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A Report to the USEPA, Kentucky Division of Water and the Kentucky Water Resources Research Institute

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EXECUTIVE SUMMARY

The removal of gravels from streambeds is a common practice in Kentucky, but the biological and geomorphic effects of these operations have not been assessed in the Commonwealth. We performed a four-year study assessing the impact of gravel removal operations in four streams (two mined streams and their paired controls) in the Buck Creek Watershed of the Upper Cumberland River basin. The specific objectives were to determine:

1) the extent of direct and indirect impacts of gravel mining on channel form and the stream biota;
2) the effects of mining on the gravel substrate; and
3) the differences in impact between intensively mined streams and those that have not been recently intensively mined.

To achieve these objectives, we:

- conducted site visits to streams throughout the basin to become familiar with the regional characteristics of stream channels;
- selected two pairs of typical and representative stream reaches; one reach included sections recently and intensively mined (referred to as mined reaches) and one reach had no observable recent or intensive mining (defined as the reference) in each pair;
- identified other impacts affecting the physical and biological conditions of the streams;
- conducted detailed topographic surveys of the paired stream reaches and floodplains;
- compared the sediment substrate characteristics in the mined and the reference stream reaches;
- compared the geomorphological characteristics of the mined and the reference reaches;
- examined the flood flow characteristics of the mined reaches versus the reference reaches;
- assessed the biological integrity of the streams using fish and macroinvertebrate biometrics; and
- evaluated physiochemical and water quality differences among the streams using water chemistry, hyporheic and sediment deposition sampling.

For both the biological and geomorphic assessments, the impacts of gravel mining were determined by comparing characteristics of intensively mined stream reaches to the characteristics of reference stream reaches (stream reaches of similar basin characteristics that were not recently intensively mined). Comparisons were made by two methods:

1) Comparison of stream characteristics of up to four reaches of the same stream, where at least one reach was extensively mined, a second reach was upstream of the mining and impacted by the mining, and a third reach was upstream of a natural grade control.

2) Comparisons of two stream sections located in similar watersheds, one stream intensively mined and a second that was not intensely mined.

Physical and geomorphic assessment activities included analysis of streambed thalweg profiles and surface substrate size gradations. Stream planform characteristics were determined from USGS maps and ground-based total station surveys. Channel geomorphology was assessed using a combination of Rosgen techniques and one-dimensional hydraulic modeling. All of the study streams showed evidence of extensive channelization but gravel mining impacts varied.

As found in other studies of gravel mining, the morphological impact of gravel extraction was found to be dependent on many factors including the specific geomorphic state of the stream and the method and quantity of gravel removal. In the streams examined in this study, channel incision caused by past channelization has created a condition where less than 1.5 meters of streambed gravel overlays a formation of shale bedrock that is exposed in deep pools in all streams examined. In highly disturbed reaches, extensive regions of bedrock bottom channels were observed. Stream reaches not directly or indirectly impacted by recent intensive gravel extraction were shown to be in a general state of aggradation with channel lateral migration driven by bank erosion. Intensive gravel mining was observed at locations in channel systems where rapid aggradation would be anticipated in the absence of mining: 1) backwater areas in tributaries upstream of confluences, and 2) regions of rapid channel lateral migration and rapid point bar building. The gravel extraction techniques observed and the impact of gravel mining varied with the morphological conditions causing channel aggradation. The impact of gravel mining varied with aggradation environment and the mining techniques.

Specific differences in the comparison of morphological features between reference and mined streams were observed. For the first stream pair, the pools were more numerous and deeper and the channel deeper, narrow and less incised and entrenched in the reference stream reaches as opposed to the mined stream reaches. In the mined reaches, the most extensive mining technique observed was complete gravel removal to the bedrock. Large areas of bedrock were exposed upstream of the primary mining reaches. Conversely, bedrock was exposed only in the deepest sections of pools in the reference stream reaches. Riffles were absent or infrequent and rapidly degrading shale bedrock steps were frequent over extensive bedrock sections upstream of frequently mined reaches.

For the second stream pair, there were no consistent differences between them attributable solely to gravel mining. Methods of gravel extraction techniques in the mined reach were less severe (removal of gravel primarily from point bars) than in the first pair. Additionally, rapid channel migration and point bar building even within mined reaches indicated that the gravel load supplied to the mined reach was higher than the amount extracted.

We used a variety of biological techniques and metrics to compare community composition and other ecological factors between mined and reference streams. Mined streams had lower Kentucky IBI scores for their fish and macroinvertebrate communities compared to reference streams. Pooled fish densities were not different between mined and reference streams, but macroinvertebrate densities and biomasses were usually lower in the mined streams than in reference streams. Most macroinvertebrate functional feeding group percentages were not significantly different between the two types of streams, but clinger and sprawler functional groups were higher and lower, respectively, in the reference streams vs. the mined streams. There were higher levels of nitrates and chlorides in the hyporheic water of the mined streams and higher densities of "intolerant" taxa in the reference streams. Surface chlorophyll a was not significantly different between mined and reference streams but ash free dry mass (AFDM) of the biofilm was higher in the mined streams. Sediment deposition was higher in the mined stream confluences.

