or tight meander bends. In many instances, these channel forming features develop along segments that also exhibit unstable banks. For example, low-lying vegetated point bars typically develop directly across the stream from a severely eroded cut-bank. Despite the instability observed at these locations, the presences of the channel-forming features indicate that the channel is developing a lower elevation floodplain as a result of lateral migration and will eventually create a floodplain low and wide enough to effectively convey floodflows without degrading.

A truly stable stream reach, which is relatively uncommon in eastern Pennsylvania, is a reach that has not been influenced by human impacts and has maintained a low, accessible floodplain elevation for many years with no signs of accelerated bed or bank scouring. Although truly stable stream segments were not identified, two particular reaches were identified that exhibit channel forming features including: 1) Assessment Reach #1 (AR#1) - a segment upstream of Beach Grove Road and 2) Assessment Reach #2 (AR#2) - a segment of Marsh Creek, which is within a separate but similar watershed approximately 11 miles north, northwest of the project reach. LandStudies conducted a detailed geomorphic assessment of these two stream segments as well as the entire project reach, referred to hereafter as Assessment Reach #3 (AR#3), to obtain specific channel measurements of the streambed profile and cross-sectional data that could be used in determining bankfull conditions, sediment regime and mobility, riffle texture and roughness and stream classification. The geomorphic assessment reaches were selected based upon the following characteristics: 1) presence of a riffle with uniform bed elevations and bed material; 2) presence of stable channel-forming features such as vegetated bars or bench features; 3) limited vertical or lateral degradation; 4) existing valley slope that is representative of the project reach and watershed.

The geomorphic survey data collected along each assessment reach include longitudinal profiles, cross-sections of riffles, cross-sections of pools, water surface slopes, thalweg bed features, threshold depths, and other pertinent morphological features. Cross-sections were plotted from field surveys perpendicular to the flow of the channel that extend from left to right, looking downstream, across the channel and floodplain for a length sufficient to characterize the area, wetted perimeter and bankfull indicators of the channel. Longitudinal profiles of each assessment reach are plotted from field surveys with stationing along the stream thalweg (deepest part of the channel). The spacing of surveyed thalweg and water surface elevations is sufficient to characterize the morphology of pools, riffles, and water surface (bankfull) slope. The field-data set also includes measurements of the streambed material size distribution using the Wolman Pebble Count methodology along representative riffles. All geomorphic data has been plotted using *The Reference Reach Spreadsheet V 2.2L,* an MS-Excel based program developed by Dan Mecklenburg of Ohio Department of Natural Resources and is included in Appendix B. Survey data was analyzed to determine the stream type of each assessment reach using the Rosgen Classification of Natural Rivers (*see Figure 5-1*). The field data collected during surveys of these assessment reaches was used as a guide in computing the hydraulic characteristics and riffle/pool dimensions for the project reach at the bankfull stage. More specifically, the data collected along AR#1 was used primarily for determining the bankfull discharge and sediment transport parameters of the project reach by correlating it with the data collected along AR#3. The data collected along AR#2 was used as reference for developing dimensionless ratios that were used as a tool to develop design dimensions, plan form, and profile for the proposed restoration of Walker Run.



KEY to the ROSGEN CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units; while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

Figure 5-1. Key to the Rosgen Classification of Natural Rivers.[1]

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[1] Rosgen, D.L. 1996. *Applied River Morphology*. Wildland Hydrology Books, Pagosa Springs, Colorado.

5.1.1 Bankfull (Threshold) Channel Discharge Determination

The bankfull, or threshold, discharge of the stream channel is the most effective channel forming flow, the flow in the channel that creates the observed morphological characteristics of the channel. All dimensions, patterns and bed features of the channel are described as a function of the bankfull discharge of a stream. The bankfull stage is also the point where the depth of flow and water surface slope over the riffle is capable of mobilizing the sediment particle sizes being supplied from the watershed. To minimize channel degradation and find stability, the designed reach should have a water surface slope and depth of flow capable of mobilizing a particle at the bankfull stage no greater than the median size particle or D_{50} of the designed riffle. Since the majority of the upstream sediment supply is derived from the streambanks and consists of mostly fine-grained silts and sands, reducing sediment mobility of the bed material to less than the D_{50} of the riffle will ensure long-term stability in a sediment-starved system where a replenishing supply of larger gravels does not exist. The focus of the detailed geomorphic assessment was to identify the properties of riffles that exhibit uniform, or near uniform, flow conditions so that the threshold parameters could be ascertained within the selected assessment reaches.

5.1.2 Bankfull (Energy) Slope

The energy slope (friction slope), S_f, for each assessment reach has been estimated for bankfull flow conditions based on field survey measurements. The slope is a critical parameter in determining threshold conditions. The slope over the assessment riffle is bound by 1) the water surface slope over just the riffle feature itself (maximum threshold slope) and 2) the water surface slope from the head of the study riffle to the head of the next riffle downstream (minimum threshold slope), which includes the pool water surface slope immediately downstream of the study riffle. Threshold conditions will typically occur somewhere between the minimum threshold slope and the maximum threshold slope. The sediment mobility analysis is used to determine the specific slope at which threshold conditions are met.

5.1.3 Channel Roughness

Channel roughness is considered to be caused primarily by the roughness of the channel bed. Estimates of Manning roughness coefficient, n, are based on the Limerinos (1970) relation given here as:

Equation 5-1. Estimation of Manning Roughness coefficient

$$n = R_h^{1/6} \frac{0.0926}{1.16 + 2 \operatorname{Log} \dfrac{R_h}{D_{84riffle}}}$$

where R_h is the hydraulic radius (feet) and D_{84} (feet) is the particle size for which 84 percent of the particles are smaller based on the pebble count of each assessment riffle surface. As indicated by this relationship, the n value changes with flow conditions. A Wolman pebble counting method (Bunte *et al* 2001) was used to describe the surface particle size distribution over the active channel portion of each assessment riffle surface. Particle sizes necessary for roughness estimates ($D_{84riffle}$) and for evaluation of the bed surface mobility $D_{50riffle}$ were measured through the pebble count analysis.

5.1.4 Bankfull Flow Estimates and Boundary Shear Stress

The average boundary shear stress produced by the bankfull discharge over each assessment riffle was computed as:

Equation 5-2. Average Boundary Shear Stress

$$\tau_b = \gamma R S_f$$

where T_b is the cross-section average boundary shear stress (lbs/ft^2) over the riffle, coefficient γ is 62.4 (lbs/ft^3), R is the hydraulic radius or mean bankfull depth, and S_f is the bankfull energy slope. Because bank resistance and backwater effects on existing riffles were considered to be minor under bankfull conditions, the average boundary stress was considered to be a good approximation for the average stress on the active channel bed.

5.2 Assessment Reach #1 (AR#1) – Walker Run

AR#1 is located approximately 1,000 feet upstream of the Beach Grove Road and includes a 320-foot longitudinal profile and 2 riffle cross-sections (AR1-XS1 and AR1-XS2) (*see Figure 5-2*). Mean bankfull depths range between 0.6 and 0.7 feet and bankfull widths range between 17.4 and 18.3 feet. Thus, this assessment reach has a high width-depth ratio of 27.1-31.0. The channel sinuosity is 1.1 and the entrenchment ratio was calculated to be 1.9-2.0. A pebble count, consisting of 196 samples, was performed over the surface area of AR1-XS2. The pebble count yielded a mean diameter particle size of 41.0 mm, which classifies the bed material as very coarse gravel along AR#1. The bankfull energy slope of AR#1 is 1.6 percent. Based on the survey data, it was determined that AR#1 is a B4c stream type. Bankfull discharges along AR#1 were calculated to range between 19.3 and 29.3 cubic feet per second (cfs) using the mean bankfull depth, Manning's equation, relative roughness, and bankfull energy slope. The results of the discharge and boundary shear stress analysis at the field-indicated bankfull stage yield boundary shear stresses between 0.55 and 0.64 pounds per square feet (psf). This boundary shear stress range is capable of initiating the motion of particle sizes equaling 35.0-40.0 mm at the bankfull discharge. The bankfull discharge was then used to estimate the bankfull stage or elevation within the cross-sections surveyed along the project reach (AR#3) where bankfull indicators were not clearly defined. Because AR#1 is a different stream type (B4c) than the project reach (F4/F5 and G4c), this assessment reach was only helpful for calibrating bankfull discharge and bankfull stage within the project reach (AR#3). Channel dimension, plan form, and profile characteristics of AR#1 were not used as reference in developing design parameters for the proposed restoration. *Table 5-1* summarizes the bankfull characteristics of the AR#1. Plotted geomorphic survey data for AR#1 is included in Appendix B.