In summary, gravel extraction, as currently conducted, is having significant negative effects on the biota in mined streams as compared to reference streams with no active gravel mining. Strong geomorphic and biologic evidence suggest that these negative impacts are associated with both a local response of high sediment production caused by bank erosion that is a response to both channelization and gravel mining as is currently conducted. The driving mechanism of bank erosion is the evolution of streams that were previously channelized. Gravel mining in some locations may be a response by local landowners to excessive sediment production from bank erosion of the evolving channels. These negative effects are evident both upstream and downstream of mining sites during periods of normal and below normal stream flow in the region.

We recommend that gravel mining should be limited only to stream reaches in which long-term detrimental aggradation of channels gravels is occurring. A review of the methods of protecting upstream channels from mining impacts, suggestions for monitoring mining activities, and methods for mining that cause minimal impacts are included in this report. Suggestions for incorporating off-channel gravel mining as part of comprehensive stream restoration plans for incised channels are also provided; however, a comprehensive watershed management plan should be developed for the Buck Creek watershed to support decisions on stream bank and bed stabilization, flood mitigation and stream restoration activities.

1.0 INTRODUCTION

1.1 General Review of Gravel Mining Practices

The mining of sand and gravel from stream and river channels has been a common practice in the United States and Europe for many decades. Much of the mining activity is associated with dredging operations for navigation maintenance or improvement projects in larger rivers, but up to 20% of the sand and gravel mined nationwide comes from smaller rivers and streams (Meador and Layher 1998). About 96% of mined sand and gravel is used for construction materials with the rest used in a variety of industries such as glassmaking (Langer 1988). The construction industry uses sand and gravel as bed materials for roads, highways, and pipelines, septic systems, and as aggregates for concrete (Kondolf 1994a). Gravels can be obtained from a number of sources and by a variety of methods, which we will classify here using the United States Army Corps of Engineers (USACE) guidelines, as "dredging" or "extraction" (USACE 1997). The USACE defines "gravel dredging" as gravel removal from a wet environment and "gravel excavation" as gravel removal from a dry environment (including gravel bars in or adjacent to streams). Instream sand and gravel deposits can be mechanically removed ("dredging") from the streambed by a number of methods including bulldozers, dredges and draglines. Gravel extraction often takes place in the floodplains near streams where pits are excavated to obtain the gravels and sands that have been deposited there (Meador and Layher 1998). Gravel excavation is the preferred method of gravel removal because of its presumed lower impact on aquatic biota (see "Impacts" section below). However, gravels obtained from instream sources are preferred because the transport of the rock through the stream systems tends to degrade the weaker materials, leaving the more resistant and valuable materials to be mined (Kondolf 1997). Sand and gravel mined from streams and rivers is inexpensive, but the price of the material roughly doubles for every 40 km it is transported (Kondolf 1994b). As a result, most mining operations are located within 50km to 80km of the areas of greatest demand (Meador and Layher 1998; Kondolf 1997).

1.2 Gravel Mining Impacts

Stream degradation caused by instream gravel mining has been known since Lane (1947). The spatial and temporal impacts of gravel mining are dependent on many factors. Current stream conditions, historical and additional current effects, and the duration, extent, intensity and methods of gravel mining all influence the degree to which gravel mining impacts stream morphology and aquatic habitat. Each stream also varies in its sensitivity to disturbance. Active, high-energy environments, such as braiding channels, will adjust dramatically to any imposed change, whereas low-gradient streams with cohesive banks will adjust less dramatically. Although impacts are often considered to be detrimental, in the case of rapidly aggrading channels gravel mining may increase channel stability. Most often, however, gravel mining reduces the supply of coarse sediments in a stream system and at least temporarily causes local stream channel instability.

In cases of long-term, intensive and/or extensive mining, the morphology of the stream system can be drastically altered. Some of the most significant impacts of and responses to gravel mining include changes to the sequence and stability of riffles and pools in streams, changes to the distribution and mobility of channel substrate, and changes in the incision of the channel streambed. The loss of the riffle-pool sequence decreases the ecological value of the stream through reduced spawning gravels and reduced macroinvertebrate habitat. Hydraulic conditions of the stream are also altered, as the disrupted riffles affect flow behavior through a channel both directly (through backwater effects) and indirectly (through the increased roughness).

Indirect impacts include the lowering of the groundwater levels where groundwater elevations are controlled by the elevation of the stream channel bed. In this way the detrimental effects of the in stream mining can extend well into the floodplain by causing a reduction of biodiversity in the hyporheic zone (the portion of unconfined, near-stream aquifers where stream water is present). This lowering of the floodplain groundwater levels can also alter the riparian floral mosaic, resulting in reduced wetland areas and their associated faunal and flood control values.

The long-term morphological response to gravel mining depends on the relative rate of gravel extraction to the rate of sediment supply required to maintain equilibrium channel condition. In channel systems where gravel extraction rates do not exceed the supply of gravel, downstream channel degradation can still be expected since this region is "starved" of its typical gravel supply. Downstream armoring and channel incision are possible. Where gravel extraction exceeds supply, the upstream propagation of headcuts may induce a general lowering of streambed elevations downstream as well as upstream.