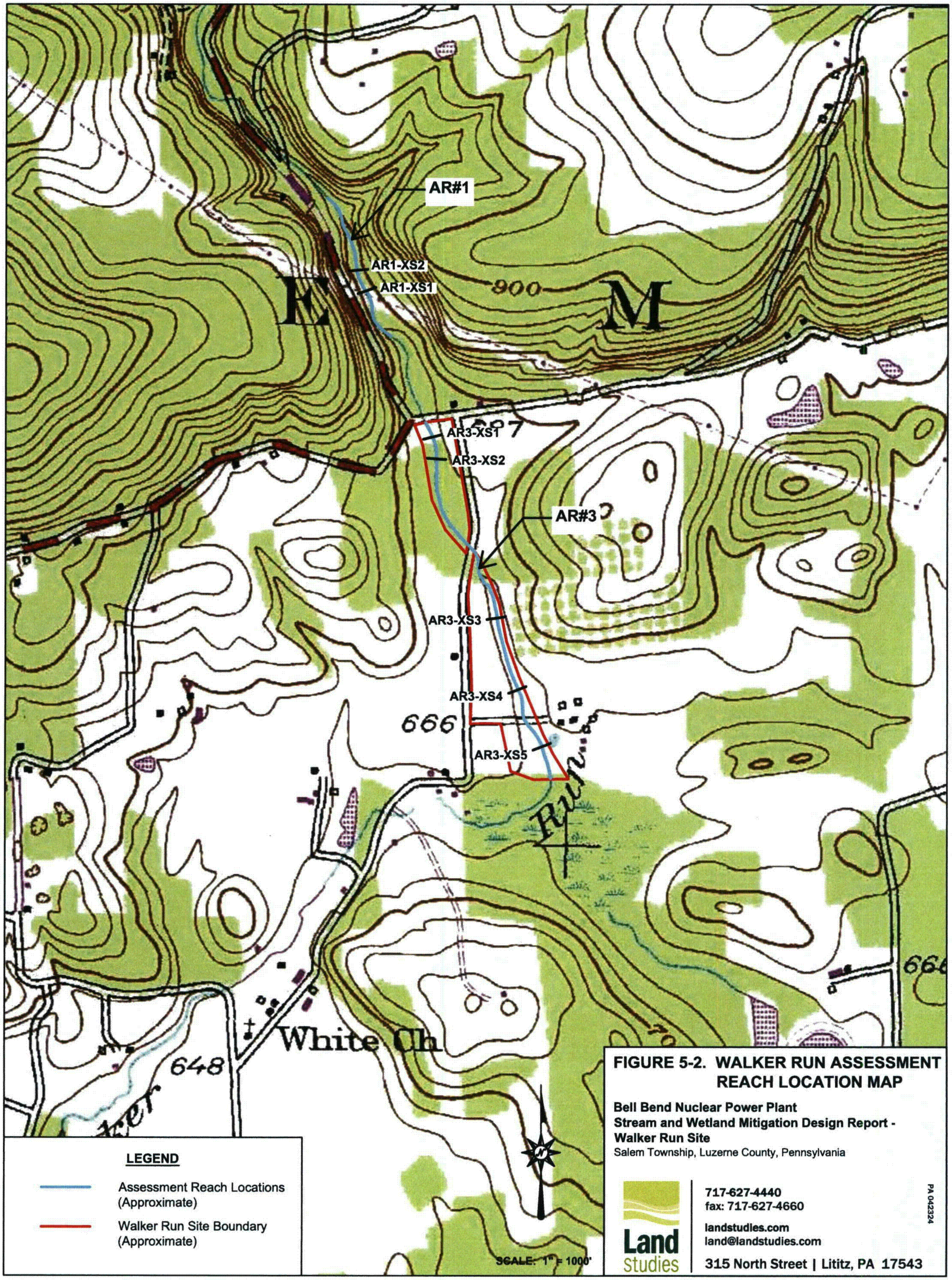

FIGURE 5-2. WALKER RUN ASSESSMENT REACH LOCATION MAP

Bell Bend Nuclear Power Plant
Stream and Wetland Mitigation Design Report - Walker Run Site
Salem Township, Luzerne County, Pennsylvania

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Figure 5-3. View of AR1-XS1 (facing upstream).

Figure 5-4. View of AR1-XS2 (facing upstream).

Cross Section	*AR1-XS1*	*AR1-XS2*
Stream Type	B4c	B4c
Cross Sectional Area (sf)	12.3	9.8
Width (ft)	18.3	17.4
Mean Depth (ft)	0.7	0.6
Max. Depth (ft)	1.1	0.9
Entrenchment Ratio	1.9	2.0
Width/Depth Ratio	27.1	31.0
Discharge (cfs)	29.3	19.3
D50 (mm)	57	57
Average Slope (ft/ft)	0.016	0.016

Table 5-1. Geomorphic characteristics for AR#1 cross-sections.

5.3 Assessment Reach #2 (AR#2) - Marsh Creek

AR#2 is located approximately 11 miles north, northwest of the project reach near the small town of Broadway in Ross Township, Luzerne County (*see Figure 5-5*). Silo Road separates the reach into a two distinct segments that are different stream types. AR#2 (including both segments) was selected as an assessment reach because 1) it is one of the most stable reaches observed in the region; 2) it has a drainage area of 2.8 mi^2 which is similar in size to the Walker Run project reach; and 3) the watershed exhibits similar characteristics (geology, land use, valley types, etc.) as the Walker Run watershed. It also exhibited characteristics of two distinct stream types; E and C, which are the same stream types that were anticipated for the proposed restoration (*refer to Chapter 7 - Restoration Design for more information*). Therefore, AR#2 served as an ideal reference condition for developing certain design parameters of the proposed restoration. *Table 5-2* summarizes the bankfull characteristics at representative cross-sections along AR#2. Plotted geomorphic survey data for AR#2 is included in Appendix B.

5.3.1 Upstream Segment of AR#2 - Marsh Creek

The upstream segment of AR#2 is a 360-foot reach located upstream of Silo Road. Survey data for this segment includes a longitudinal profile and a representative riffle cross-section (AR2-XS1). It exhibited a mean bankfull depth of 1.2 feet and a bankfull width of 8.1 feet. Thus, this segment has a low width-depth ratio of 6.6. The channel sinuosity is approximately 1.1 and the entrenchment ratio was calculated to be 16.0. Bed materials are dominated by very fine sand. The bankfull energy slope is only 0.11 percent. Other than having a low sinuosity, this upper segment exhibited dimensions and bed materials that would classify it as an E5 stream type. Bankfull discharges along the upstream segment of AR#2 were calculated to be 17.5 cfs. The results of the discharge and boundary shear stress analysis at the field-indicated bankfull stage yield a reach-averaged boundary shear stress of 0.07 psf. This boundary shear stress is capable of initiating the motion of a 4.7 mm particle at the bankfull discharge.