In the processes of gravel dredging, the resulting pit in the streambed creates a change in gradient that results in higher water velocities (Figure 1.1a). The upstream portion of the pit may become a headcut area that propagates upstream. As the headcut moves upstream, there is increased substrate mobilization upstream of the pit, increasing the bedload of the stream (Fig. 1.1b). The pit however may intercept the transported bedload and begin to refill. This process reduces the bedload of the water as it passes over the pit, increasing the capacity of the water ("hungry water" in the terminology of Kondolf [1994b]). Thus, streambed erosion may increase downstream from the dredging operation as well (Fig. 1.1c.) As the cycle of dredging and gravel replacement continues, the streambed may incise, leading to the widening and deepening of the stream channel (Kondolf 1994b). As a result, progressively larger flood events are contained within the channel of the stream.

If enough gravel is removed and incision continues long enough, the stream may incise completely down to the underlying bedrock or armor layer (Kondolf 1994b). Such incision events can destabilize banks and channels, lower water tables, damage riparian vegetation, lead to bed coarsening (or fining), interrupt bedload transport, increase gradients along the streambed and undermine structures (Meador and Layher 1998; Kondolf
1994a; Kondolf 1994b; Kanehl and Lyons 1992). Incision can propagate up tributaries as these streams begin to adjust their channel forms to the newly lowered bed of the receiving stream; similar impacts may occur in gravel extraction areas as well. In this way the incision is self-propagating: a dynamic and complex response from the channel should be expected.

This propagation extends upwards into tributaries and is not confined to the mined stream, although it is likely that controls such as local bed armor and/or bedrock will limit headcutting in upland reaches. A summary of immediate, short-term, secondary, and long-term impacts of gravel mining on stream reaches can be found in Appendix I.

Mining of sand and gravel outside of the active stream channel (excavation), either by gravel bar skimming or mining in the floodplain, avoids the immediate erosion impacts of gravel dredging, but may lead to other problems. For example, floodplain mining can result in a series of pits alongside a river. If a flood reaches the floodplain, these pits may headcut upstream. The pits may join and even capture the stream flow, potentially causing the stream to change course (Kondolf 1994b). In some cases, such as in rapidly aggrading systems, removal of bedload may have some positive societal benefits. In a few studies, the effects of gravel mining have been considered to be beneficial for controlling floods and stabilizing channels by reducing the levels of overbank floods and by deterring the avulsion of channels (see Appendix I). However, while channel stability has been