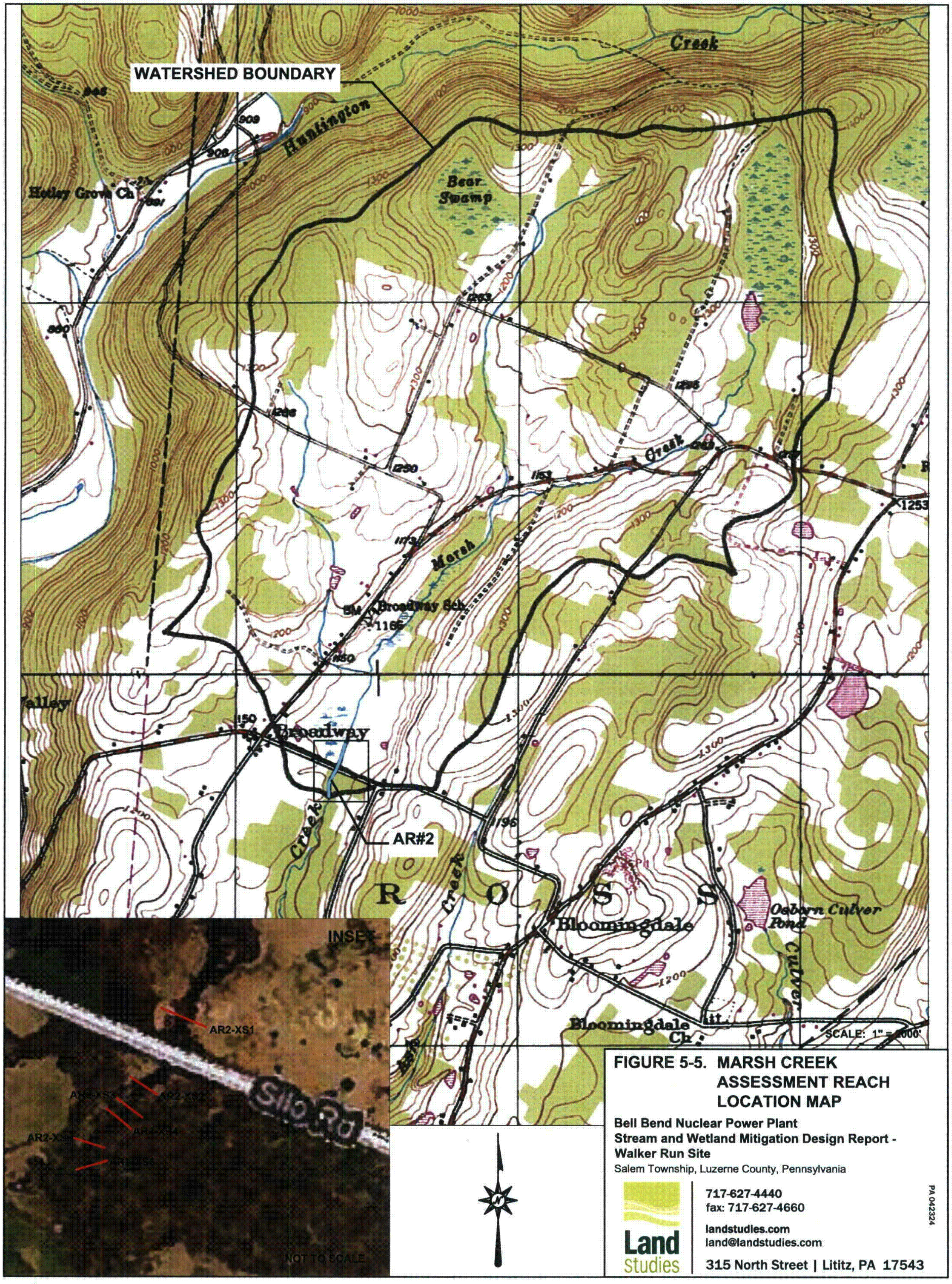

FIGURE 5-5. MARSH CREEK ASSESSMENT REACH LOCATION MAP

Bell Bend Nuclear Power Plant
Stream and Wetland Mitigation Design Report - Walker Run Site
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Figure 5-6. View of the upstream segment of AR2 (facing upstream).

Figure 5-7. View of AR2-XS1 – assessment riffle (facing upstream).

5.3.2 Downstream Segment of AR#2 – Marsh Creek

The downstream segment of AR#2 is a 440-foot reach located downstream of Silo Road. Survey data for this segment includes a longitudinal profile, 3 riffle cross-sections (AR2-XS3, AR2-XS5, and AR2-XS6), and 2 pool cross-sections (AR2-XS2 and AR2-XS4). It exhibited mean bankfull depths that range between 0.7 and 0.8 feet and bankfull widths that range between 13.6 and 16.8 feet. Thus, this segment has a higher width-depth ratio of 16.5-22.5. The channel sinuosity is approximately 1.1 and the entrenchment ratio was calculated to be 2.0-4.3. A pebble count, consisting of 341 samples, was performed over the surface area of AR2-XS3. This pebble count yielded a mean diameter particle size of 20.3 mm, which classifies the bed material as coarse gravel along the lower portion of AR#2. The average bankfull energy slope is 0.37 percent. Based on the survey data, it was determined that the downstream segment of AR#2 is a C4 stream type. Bankfull discharges along this segment were calculated to range between 16.5 and 22.7 cfs using the mean bankfull depth, Manning's equation, relative roughness, and bankfull energy slope. The results of the discharge and boundary shear stress analysis at the field-indicated bankfull stage yield boundary shear stresses between 0.16 and 0.19 psf. This boundary shear stress range is capable of initiating the motion of particle sizes equaling 9.5-12.0 mm at the bankfull discharge.

Figure 5-8. View of AR2-XS2 – assessment pool (facing upstream).

Figure 5-9. View of AR2-XS3 – assessment riffle (facing downstream).

Figure 5-10. View of AR2-XS4 – assessment pool (facing downstream).

Figure 5-11. View of AR2-XS5 – assessment riffle (facing upstream).

Figure 5-12. View of AR2-XS6 – assessment riffle (facing downstream).

Cross Section	AR2-XS1 (riffle)	AR2-XS2 (pool)	AR2-XS3 (riffle)	AR2-XS4 (pool)	AR2-XS5 (riffle)	AR2-XS6 (riffle)
Stream Type	E5	C4	C4	C4	C4	C4
Cross Sectional Area (sf)	10.0	25.8	11.2	23.8	9.8	12.6
Width (ft)	8.1	17.4	13.6	17.6	14.2	16.8
Mean Depth (ft)	1.2	1.5	0.8	1.4	0.7	0.7
Max. Depth (ft)	2.2	4.9	1.1	2.0	1.1	1.1
Entrenchment Ratio	16.0	2.0	4.3	1.7	2.3	2.0
Width/Depth Ratio	6.6	11.8	16.5	13.0	20.6	22.5
Discharge (cfs)	17.5	—	21.5	—	16.3	22.7
D50 (mm)	0.06	—	16	—	16	16
Average Slope (ft/ft)	0.0011	0.0037	0.0037	0.0037	0.0037	0.0037

Table 5-2. Geomorphic characteristics for AR#2 cross-sections.

5.4 Assessment Reach #3 (AR#3) – Walker Run Project Reach

AR#3 consists of the entire project reach beginning just downstream of Beach Grove Road and extending approximately 3,700 feet downstream (*refer to Figure 5-2*). This assessment reach is separated into two segments (Site A and Site B), which are divided by Market Street. The analysis of this assessment reach is intended to effectively characterize the existing conditions of the project reach as influenced by the bankfull discharge calibrated at AR#1. *Table 5-3* summarizes the bankfull characteristics at representative cross-sections along AR#2. Plotted geomorphic survey data for AR#3 is included in Appendix B.

5.4.1 Site A – Project Reach between Beach Grove Road to Market Street

Site A includes approximately 1,300 feet of the project reach between Beach Grove Road and Market Street. Survey data for this reach includes a longitudinal profile and 2 representative riffle cross-sections (AR3-XS1 – AR3-XS2). The mean bankfull depth is 0.7 feet and bankfull widths range between 8.9 and 17.7 feet. Thus, this assessment reach has a high width-depth ratio of 13.0-17.8. The channel sinuosity is approximately 1.4 and the entrenchment ratio was calculated to be 1.2-1.5. A pebble count, consisting of 100 samples, was performed over the surface area of AR1-XS2. The pebble count yielded a mean diameter particle size of 0.1 mm, which classifies the bed material as very fine sand. This pebble count was conducted along this riffle location because it is representative of the majority of the Site A reach. However, it should be noted that the bed materials at the upstream-most and downstream-most ends of this segment include coarser gravels. The bankfull energy slope of this segment of AR#3 is 0.34 percent. Based on the survey data, it was determined that this segment of AR#3 is an F4/F5 stream type. Bankfull discharges were calculated to be approximately 19.6 cfs. The results of the discharge and boundary shear stress analysis at the field-indicated bankfull stage yield boundary shear stresses between 0.13 and 0.14 psf. This boundary shear stress is capable of initiating the motion of a 8.2-9.0 mm particle at the bankfull discharge.

Figure 5-13. View of AR3-XS1 (facing upstream).

Figure 5-14. View of AR3-XS2 (facing downstream).

5.4.2 Site B – Project Reach Downstream of Market Street

Site B includes approximately 2,100 feet of the project reach beginning just downstream of Market Street. Survey data for this reach includes a longitudinal profile and 3 representative riffle cross-sections (AR3-XS3 – AR3-XS5). Mean bankfull depths range between 0.9 and 1.1 feet and bankfull widths range between 8.2 and 9.7 feet. Thus, this assessment reach has a lower width-depth ratio of 7.6-10.9. The channel sinuosity is 1.12 and the entrenchment ratio was calculated to be 1.2-1.5. A pebble count, consisting of 113 samples, was performed over the surface area of AR1-XS3. The pebble count yielded a mean diameter particle size of 2.3 mm, which classifies the bed material as very fine gravel. This pebble count was conducted along this riffle location because it is representative of the majority of the Site B reach. The bankfull energy slope of this segment of AR#3 is 0.44 percent. Based on the survey data, it was determined that this segment of AR# is a G4c stream type. Bankfull discharges were calculated to range between 21.9 and 25.1 cfs using the mean bankfull depth, Manning's equation, relative roughness, and bankfull energy slope. The results of the discharge and boundary shear stress analysis at the field-indicated bankfull stage yield boundary shear stresses between 0.23 and 0.26 psf. This boundary shear stress range is capable of initiating the motion of particle sizes equaling 13.0-16.0 mm at the bankfull discharge.

Figure 5-15. View of AR3-XS3 (facing downstream).

Figure 5-16. View of AR3-XS4 (facing downstream).

Figure 5-17. View of AR3-XS5 (facing downstream).

Cross Section	*AR3-XS1*	*AR3-XS2*	*AR3-XS3*	*AR3-XS4*	*AR3-XS5*
Stream Type	F5	F5	F5/Incised G5	F5/Incised G5	F5/Incised G5
Cross Sectional Area (sf)	6.0	7.7	8.8	9.4	8.7
Width (ft)	8.9	11.7	8.2	9.1	9.7
Mean Depth (ft)	0.7	0.7	1.1	1.0	0.9
Max. Depth (ft)	1.2	0.9	1.6	1.4	1.4
Entrenchment Ratio	1.5	1.2	1.5	1.2	1.2
Width/Depth Ratio	13.0	17.8	7.6	8.9	10.9
Discharge (cfs)	19.6	19.6	24.7	25.1	21.9
D50 (mm)	0.13	0.13	6.2	6.2	6.2
Average Slope (ft/ft)	0.0034	0.0034	0.0044	0.0044	0.0044

Table 5-3. Geomorphic characteristics for AR#3 cross-sections.

5.5 Summary of Detailed Geomorphic Assessment Reach

The purpose of the geomorphic assessment reach analyses is to determine and calibrate the bankfull and sediment transport parameters of Walker Run in the vicinity of the proposed project site. The riffles selected within each assessment reach exhibited uniform or near uniform flow conditions, and exhibited fairly stable channel-forming features, or bankfull indicators, during the time of this investigation. Each reach was selected because they appeared to be capable of transporting the bedload of the watershed and had formed bankfull indicators at consistent elevations. The collected field data was used for the computation of hydraulic characteristics and riffle dimensions for the project reach at the bankfull stage. Even though they reflect the limited stability inherent under current watershed conditions, they offer the best available data in the vicinity of the project site.

6 Sediment Sampling, Analysis, and Critical Shear Stress

A major premise of the sediment mobility analysis is that threshold conditions defined by any critical shear stress method represent a condition of very low transport rate (Wilcock 1988). A second assumption is that statically armored riffles satisfy the conditions of near-equal mobility; that is, the largest sediments in a sediment mixture require slightly higher shear stresses than do smaller sizes. Very large particles from colluvial material or large fragments of bedrock plucked from the streambed or bank during infrequent high flows may not be mobile although they can effectively hide or shelter other smaller particles. The largest particles on the bars or in the sub-surface represent the maximum size present in the bedload.

6.1 Sediment Assessment

Based on a visual reconnaissance of the project site, there were no active (un-vegetated) bars forming along the inside of meander bends, which would indicate that the stream is currently transporting the majority of sediment introduced into the project reach through the system. There were, however, a few number of depositional bars identified between Beach Grove Road and Market Street that consisted of fine sands, small gravels, and silts that appeared to be forming in hydraulic conditions created by backwater conditions and debris jams. Additionally, active bar deposition was investigated upstream within the supply reach at an identified assessment reach described earlier (*see Figure 6-1*). This is the material that is believed to be transported through the system from the upper watershed. However, it is also understood that not all this material may be making it through the bridge crossing at Beach Grove Road due to backwater conditions created by this hydraulic structure. The sediment material identified on the assessment reach depositional bar consisted of material that ranged from 15 mm to 24 mm, with the majority of the material consisting of 15 mm and less.

Based upon this sediment analysis upstream of the project reach, it is assumed that the only particles being transported into the project reach would include materials in the range of 15 to 20 mm, with any larger material (>20mm) being deposited upstream due to the hydraulic control at the Beach Grove Road bridge. This assumption can be corroborated by the fact that there is not a major depositional bar forming upstream of Beach Grove Road where this material would be believed to be depositing and therefore, the sediment supply being contributed from the upstream condition is determined to consist only of small gravels, sands, and silts. Based on these assumptions, the restoration design was developed to minimize the average shear stress in the proposed channel in order to preserve the existing substrate within the restored reach because there will be minimal replenishment of larger-sized gravels and cobbles due to the low sediment supply being contributed to the project reach. In other words, the proposed design will eliminate the possibility of the substrate within the restored reaches from being mobilized during the more frequent flow events and be able to sustain the streambed substrate over the range of flows from bankfull to major flow events.

Figure 6-1.Typical material identified in active bar formation in upstream supply reach. The bar is composed of bed materials that appear to be mobile during varying flow events. Material consisted of fine sands to medium/coarse sized gravels.

6.2 Pebble Count Data Analysis

Pebble count data was collected at two locations throughout the project reach. It was determined that the streambed substrate at these two locations was representative of the streambed substrate throughout the project reach. Surface particles on two riffle sections were sampled using the Wolman Pebble Counting procedure. The cumulative size distributions obtained from these pebble counts and relative roughness calculations for existing conditions are included in Appendix B.

6.3 Computation Methods of Critical Shear Stress for Marginal Transport

Methods considered here for computation of the dimensionless average stress condition for margin transport of a specific size fraction in mixed grained sediment (Andrews 1995) have the form:

Equation 6-1. Critical Shear Stress for Marginal Transport.

$$\tau_{ci}^{*} = a\left(\frac{D_1}{D_2}\right)^{b}$$

where τ_{ci}^{*} is the dimensionless reference shear stress for a very low transport rate for the specific size fraction in the matrix of the riffle armor layer, a = 0.0384 and b = -0.887 for Andrews (1995) surface material equation. *Equation 6-1* is used to estimate the conditions under which marginal transport will exist in the channel. An assumption is made that the minimum shear stress under bankfull conditions in the assessment riffle should be that which mobilizes the largest particles in the bedload. The variables D1 (largest particle mobilized from bar) and D2 (D50 of the riffle) are representative sizes of the sediment samples. The average boundary shear stress for marginal transport rate of the largest size fraction in the bedload corresponding to τ_{ci}^{*} is given as:

Equation 6-2. Average Boundary Shear Stress for Marginal Transport.

$$\tau_{ci} = \tau_{ci}^{*}\,(S-1)\,\gamma\,D_i$$

where D_i represents the largest size fraction that is considered to be mobile, S is the specific gravity of the sediment (typically 2.65) and γ is the specific weight of water (62.4 lbs/ft^3).

6.4 Sediment Transport Analysis Results

The results of the critical shear stress analysis at each assessment reach riffle using Andrews' 1995 methodology are described below. *Table 6-1* summarizes entrainment data for each assessment riffle based on all measured bed material.

Assessment Reach No.	*AR1-XS1*	*AR1-XS2*	*AR2-XS1*	*AR2-XS3*
D_{50} = Mean Riffle Bed Material Size (mm)	*57.0*	*57.0*	*very fine sand*	*16.0*
D_i = Mobilized Particle Size (mm)	*18.0*	*18.0*	*silt*	*2.0-4.0*
s = Threshold Slope (ft/ft)	*0.016*	*0.016*	*0.0011*	*0.0037*
τ_{ci}^{*} = Critical Dimensionless Shear Stress	*0.1182*	*0.1182*	*0.7386*	*0.1985*
τ_{ci} = Critical Shear Stress (psf)	*0.72*	*0.72*	*0.02*	*0.20*
d_r = Required Critical Depth (ft)	*0.72*	*0.72*	*0.44*	*0.87*
τ_b = Boundary Shear Stress (psf)	*0.64*	*0.55*	*0.07*	*0.16-0.19*
d_e = Field-Determined Threshold Depth (ft)	*0.70*	*0.60*	*0.70-1.10*	*0.70-0.80*

Table 6-1. Summary of entrainment data (Andrews 1995 Methodology) for all riffle bed features.

6.5 Summary of Bankfull Flow Parameters and Classification

The dimensions obtained from the survey data of all assessment cross-sections were utilized in calculating bankfull parameters and developing dimensionless ratios for the proposed restoration design. *Table 6-2* summarizes the geomorphic data collected on each assessment riffle. This table also provides the natural channel stream classification (Rosgen 1996) for each assessment riffle. The stream classification is based on the measured geomorphic properties of each assessment riffle, including entrenchment ratio, width-to-depth ratio, sinuosity, slope, and channel material. An assumption of constant flow and rate was used to compute the energy slope required to satisfy the conditions of the equations used. The Manning coefficient was obtained independently using the Limerinos (1970) relation and bed characteristics at each assessment riffle cross-section. Critical shear stress values are those computed for all riffle bed materials.