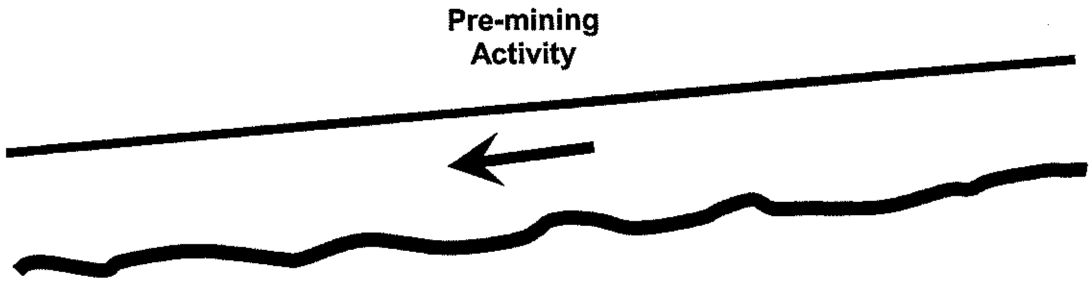

Fig. 1.1a

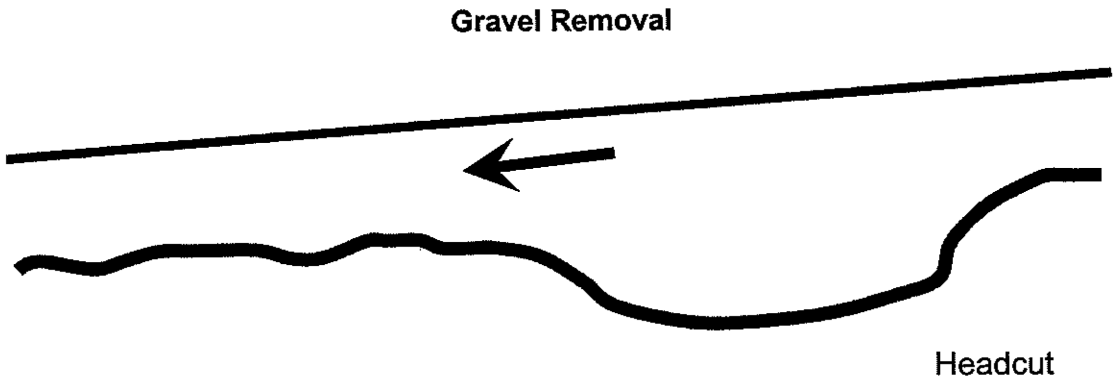

Fig. 1.1b

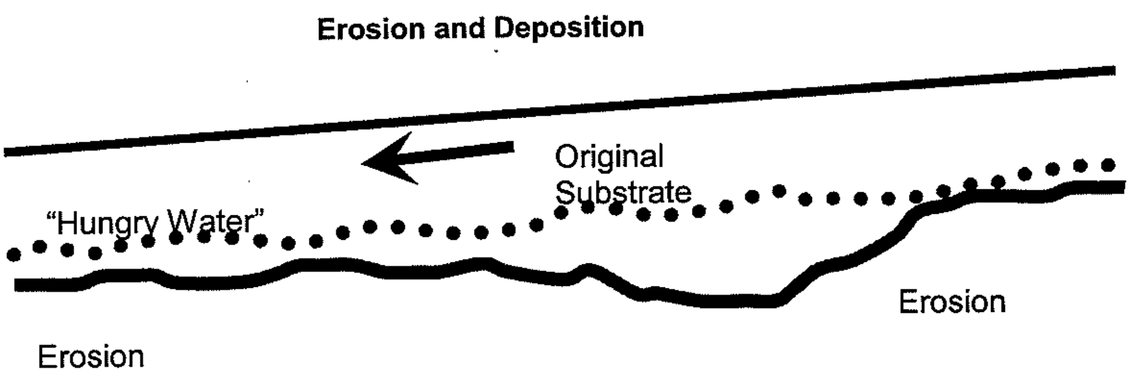

Fig. 1.1c

Figure 1.1a-c: Erosion sequence resulting from in-stream gravel mining. Fig.1.1a, Pre-mining. Fig.1.1b, Gravel removal. Fig.1.1c, Subsequent erosion upstream and downstream from mined location. "Hungry Water" represents stream water with much of its bedload removed. Modified from Kondolf (1994b).

achieved in some cases, benefits to stream habitat have not been demonstrated. In most studies, the morphological response of the streams has been shown to be detrimental to stream habitat and to human infrastructure including bridges, culverts, and pipeline crossings (Table 1.1). It must be noted, however, that gravel extraction and excavation operations are usually not the only impacts affecting stream channel form and the biology of resident organisms in mined streams. Past land use practices such as agriculture and present impacts such as reservoirs may make it difficult to distinguish mining effects from other impacts in the watershed (Kondolf and Swanson 1993).

Table 1.1. Summary of impacts of gravel extraction on selected streams in the United States*. Table data from Kanehl and Lyons, 1992. DR=dredging, EX=excavation.

Stream/Location	Type	Physical Impacts	Biological Impacts
Seigal Creek, ID	DR	High turbidities, temperatures, silting	Whitefish reduced
Brazos River, TX	DR	Substrate changes, increased depths and turbidities	97% reduction of invertebrates at dredge site
Cache Creek, CA	DR/EX	Severe erosion, undermining of piers, headcuts, groundwater depletion	Not studied
Alaskan streams, AK	DR/EX	Changes in hydraulic geometry, headcuts and channel degradation	Reductions in densities of invertebrates, decrease in density/diversity of fish communities
Kansas River, KS	DR	Channel widening, bank erosion; increased depths	Invertebrate densities higher than at control sites; diversity/density of fish species less than control sites
Chattahoochee River, GA	DR	Removal of woody debris, headcuts, "excessive" turbidities, bank erosion	Biological impacts confounded by power generation effects; trout condition poorer in dredged areas vs. undredged

*A more complete literature review of gravel mining impacts may be found in Appendix I.

1.3 Stream Reach Sediment Budgets

In order to quantify the impacts of gravel mining as well as to minimize environmental impact through management of gravel mining operations, the development of a sediment budget is required. A simple application of mass conservation of gravels through the development of a sediment budget has been performed on several rivers in as described by Dunne (1989) and Collins and Dunne (1990). The basic equation of mass flow rate of gravels can be expressed as:

$$Q_{si} - Q_{so} - M/DT = DS/Dt \quad (1)$$

where Q_{si} is the mass rate of sediment inflow to the stream reach including contributions from tributaries; Q_{so} is the mass flow rate of sediment exiting the stream reach; M/Dt is the mass rate at which gravel is mined from the reach; and DS/Dt is rate of change of sediment mass stored in the streambed (including bars), along streambanks or on the floodplain. Net erosion occurs when the left hand side of Equation 1 is negative (decrease in sediment storage, $DS/Dt < 0$) and net deposition occurs when it is positive (increase in sediment storage, $DS/Dt > 0$). Equation 1 shows clearly that the impact of mining on the sediment budget is dependent not only on the rate of sediment supply, but it is also dependent on the rate of sediment transport out of the reach.

The way in which sediments are removed from and added to storage in the streambed, including changes in morphological features such as gravel bars and streambanks, is complex. For example, as gravels are mined the channel geometry is changed because the transport of gravels out of the reach is reduced. In addition, the transport of upstream sediment may increase as a consequence of headcut migration and subsequent upstream bank mass failure. As a result, evaluation of terms in Equation 1 over time is often very difficult. Equation 1 does illustrate the fact that even low rates of mining may cause significant change in streams with high sediment supply (Q_{si} high).

Gravel mining has been used to increase stream stability in aggrading streams ($DS/Dt > 0$; see above). In aggrading systems, sediment inflow is greater than sediment outflow and sediment is being stored as bar, bank and/or bed materials. Sediment storage in bars frequently leads to lateral channel migration and bank erosion that can further increase sediment load. In theory, then, gravel extraction can be used as a method to return the stream to an equilibrium state. However, in practice the methods of removing the gravel through mining can alter geometric characteristics of the channel, producing an unintended or undesirable impact on stream morphology. Of particular importance is a local increase in slope, which, as previously mentioned, can cause headcuts that propagate upstream and release additional sediment.