Bankfull Flow Parameters	*AR1-XS1*	*AR1-XS2*	*AR2-XS1*	*AR2-XS3*
Stream Type	*B4c*	*B4c*	*E5*	*C4*
Drainage Area (sq. mi.)	*2.0*	*2.0*	*2.79*	*2.79*
Cross Sectional Area (sf)	*12.3*	*9.8*	*10.0*	*9.8-12.6*
Width (ft)	*18.3*	*17.4*	*8.1*	*13.6-16.8*
Mean Depth (ft)	*0.7*	*0.6*	*1.2*	*0.7-0.8*
Width / Depth Ratio	*27.1*	*31.0*	*6.6*	*16.5-22.5*
Maximum Flow Depth, d_{mbkf} (ft)	*1.1*	*0.9*	*2.2*	*1.1*
Hydraulic Radius (ft)	*0.6*	*0.5*	*1.0*	*0.7-0.8*
Manning 'n'	*0.059*	*0.064*	*0.028*	*0.041-0.042*
Flood-Prone Width (ft)	*34.7*	*34.3*	*130.0*	*32.9-58.1*
Entrenchment Ratio	*1.9*	*2.0*	*16.0*	*2.0-4.3*
Riffle Surface D_{50} (mm)	*57.0*	*57.0*	*very fine sand*	*16.0*
Riffle Surface D_{84} (mm)	*140.0*	*140.0*	*fine sand*	*31.0*
Energy (Friction) Slope (ft/ft)	*0.016*	*0.016*	*0.0011*	*0.0037*
Discharge (cfs)	*29.3*	*19.3*	*17.5*	*16.3-22.7*
Average Boundary Shear Stress (psf)	*0.64*	*0.55*	*0.07*	*0.16-0.19*
Largest Mobile Particle Size (mm)	*18.6*	*18.6*	*1.0*	*2.0*
Critical Shear Stress (psf)	*0.72*	*0.72*	*0.02*	*0.20*
Critical Depth (ft)	*0.72*	*0.72*	*0.44*	*0.87*

Table 6-2. Summary of bankfull flow parameters at geomorphic assessment riffles.

The geomorphic assessment reach data above **provides guidance** for establishing proper or stable channel parameters in the proposed design by understanding the existing channels parameters that drive sediment mobility and long-term stability. Bankfull flow discharge was taken from the detailed geomorphic assessment of the reach along Walker Run upstream of the project (AR#1). The information collected at this assessment reach was used to determine the bankfull discharge and like geomorphic features for that assessment reach. The stream type that was observed in this geomorphic setting upstream of the project reach would be classified as a B4c stream type that is relatively stable. The sediment regime in this reach consists of small gravels and sands as identified earlier in *Chapter 4.3 - Supply Reach*. The Marsh Creek Assessment Reach (AR#2) was used to identify geomorphic features that could be used to develop dimensionless ratios and used as a guide to develop specific design criteria for the proposed restoration reach along Walker Run.

7 Restoration Design

The stream restoration design incorporates the principles of fluvial geomorphology in developing the design criteria to restore the Walker Run project reach. The design criteria was based upon the "Guidelines for Natural Stream Channel Design for Pennsylvania's Waterways - March 2007", developed by the Keystone Stream Team.

Data collection included surveying existing conditions of the project reach and identifying/surveying assessment reach conditions upstream of the project reach and along a segment of Marsh Creek, which is located in a separate watershed that exhibited similar characteristics (drainage area, valley slope, geology, etc.). Additional reference condition data was provided by past surveys along Mount Rock Spring Creek in Cumberland County, Pennsylvania. This data was used as guidance to determine the bankfull discharge and channel forming flow of the project reach. The bankfull discharge of the watershed is a function of stream slope, valley slope, valley type, watershed rainfall/runoff characteristics, size of bedload, channel roughness, and discharge, while at the same time distributing excessive energies into adjacent floodplains during higher flow events than the channel-forming discharge. The sediment discharge significantly influences the design criteria of the proposed restoration. The proposed channel design incorporated all of these factors into developing stable channel dimensions (width and depth), pattern (flow path), and profile (bed elevations).

7.1 Design Objectives

Implementation of the proposed design will restore approximately 4,774 feet of Walker Run and the adjacent floodplain. The overlying goal of the restoration is to provide mitigation for stream and wetland impacts associated with the Bell Bend Nuclear Power Plant development. In order to successfully provide this mitigation, the proposed restoration design will address the following objectives:

- Create a stable system using the principles of fluvial geomorphology to improve channel stability along the Walker Run Project Reach;
- Create varying in-stream conditions that are ideal for both trout habitat and spawning.
- Improve water quality by reducing bank erosion and by creating a vegetated floodplain with elevations closer to the seasonal water table that may store and treat surface runoff;
- Provide flood flow storage and infiltration opportunities in the restored floodplain;
- Improve aquatic and riparian habitat;
- Reduce non-point source pollution, including sediment, nutrient and thermal pollution; and
- Provide a floodway that reduces the current flood flow elevations

7.2 Design Justification

The proposed Project Reach is separated into two sites: Site A and Site B. Site A includes the reach between Beach Grove Road and Market Street. As discussed earlier, the existing reach is disconnected from its floodplain with high, vertical banks that are subjected to frequent erosion from high shear stresses during high flows. It flows relatively straight through a wide and relatively flat valley. Much of the reach is pinned against the west valley wall before it bends gradually towards the Market Street bridge. The majority of the land surrounding the project reach is forested with one area along the northeast corner of the site that is mowed. An analysis of the existing soil stratigraphy exposed within trenches excavated within the existing floodplain and along existing cut-banks revealed that approximately 2 feet of historic deposition exists within the floodplain of the Site A project reach with depths increasing to as much as 4 feet downstream. Beneath these historic sediments is a fine sand layer over 2 feet thick which transitions into a 1-foot thick coarser sand layer that contains remnants of wetland plants thousands of years old. The sand transitions into gravel and boulder layer from glacial moraine deposits beginning at a depth of approximately 6 feet. In some locations, the existing stream bed has downcut into the glacial gravel and boulder layer.

Site B includes approximately 1,977 linear feet of the existing reach beginning approximately 150 feet downstream of Market Street. It flows directly towards the steep east valley wall before bending sharply southward. The existing reach continues to flow straight along the east valley wall to the existing farm access road bridge. After flowing under the bridge, the channel bends sharply to southeast for approximately 200 feet before meandering sharply again to flow southward. The remaining portion of the existing reach is relatively straight as it flows past an existing farm pond before meandering hard to the right where it meets its confluence with an unnamed tributary. As with the reach in Site A, the Site B reach is severely incised and disconnected from its floodplain. High flows are trapped within the channel which causes high shear stresses along its banks. The geomorphic analysis of soil stratigraphy in trenches excavated at Site B revealed that approximately 1.3 feet of historic deposits exist within the floodplain of the Site B project reach. Below the historic deposition is a layer of clay-rich sand approximately 1.2 feet thick that was deposited within the valley over the thousands of years prior to settlement. The clay rich sand overlies a coarser, more stratified sand layer beginning at a depth of 2.5 feet below the present ground surface. This sand was probably deposited as alluvial outwash during a high energy period near the end of glaciation. The sand is coarser with depth and transitions into cobble- and boulder-rich glacial moraine deposits. Along most of reach, the channel bed elevations intersect these glacial moraine deposits, which indicates that the reach was most likely artificially ditched to the present bed elevations.

Past human impacts have directly caused unstable conditions described above along the entire project reach whether the stream downcut or was artificially ditched to its current bed elevations. Upon reaching the more resistant glacially or post-glacially deposited gravel/cobble, the channel has been or will begin to laterally migrate. Under these conditions, boundary shear stresses in the active channel exceed the critical threshold levels of the streambed gravels and streambank materials along much of the reach. On-going degradation within the stream corridor should be expected as the stream attempts to evolve toward a C4 or E4 natural channel. The floodplain widening process will continue until the channel can lower its shear stresses to a level where sediment transport achieves equilibrium of incoming and outgoing sediment transport, so that the reach can function in a stable state. This floodplain-widening process, which may span decades, usually comes at great expense to local property, infrastructure, and the downstream environment by eroding the land and contributing a tremendous quantity of sediment and nutrients (nitrogen and phosphorus) to the downstream reaches and/or receiving waters. The primary source of fine sediments being eroded along the project reach are historic sediments that were deposited in the floodplain within the last 200-300 years. The proposed restoration will significantly reduce bank erosion by removing the source of sediment within the proposed floodplain.

7.3 Basis of Proposed Design

The proposed stream and floodplain restoration design is based on an analysis of existing site characteristics, a historical analysis, a visual assessment of the project reach and the surrounding watersheds, a detailed geomorphic assessment of the unstable project reach and stable reference conditions, a geomorphic analysis of existing soil stratigraphy, and a sediment transport analysis for existing and proposed conditions. The analysis of existing site conditions involved researching the geographic setting, hydrology, underlying geology, sediment supply, and land use. Research of historical maps and documents provided insight as to how the watershed has been impacted by human activities. During the detailed geomorphic assessment, important morphological data was collected along the project reach and off-site assessment reaches to document existing conditions and to serve as reference for the design. The morphological data included measurements of existing unstable features, stable features, stream slopes, and bed material. Stream segments that exhibited channel-forming bankfull indicators such as low-lying vegetated bench features were selected as assessment reaches and surveyed in detail. Further important data was collected during the geomorphic analysis of the existing soil stratigraphy exposed in the trenches excavated along the project reach (*see Appendix A*). The data collected during the soil stratigraphy analysis included the depth/age of historic sediments, pre-settlement bed elevations, and depths to underlying glacial deposits. An important conclusion resulting from the soil stratigraphy analysis is that the soil stratigraphy observed within the trenches directly correlated to the soil stratigraphy of the eroded stream banks along the project reach and that the pre-settlement bed materials were found at uniform sloping elevations throughout the floodplain of the project reach. An analysis of the morphological data and a sediment transport analysis were completed to calculate proposed bed elevations, bankfull elevations, and shear stress limits, which are necessary to create a stable plan form, profile, and channel/floodplain dimensions that will transport the sediment load from the upper watershed over time without degrading.

The planform, profile and cross-section characteristics were developed by the following procedure:

1) develop a channel alignment by examination of valley or land use constraints and the expected flood flow pattern;
2) create a longitudinal profile that corresponds to the proposed alignment with riffles in the straight portions of the planform and pools in the bends. The proposed bed invert (thalweg) elevations of the longitudinal profile matches the upstream and downstream tie-in grades and the pre-settlement bed elevations observed along exposed bank profiles and within trenches during the geomorphic assessment;
3) determine the cross-sectional characteristics of proposed riffles and pools that correlates to assessment reach survey data and will be able to convey the bankfull flow and maintain marginal transport of the largest particle in the bedload; and
4) modify the planform and repeat processes until planform pattern, longitudinal profile and cross-sectional characteristics are determined within reasonable limits.

An important missing link involving flow and sediment transport in the design of channels is a coherent and rational method for designing channel bends. The concept of marginal transport of the largest particles in the bedload may be useful to examine the transport of bedload particles through riffles; however, no such concept is available for flow and sediment transport in stream bends. Additionally, reference reaches in similar streams with stable channel bends are difficult to locate in the heavily manipulated streams of Pennsylvania. Because of the lack of a rational method for designing bends with relation to flow conditions, the following general considerations were used:

1) bends with radii of curvature less than 1.5 times the channel bankfull width, on specific stream types, are prone to forming impingements on the outside of bends and large flow separation areas on the inside of bends (Bagnold 1960);
2) bends with radii of curvature greater than four times the channel width are prone to forming multiple pools with intermediate glides or riffles; and
3) pool to pool spacing of approximate 5 to 10 times the channel bankfull width are typical (Knighton 1999).

Another assumption made was that if channel bend cross-sectional areas are constructed larger than riffle areas, deposition will occur on the inside or outside of the bend to lengthen or shorten the channel, respectively. Therefore, slight adjustment in the bend characteristics of the proposed channel is anticipated.

The design of each riffle was developed utilizing the concept that marginal sediment transport of the largest particles in the bedload occur at the bankfull conditions and the Andrews (1995) surface-based equation as an adequate representation of this condition. The following specific considerations were used in the design:

1) virtually all of the drop between the upstream and downstream extents of the relocation occurs in riffle reaches, rather than bend reaches:

2) the planform, slope and valley constraints dictates the specific number of riffles:
3) the riffle must convey the bankfull flow as well as the largest particles of the mobile sediment load at bankfull flow;
4) the combination of adjustment in riffle texture, minor changes in riffle slope, adjustment in channel bend length is sufficient to maintain stream stability if the stream planform pattern, vertical profile and cross-section characteristics are within reasonable limits required to transport the mobile sediment load during near-bankfull events;
5) Andrews (1995) surface-based reference marginal bedload transport equation represents a rational basis for a method to relate the slope of the riffle, the cross-sectional characteristics and the maximum particle size that must be transported in the bedload;
6) where necessary, a static armor layer can be developed by the placement of large particles in the riffle reaches. The texture of the riffle will respond to sediment loads by transporting the sediment over the riffle as long as the initial material is sufficiently large. Deposition of fines will increase sediment transport capacity whereas erosion of fines will decrease sediment transport capacity; and
7) the simple Manning equation for uniform flow is sufficient to develop the cross-sectional characteristics of riffle sections of the channel.

For the proposed stream and floodplain restoration design to remain stable through a range of flow events, the system must be able to transport the available sediment load. Typically, the designed channel should have a water surface slope and depth of flow capable of mobilizing a particle at the bankfull stage no greater than the mean particle size, or D_{50}, of the designed riffle. The amount of sediment that enters a reach should be equal to the amount of sediment exiting the reach over time. This balance of sediment transportation throughout the river network is critical for a natural channel to remain in a stable form. Typically, the D_i size is estimated to be the largest mobile particle that can be sustained in a stable manner for routine bankfull events over the long-term, given that there is an available sediment load from the upstream reaches. The absence of a sustained supply of large gravels or cobbles discovered during the geomorphic assessment suggests that the majority of the bedload consists of fine-grained gravel, sand, and silt eroding from the vertical streambanks upstream. The absence of large gravels or cobbles found in the pre-settlement floodplain sediments during the geomorphic analysis of soil stratigraphy further suggests that historically the stream channels did not readily transport large material found in the streambeds. Historically, the presence of a highly attached floodplain at a low elevation relative to the streambed reduced shear stresses to levels incapable of transporting large sediments.

7.4 Design Summary

It has been determined that most influential factor on the current channel instability observed along the project reach is channel incision, or entrenchment, which prevents an effective connection between the channel and its floodplain. Furthermore, the banks are composed of fine-grained sediments that have accumulated in the valley bottom since the end of glacial times and most significantly during the post-settlement period. These fine-grained sediments are eroded from the banks and mobilized during high flows because of the shear stresses resulting from the channel incision.

To effectively accomplish the design objectives, the proposed design involves lowering the floodplain to elevations that intersect the existing pre-settlement bed materials, which were observed at uniform elevations throughout the project reach. The proposed bankfull and floodplain elevations are low enough to allow higher flows to access the floodplain more frequently thereby alleviating erosive shear stresses on the banks during high flows. In addition, these elevations are closer to the average water table, which will allow the root zones of riparian vegetation to intersect the groundwater and improve floodplain's nutrient filtering function. The project reach will be relocated to create a stable pattern and profile that will transport the natural bedload of the watershed without degrading. The restored channel will follow a gentle meandering riffle-pool sequence pattern that is not only more stable but also ideal for aquatic habitat.

In-stream structures including 4 cross-rock vanes, shall be installed at proposed tails of riffles near the upstream and downstream tie-in locations of each project reach segment (Site A and Site B) to establish grade control, direct flow to the center of the channel, further stabilize the banks, and provide in-stream habitat. Numerous log-sills shall be installed along the project reach at 6-inch vertical intervals for added in-stream grade control. The proposed cross-rock vanes and log sills will have invert elevations that match proposed bed elevations. Numerous mud sills and log cover habitat structures shall also be installed throughout the length of the project reach to provide in-stream habitat specifically for fish. During construction, additional woody debris may be installed along the banks of the project reach at the discretion of the project designer to provide additional in-stream habitat, channel roughness, and bank stability.

Installed native wet-tolerant herbaceous and woody vegetation shall provide improved habitat, nutrient uptake, additional bank stabilization, erosion control, and overhead cover for aquatic organisms along the restored stream channel and within the floodplain corridor. The proposed floodplain will have widths ranging between 80 and 150 feet in Site A and between 80 and 310 feet in Site B. Variations in the available floodplain width through the project site are a direct function of where existing infrastructure, wetlands, or valley walls are located and how much land the landowner could reasonably provide for the restoration effort. It is anticipated that floodplain grading will promote at least over 8 acres of wetlands and native riparian buffer establishment.