In incising streams (vertical degradation), sediment output is greater than sediment input ($DS/Dt < 0$). Sediment is depleted from storage of sediment in bars, banks and/or the streambed without gravel mining. Incising channels frequently develop armor layers or increase exposure of bedrock that reduces the rate of channel vertical degradation. Kondolf (1994) states that most rivers in the US are in a state of incision because of the interception of bedload transport by dams. The processes and sequencing of processes that result in the accumulation and depletion of sediments in aggrading and degrading systems are complex but Collins and Dunne (1990) and Kondolf and Swanson (1993) have shown that a sediment budget can be developed and used to evaluate the magnitude of mining impacts.

An important component of management is data of gravel extraction rates. Records of the quantity of gravel mined are essential for effective management. Table 1.2 summarizes the impact of gravel mining and sediment storage rate on the response on an alluvial channel.

Collins and Dunne (1990) provided recommendations to assess the potential impact of gravel mining and information for effective management of mining operations. Their recommendations are summarized below:

1. An assessment of existing channel conditions should be conducted to establish extraction rates and impacts.
2. Records of gravel extraction volumes should be maintained.
3. A simple and effective monitoring program that includes repeated measurements of riffle cross-sections upstream and downstream of the mining activity should be established.

The use of aerial photography was also recommended. Recorded gravel extraction rates and monitoring data should be reviewed periodically to determine the need for adjustment of permitted extraction rates.

1.4 Gravel Mining Regulations

Because of the potential problems associated with gravel mining operations, many agencies worldwide have proposed regulations to try to prevent or at least minimize the negative effects of gravel dredging or extraction. In France and Germany, gravel mining in alpine streams (along with other hydrologic modifications) has led to widespread incision. As a result, both governments have banned the practice in these systems and added artificial grade controls and initiated gravel replenishment programs to control the downcutting (Kondolf 1994a). The USACE (1997) has also established guidelines for gravel excavation operations. The guidelines can vary from one permitted operation to another and other agency and state regulations still apply.

Table 1.2 Impact of Gravel Mining and Sediment Storage Rate on Alluvial Channel Response**

Pre-mining channel conditions	Rate of channel mining (M/Dt) relative to pre-mining channel sediment storage rate(|DS/Dt|)				
	Low M/Dt <<|DS/Dt|	**Medium** M/Dt <|DS/Dt|	**High** M/Dt =|DS/Dt|	**Very High** M/Dt >|DS/Dt|	**Extreme** M/Dt >>|DS/Dt|
Rapidly Incising Stream $Q_{si} << Q_{so}$	Minor increase in degradation rate	Increase in degradation rate	Rapid increase in degradation rate	Extreme increase in degradation rate	Extreme increase in degradation rate
Gradually incising stream $Q_{si} < Q_{so}$	Minor increase in degradation rate	Rapid incision	Rapid increase in degradation rate	Extreme increase in degradation rate	Extreme increase in degradation rate
Equilibrium $Q_{si} = Q_{so}$	NA	NA	NA	Channel Incision	Extreme increase in degradation rate
Gradually aggrading stream $Q_{si} > Q_{so}$	Minor decrease aggradation rate	Decrease aggradation rate	Equilibrium*	Slow degradation	Rapid incision
Rapidly aggrading stream $Q_{si} >> Q_{so}$	Minor decrease aggradation rate	Decrease aggradation rate	Equilibrium*	Slow degradation	Rapid incision

*Equilibrium in this chart is used with reference to the sediment load only and does not imply that the channel form is in equilibrium form.
**Note that coarse sediment armoring or bedrock exposure may limit the channel incision.

The USACE guidelines are:

- The permittee shall conduct the work during low stream flow conditions.
- An undisturbed 15 foot buffer zone shall be left at all times between the excavation site and the stream flow.
- Excavation equipment and trucks shall operate outside the stream flow at all times.
- The bottom elevation of the excavated area shall not be lower than groundwater contained in the gravel bed.

- The permittee shall not stockpile excavated material on the gravel bar. All material excavated shall be immediately loaded onto trucks and hauled away to upland sites for use or storage.
- Existing access roads to the gravel bar shall be utilized to enter and depart the work area with trucks and excavation equipment.
- The permittee shall, after completion of the day's activity, level and smooth the entire work area in order to reduce erosion potential should high flow conditions occur during the excavation period.
- Existing forested riparian zones shall be left intact and totally undisturbed
- The permittee will notify the U.S. Army Corps of Engineers 10 days prior to excavation to provide representatives of the District and other interested agencies the opportunity to inspect ongoing work.

These guidelines are designed to limit the impacts of sand and gravel removal from stream and river channels. In particular, the guidelines pertaining to the 15-foot buffer zone, staying above the water table, and leveling the mining area after a day's work address erosion concerns.

Other entities such as states may also have regulatory authority over gravel mining operations. The State of California is the largest aggregate producer in the nation, with 30% of total production of the US (Kondolf 1994a). Because of the size of its industry, the state has gravel mining regulations in place but there are a multitude of agencies that have a least some jurisdiction over mine permitting. Various aspects of gravel mining fall under the California Surface Mining Recovery and Reclamation Act, California Fish and Game, California Transportation (CalTrans) and the California Environmental Quality Act (Kondolf 1994a). The confusing patchwork of regulations actually puts responsible applicants at a competitive disadvantage in the aggregate market place as they have the regulatory burdens that "wildcat" operators do not have.