Implementation of the proposed restoration design will improve the connection between the stream channel and floodplain, which will provide the following benefits:

- Reduced shear stresses on the bed and banks;
- Increased flood storage and attenuation, which will reduce localized flooding;
- Filtering and settling of sediment-laden water during flood flows;
- Storage and treatment of stormwater;
- Improved water quality;
- Wetland establishment;
- Improved groundwater infiltration;
- Improved/increased riparian and aquatic habitat

Using principles of fluvial geomorphology and natural stream channel design (NSCD), the proposed channel dimensions (width and depth), pattern (flow path), and profile (bed elevations) were designed based on data collected at geomorphic assessment reach locations that exhibit characteristics of channel stability. The proposed bed and floodplain elevations were designed based on data collected during the geomorphic analysis of the existing soil stratigraphy.

One of the most important design objectives is to create varying in-stream conditions that are ideal for both trout habitat and spawning. Trout spawning typically requires relatively shallow, well-defined riffle beds composed of coarse gravels, while trout habitat typically requires deeper pools and overhead cover. To meet this objective, the proposed project reach will include two distinct stream types that exhibit characteristics ideal for trout habitat and spawning while maintaining a pattern and profile that appropriately matches the existing valley type. The project reach within Site A shall be a C4 stream type, which will have a high average width-depth ratio and a bed dominated by gravel. The project reach within Site B shall begin as a C4 stream type with a high average width-depth ratio and a bed dominated by gravel for the first 740 feet and transition into an E4/E5 stream type, which will have a lower average width-depth ratio and have a bed dominated by gravel or sand. The wide and shallow dimensions of the C stream type is intended to provide ideal trout spawning, while the narrow and deep dimensions of the E stream type is intended to provide ideal trout habitat. Proposed cross-section data is included in Appendix C. *Table 7-1* summarizes proposed design parameters for each segment of the project reach. The Morphologic Characteristics Summary Table in Appendix D provides a comprehensive summary of all parameters associated with assessment reaches and proposed conditions.

Project Reach	**Site A (Sta. 0+00 to 8+49)**	**Site B (Sta. 0+00 to 7+40)**	**Site B (Sta. 7+40 to 33+10)**
Stream Type (Rosgen)	C4	C4	E4/E5
Drainage Area (mi^2)	2.0-2.3	2.3	2.3-2.4
Cross-Sectional Area (ft^2)	8.4-12.6	9.6-14.0	7.2-14.4
Width (ft)	12.0-14.0	12.0-14.0	8.0-12.0
Mean Depth (ft)	0.7-0.9	0.8-1.0	0.9-1.2
Max. Depth (ft)	1.0-1.4	1.0-1.4	1.0-1.4
Width/Depth Ratio	13.3-20.0	12.0-17.5	6.7-13.3
Hydraulic Radius (ft)	0.7-0.9	0.8-1.0	0.8-1.2
Flood-prone Width (ft)	80.0-150.0	80.0-250.0	190.0-310.0
Entrenchment Ratio	5.7-10.7	6.7-20.8	19.0-31.0
Bankfull Energy Slope (ft/ft)	0.0029	0.0033	0.0024
Riffle Slope (ft/ft)	0.0035-0.0044	0.0040-0.0050	0.0026-0.0029
D_{50} (mm)	30.0-50.0	30.0-50.0	—
D_{84} (mm)	67.0-77.0	67.0-77.0	—
Manning 'n'	0.030	0.030	0.030
Mean Velocity (ft/sec)	2.3	2.5	2.3
Discharge (cfs)	19.3-29.0	24.0-35.0	16.6-33.1
Pool Width (ft)	13.2-19.6	13.2-19.6	8.0-14.4
Pool Max. Depth (ft)	1.8-3.2	2.0-3.5	1.4-3.0
Pool Slope (ft/ft)	0.0006-0.0015	0.0007-0.0017	0.0019-0.0022
Pool Cross-Sectional Area (ft^2)	15.5-23.3	16.2-23.6	12.2-24.3
Pool to Pool Spacing (ft)	70.0-98.0	54.0-84.0	32.0-70.0
Radius of Curvature (ft)	35.0-42.0	30.0-36.0	16.0-30.0
Meander Length (ft)	143.0-175.0	114.0-185.0	70.0-190.0
Belt Width (ft)	45.0-72.0	75.0-100.0	20.0-102.0
Valley Slope (ft)	0.0038	0.0049	0.0047
Sinuosity	1.3	1.5	2.0

Table 7-1: Summary of bankfull parameters and plan form characteristics along the proposed project reach. Values are for bankfull flow conditions at proposed riffles unless otherwise noted.

For the proposed project reach in Site A and the first 740 feet of Site B, proposed riffle dimensions were developed to resemble the relatively stable dimensions observed along the lower segment of the Marsh Creek assessment reach, which exhibited distinct channel-forming bankfull indicators. Proposed pool dimensions were developed using the existing pool dimensions surveyed along this segment of Marsh Creek assessment reach as a guide in combination with standard ratios for C4 stream type average values[2] (*see Appendix D*). It was determined during the detailed geomorphic assessment that this segment of Marsh Creek assessment reach would not provide reliable reference conditions for developing plan form characteristics (i.e. meander length, radius of curvature, belt width, or sinuosity). Therefore, plan form parameters were calculated using standard ratios for C4 stream type average values. As discussed earlier, the proposed riffle beds are proposed to be at or near pre-settlement substrate. It is anticipated that gravels of adequate size for trout spawning

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[2] River Restoration and Natural Channel Design – Field Guide. Level IV Rosgen Short Course. Wildland Hydrology, Inc. 2002.

exist throughout the valley bottom at these elevations. However, if during construction the presence of less coarse material such as sand is dominant at the proposed riffle bed elevations, then it will be necessary to over-excavate the proposed channel and add appropriately-sized gravel to match the proposed grades. This would require harvesting gravel on-site from areas within the proposed limit of disturbance or importing native gravel from another location. The gravel size range should have a D_{50} of approximately 30-50 mm, which will provide acceptable streambed particle sizes for trout to build redds and also limit excessive mobilization of the riffle bed surface[3] (*refer to Morphological Characteristics Summary of Existing and Proposed Conditions in Appendix D for proposed riffle particle size distributions*).

For the remaining 2,570 feet of the proposed project reach in Site B, proposed riffle dimensions were developed to resemble the relatively stable dimensions observed along the upper segment of the Marsh Creek assessment reach. It was determined during the detailed geomorphic assessment that existing pool dimensions and plan form characteristics along this segment of the Marsh Creek assessment reach would not provide reliable reference conditions for the design. Therefore, pool dimensions and plan form characteristics were calculated using dimensionless ratios developed from E stream type reference conditions observed along Mount Rock Spring Creek in Cumberland County, Pennsylvania as a guide. This reference reach has a drainage area roughly double that of the Walker Run project reach. While this reference reach proved to be a useful guide for most of the design parameters, it did not apply for others such sinuosity and average pool slope. Therefore, these design parameters were developed to be consistent with typical E stream type conditions described by the Rosgen Classification of Natural Rivers, which are based on extensive research and field-surveys of reference conditions throughout the United States. In general, E stream type channels are highly sinuous, have a higher ratio of average pool slope to average bankfull slope, and a lower ratio of maximum pool depth to average riffle depth. Dimensionless ratios used in calculating proposed design parameters are summarized in *Table 7-2*. The strategy for designing the E stream type segment of the project reach was to create a highly sinuous plan form, which maximizes the total stream length and minimizes the stream slope. A lower slope limits bankfull velocities, which allows the proposed channel to have a low width-depth ratio without causing excessive shear stress, thereby maintaining stability as well as providing good trout habitat. As discussed earlier, it is anticipated that gravels exist throughout the valley bottom at proposed riffle bed elevations. However, because this segment of the project reach is designed specifically for trout habitat, it is acceptable to have a dominance of gravel or sand at proposed riffle bed elevations. Therefore, it will not be necessary to place harvested or imported gravel along the riffle beds through the E stream type segment of the project reach.

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[3] Habitat Suitability Index Models and Instream Flow Suitability Curves: Brown Trout. Biological Report 82(10.124). U.S. Fish and Wildlife Service. U.S. Department of the Interior. 1986.

Dimensionless Ratios	*C4 Stream Type Site A (Sta. 0+00 to 8+49) & Site B (Sta. 0+00 to 7+40)*	*E4/E5 Stream Type Site B (Sta. 7+40 to 33+10)*
Riffle Max. Depth to Bankfull Depth	1.2-1.4	1.0-1.2
Pool Max. Depth to Bankfull Depth	2.5-3.5	1.5-2.5
Pool Width to Bankfull Width	1.1-1.4	1.0-1.2
Riffle Slope to Bankfull Slope	1.2-1.5	1.1-1.2
Pool Slope to Bankfull Slope	0.2-0.5	0.8-0.9
Radius of Curvature to Bankfull Width	2.5-3.0	2.0-3.0
Pool to Pool Spacing to Bankfull Width	4.5-7.0	4.0-7.0
Meander Length to Bankfull Width	9.0-14.0	8.0-12.0

Table 7-2: Summary of dimensionless ratios used for calculating proposed design parameters. Ratios that include "bankfull" refer to average bankfull conditions at riffles.

7.5 Proposed Boundary Shear Stress for Marginal Transport

In order to ensure that the proposed stream channel would have adequate energy to move its natural bedload, it is necessary to calculate the average boundary shear stress. To do this, it is necessary to use the Shield's equation as follows:

Equation 7-1 - Average Boundary Shear Stress

$$\tau_b = \gamma \, RS_f$$

where:

τ_b = cross-section average boundary shear stress,
γ = density of water or 62.4 lbs/ft^3
R = hydraulic radius or mean depth
S_f = friction slope (ft/ft)

As discussed earlier, the proposed project reach has been divided into two separate sites: Site A and Site B. At Site A, the project reach between proposed station 0+00 and 8+49 has a proposed bankfull (friction) slope of 0.0029 ft/ft and a hydraulic radius of 0.7-0.9 feet. Therefore, the proposed average boundary shear stress ranges between 0.13 and 0.16 pounds per square foot (lbs/ft^2), which is capable of initiating the motion of particle sizes ranging between 8.2 mm and 9.5 mm at the bankfull discharge according to the Shield's Diagram (see *Figure 7-1*). At Site B, the project reach between proposed station 0+00 and 7+40 has a proposed bankfull (friction) slope of 0.0033 ft/ft and a hydraulic radius of 0.8-1.0 feet. Therefore, the proposed average boundary shear stress ranges between 0.16 and 0.21 lbs/ft^2, which is capable of initiating the motion of particle sizes ranging between 9.5 mm and 14.0 mm at the bankfull discharge. At Site B, the project reach between proposed station 7+40 and 33+10 has a proposed bankfull (friction) slope of 0.0024 ft/ft and a hydraulic radius of 0.8-1.2 feet. Therefore, the proposed average boundary shear stress ranges between 0.12 and 0.18 lbs/ft^2, which is capable of initiating the motion of particle sizes ranging between 7.6 mm and 12.0 mm at the bankfull discharge. Shear stresses were calculated using the proposed average bankfull slopes. Based upon this determination, the anticipated boundary shear stress at the bankfull flow will be adequate to transport the majority of the sediment that is currently being mobilized by the project reach without degrading. Proposed boundary shear stress values are summarized in *Table 7-3*.

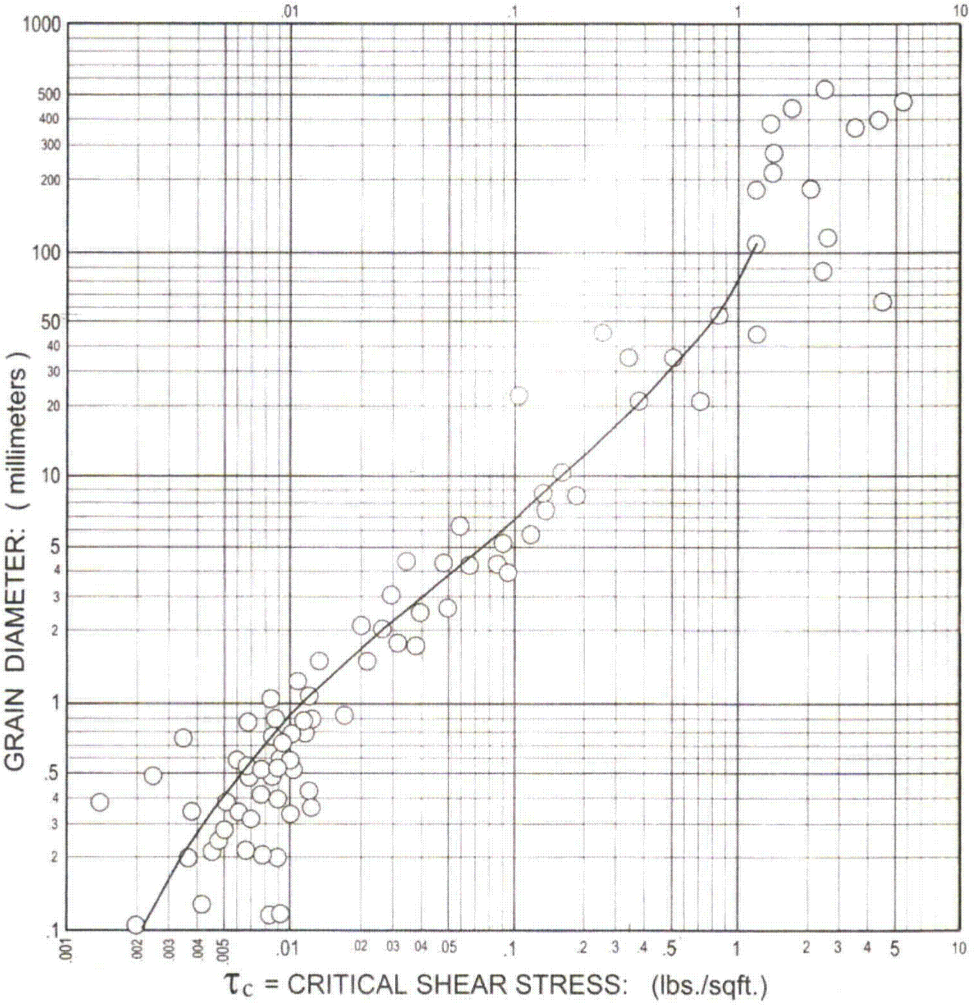

Figure 7-1. Shield Diagram. (Source: The Reference Reach Field Book, p. 190, Wildland Hydrology, 1998)

Project Reach	***Site A*** (*Sta. 0+00 to 8+49*)	***Site B*** (*Sta. 0+00 to 7+40*)	***Site B*** (*Sta. 7+40 to 33+10*)
D_{50} = Mean Riffle Bed Material Size (mm)	40	40	variable
s = Proposed Threshold Slope (ft/ft)	0.0029	0.0033	0.0024
D_{bkfl} = Proposed Mean Bankfull Depth (ft)	0.7-0.9	0.8-1.0	0.8-1.2
τ_b = Boundary Shear Stress (psf)	0.13-0.16	0.16-0.21	0.12-0.18
D_m = Threshold Grain Diameter (mm)	8.2-9.5	9.5-14.0	7.6-12.0

Table 7-3: Summary of entrainment data (Andrews 1995 Methodology) for proposed riffles.

Our field investigations determined that the incoming sediment supply consists primarily of fine gravels, sands, and silts less than 20 mm in size, which requires a shear stress of approximately 0.37 lbs/ft^2 to be mobilized. The proposed boundary shear stress through Site A will equal 0.13-0.16 lbs/ft^2. The proposed boundary shear stress through Site B will equal 0.16-0.21 lbs/ft^2 along the first 740 feet and 0.12-0.18 lbs/ft^2 along the remaining 2,570 feet. This translates into a mobile particle size of 8.2-9.5 mm in size through Site A, 9.5-14.0 mm through the first 740 feet of Site B, and 7.6-12.0 mm through the remaining length of Site B. Therefore, the proposed channel will be able to transport the majority of incoming sediment load during bankfull conditions. However, it will not mobilize the larger sized bed materials that will make up the majority of riffle beds within the project reach.

As bankfull flows recede, smaller-sized particles will likely deposit and be sheltered within the larger riffle material. Therefore, some degree of temporary aggradation within the project reach may occur between bankfull flows. It should be assumed that flows exceeding bankfull will not initiate the mobilization of particles larger than those mobilized during bankfull flows because these flood flows will access the proposed lower-elevation floodplain corridor, thereby alleviating increases in shear stress. It should be noted that, among its many functions, the proposed floodplain is intended to serve as a sediment "sink". In other words, it is anticipated that fine-grained silts and sands that are suspended within flood flows will likely deposit evenly throughout the surface of the floodplain as the flood flows recede. Deposition may be more noticeable within the floodplain near the downstream end of the project reach where proposed floodplain elevations tie into existing grades. It is unlikely that any potential aggradation of fines within the floodplain will accumulate in quantities that impede future flood flows. However, as an assurance measure, lower wetland pockets shall be created at numerous locations within the floodplain to capture suspended sediment. Proposed cross-section and longitudinal profile data is included in Appendix C. The Morphologic Characteristics Summary in Appendix D provides a comprehensive summary of all existing and proposed conditions.

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