1.5 Needs of the Commonwealth

While there have been many gravel mining impact studies conducted, it is important to note that most have been conducted in watersheds with deep alluvium, systems which are uncommon in Kentucky except for the Jackson Purchase Physiographic Region of Western Kentucky. In addition, few studies have attempted to separate confounding factors in watersheds such as channel straightening, riparian disturbances, reservoir effects and agricultural impacts which make it difficult to attribute effects such as incision and bank erosion solely to gravel dredging or extraction (Kondolf and Swanson 1993).

In addition, there is a social dimension to gravel mining in the Commonwealth that may not be as evident in the large, "industrial" extraction or dredging operations in other states. Many landowners in a basin may practice small-scale gravel removal for a number of reasons other than the sale of the gravels. For example, some landowners believe that the removal of gravel from the streams is necessary to reduce flooding or that aggradation of gravel bars causes bank erosion and land loss.

In order for the Kentucky Division of Water (KDOW) to make the best possible permitting decisions to protect the state's water resources, this study was funded by the United States Environmental Protection Agency (USEPA) and the KDOW to assess the impacts of gravel mining on streams in southeastern regions of the Commonwealth. The Buck Creek watershed, in the Upper Cumberland River basin in southeastern Kentucky, was chosen because it was the site of several known mining operations and there was local stakeholder interest in continuing gravel extraction.

A study of biological impacts and physical impacts of gravel mining was conducted through a cooperative effort between the University of Louisville Biology Department and the Department of Civil and Environmental Engineering. This study was conducted to determine the effects of gravel dredging on the biotic and abiotic stream characteristics. Two streams with active mines were compared to two streams with no known current mining activities ("unmined" reference streams) that had similar watershed characteristics. The stream physical environments were compared using standard geomorphic and hydraulic engineering methodologies that include Rosgen morphological assessment procedures (Rosgen 1996) and one-dimensional hydraulic modeling techniques (Brunner 2001) to identify physical and active morphological process differences among the streams.

The biological communities were compared in several ways. Standard metrics for assessing fish, macroinvertebrate and periphyton communities and surface water chemistry were used to compare mined and unmined (reference) streams every spring and fall (when water levels permitted) for four years. While the impacts of gravel mining on stream geomorphology have been the subject of a large amount of research, the impact on the ecology and biota of streams has received less attention. In two earlier studies, Brown et al. (1998) and Rivier and Sequier (1986) found it difficult to assess potential negative impacts of gravel mining on stream communities unless the impact was severe and the samples were taken either during or immediately after mining activity. Part of the reason for this may in fact be the nature of gravel mining and other physical impacts. Most macroinvertebrate indices of biological integrity (IBIs) are based on the relative tolerances of various macroinvertebrates, particularly insects, to organic or toxic pollutants; thus gravel-mining effects on water quality may be subtle and difficult to detect using IBIs (Meador and Layher 1998). However, Brown et al. (1998) did find that macroinvertebrate densities and biomass could be reduced at their extensive (smaller, less intensely mined) sites, and functional feeding group compositions could be altered by gravel dredging activities at their intensive (large, intensely mined sites) and extensive sites. Rivier and Sequier (1985) reported that the biomass and densities of macroinvertebrates in their study system were reduced in areas impacted by gravel extraction, primarily due to increased sediment transport. The impact included decreases in Plecoptera, Trichoptera, Ephemeroptera, Coleoptera, and mollusk (pollution intolerant taxa) densities, while other groups such as chironomids and oligochaetes (pollution tolerant taxa) increased. Thus, we decided to include standard fish and macroinvertebrate bioassessments of the streams as part of the investigation. The stream surface water and hyporheic zones were also compared by assessing water chemistry and invertebrate communities.

We hypothesized:

a) Streams with active gravel mining operations would show more incision (higher bank heights) than reference streams.
b) Streams with active gravel mining would have degraded or less developed pools and riffles (lower frequency of riffles and pool depths) than reference streams (Fig 1.2).
c) Streams with active gravel mining would have a higher degree of streambed armoring (decreased substrate mobility or increased exposure of bedrock) than reference streams.
d) Mined streams would show lower total densities, taxa richness and lower IBI scores for fish and macroinvertebrate than did the reference streams.
e) Mined streams would show higher chlorophyll a and AFDM values than the reference streams.
f) Mined streams would show shifts in functional feeding groups and habitat groups compared to reference streams.

This report summarizes the specific findings of the investigation and presents Conclusions and Recommendations to the KDOW for the future management of mining activities in the Commonwealth of Kentucky.

2.0 METHODS

2.1 Site Descriptions

Four gravel bed creeks in the Buck Creek drainage basin were selected for detailed study following examination of streams in the Buck Creek, Pitman Creek, and Fishing Creek watersheds. Several stream reconnaissances were conducted in which a team of biologists, engineers and geologists examined several miles of stream channels throughout the Buck Creek and Pitman Creek watersheds. All major tributaries to Buck Creek were examined. One goal of the examinations was to identify stream reaches that had been intensively mined and stream reaches that had not been intensively mined. The latter streams would be used as reference reaches for comparison of stream characteristics and processes. These "reference" streams should be considered "typical" or "representative" streams rather than pristine systems in which impacts are minimal. As will be explained later in this report, all of the streams in the Buck Creek watershed visited by the project team were intensively manipulated or suffered from current downstream or upstream impacts as well as historic impacts.

Buck Creek is located in the Pennyroyal physiographic region within the Upper Cumberland River basin in southeastern Kentucky and drains into the Cumberland River upstream of Lake Cumberland. The geologic formations and surface rock material were examined through a detailed study of the literature on the geology of the Buck Creek watershed. The information obtained from this literature was valuable in providing information on the stream valley characteristics as well as the streambed and bank materials. As will be explained in the Results section, one of the most important factors in the formation of the very wide valleys of the Buck Creek watershed is the occurrence of a deep and extensive shale formation called the New Providence shale. These shales are present in the lower elevations of the valley wall, underlay the valley alluvium in the wide floodplain areas and were present in part of the streambed at all sites visited and studied. This formation also appears as the streambed in long reaches upstream of intensively mined stream reaches. A detailed description of the regional and local geology is provided in Appendix II.

2.1.1 Source Sediments, Bedrock, and Basin Geology

The Mississippian age rocks that form the surficial rock units in the Buck Creek watershed are composed of shale, siltstone and limestone as explained in detail in Appendix II. Sedimentary rocks that developed from marine and fresh-water deposits dominate the Mississippian aged bedrock (360 to 325 mya) in the study area. Such bedrock includes sandstone, as well as Lower Mississippian shale and siltstone (mixed deltaic deposits) and thin limestone, which are all Nancy and Halls Gap Members of the Borden Formation (Ross 1974). Parts of the Mississippi plateau were also covered by gravel, sand and fine-grained sediments in the Tertiary Period and these unconsolidated sediments may also influence the nature of local colluvial and alluvial deposits. The uplands surrounding the stream valleys in Pulaski County are formed of Muldraugh siltstone, chert and Upper Mississippian limestone, which release significant geode deposits into the stream valleys upon erosion. All such materials may provide sediment (bedload) to the studied creeks of relatively predictable shape and even size.

A thick unit of very slakeable shale was present throughout the Buck Creek watershed at the elevation of tributaries and main channel of Buck Creek north of KY 461. The shale was exposed over large sections of stream where streams were mined and/or channelized and in the deepest pools of all streams examined. Exposure and drying of the shale bedrock and of large shale boulders dislodged from the bedrock streambed caused rapid degradation. Large boulders found after high flow events disintegrated into piles of silt and clay within months. Exposure of large regions of shale bedrock streambed degraded rapidly over dry periods. Incision of some stream channel bed into the shale bedrock was considered to be a combination of erosion of bedrock shale at headcuts and surficial slaking of large areas of streambed exposed to drying.

The gravels in streambeds were identified as siltstone, limestone, chert and geodes. Siltstone and limestone boulders found in a few locations were derived from colluvial (hillside) materials or fractured and weathered bedrock from the streambed.

Section 2.1.2. Site characteristics and landuse

The study creeks are located in the headwaters of Buck Creek in Pulaski and Lincoln counties. Indian Creek and Briary Creek have active gravel mining occurring in their lower sections near their confluences with Buck Creek. Clifty Creek and Gilmore Creek are the reference creeks for Indian and Briary Creeks, respectively. They were chosen as reference creeks because no known active gravel mining operations were occurring within their channels at the time of their selection and their watershed areas are similar in size to Indian and Briary Creeks. The location of each study creek is shown in Figure 2.1. The watershed maps of each stream are shown in Figures 2.2-2.5.

An aerial-based reconnaissance of the basin was conducted in March 1999. The flight was useful in determining the location of gravel mining activities or other very recent direct stream manipulations. Repeat aerial reconnaissance was not used as a method for examining impacts because riparian vegetation blocked the view of the majority of channel banks in large sections of channel streambeds.

A detailed analysis of landuse was conducted on the four study creeks' watersheds using the GIS program ARCView 7.0. The source data was landuse compilation from 1978-79 USEPA landuse maps and color aerial photography. The streams cover layer was compiled in the early to mid 1980's from the most current topographic maps at that time. This analysis showed that the vast majority of land in all four watersheds is used for agricultural purposes or is forested, with little residential, industrial, and urban landuse. Detailed landuse analysis data for each stream are presented in Table 2.1 and mapped in Figures 2.6-2.9.

Indian Creek (Mined Stream)

Indian Creek is a 3rd order creek at our study sites. Its confluence with Buck Creek is less than 1/3 km upstream from the state highway 39 bridge (Fig 2.2). Indian Creek's channel has been extensively and continuously mined in a number of locations along the last kilometer or so of its length over several decades (Skaggs, personal communication). Compton and Schuster (1997) and Moeykens and Schuster (1997) also reported mining activity at this site. Mining operations in this creek do not follow the USACE guidelines: the gravel is dredged from the wetted channel, there is no 15-foot buffer, gravel is removed from below the water table, and gravel removal vehicles use the stream channel. Approximately 1.3 km upstream from Indian Creek's confluence with Buck Creek, a landslide has dropped colluvium containing large boulders into the stream. In addition, a siltstone layer of bedrock present in the streambed at this location has been undermined and degraded to form a region of large boulders. These boulders may be acting to mitigate rapid vertical degradation (headcuts) upstream of this location. The region upstream of this grade control section was used in the morphological study as an upstream reference reach.

Clifty Creek (Reference Stream)

Clifty Creek, a 3rd order stream, is the reference stream for Indian Creek (Fig 2.3.) Clifty Creek was found to have a far more variable streambed profile than Indian Creek in the study reaches indicating the presence of numerous riffles and pools (Lowe, 1999). The thalweg within Clifty Creek is composed almost entirely of gravel with bedrock being exposed only in the bottom of pools (Lowe, 1999).

Briary Creek (Mined Stream)

Briary Creek, a 4th order stream, has gravel-mining sites about 1.5 km upstream from its confluence with Buck Creek (Fig 2.4.) The mining activities in Briary are not as intensive as they are in Indian Creek.) Extraction equipment when observed was not in the channel, but gravel is mined below the water table, and the area is not smoothed out after daily operations. Additionally, high flows get out of the channel and into mined areas.

Gilmore Creek (Reference Stream)

Gilmore Creek, the reference stream for Briary Creek, is a 3rd order stream (Fig 2.5.) Landuse in Gilmore Creek's watershed is somewhat different than that of Briary, with a lower percentage agricultural and a higher percentage of deciduous forest. Moreover, unlike Briary, Indian or Clifty Creeks, much of the forested land in Gilmore's watershed is located along the stream channel (Table 2. 1, Fig 2.9).

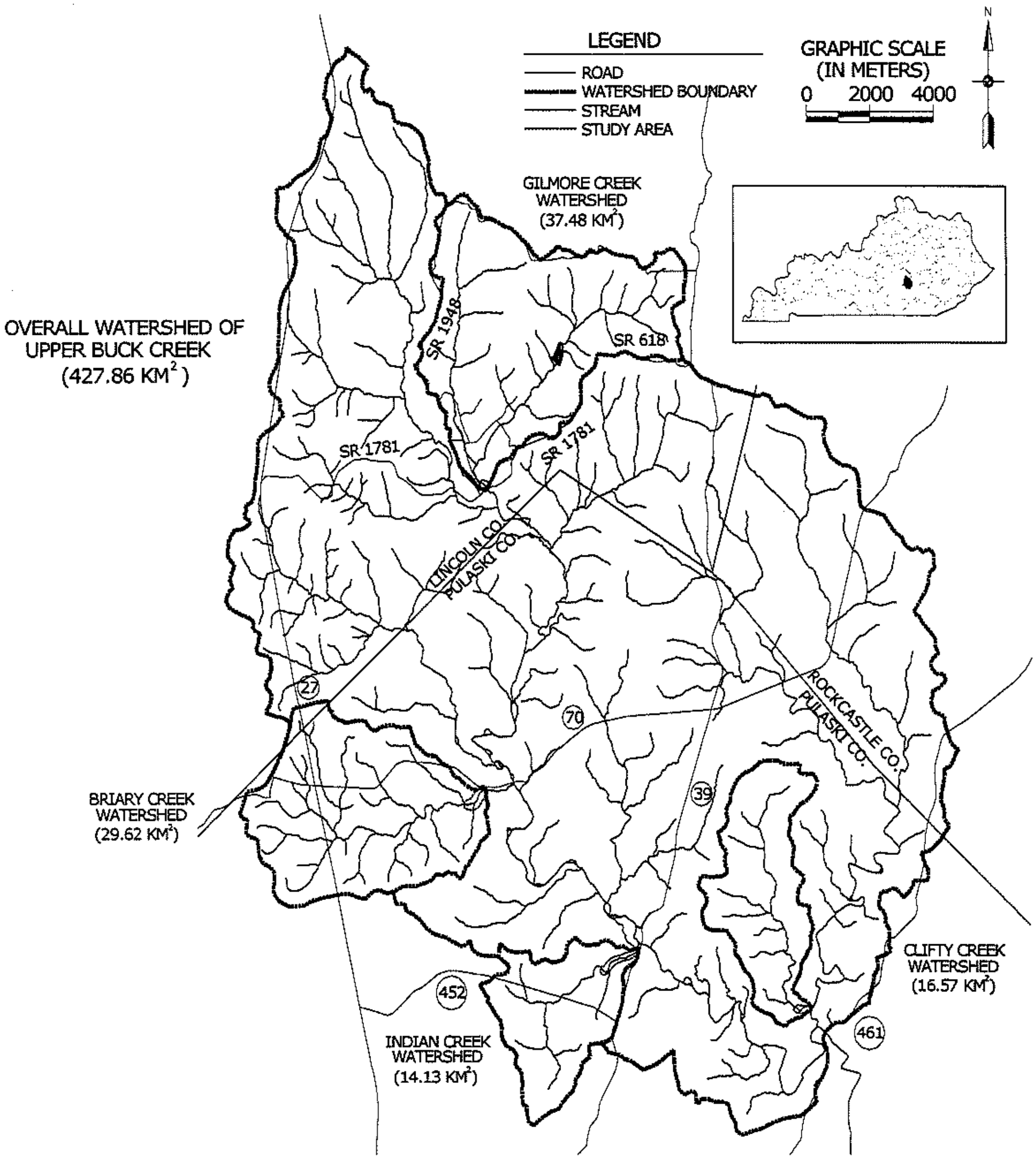

Figure 2.1. Buck Creek drainage and study watersheds, including major roads and political boundaries.

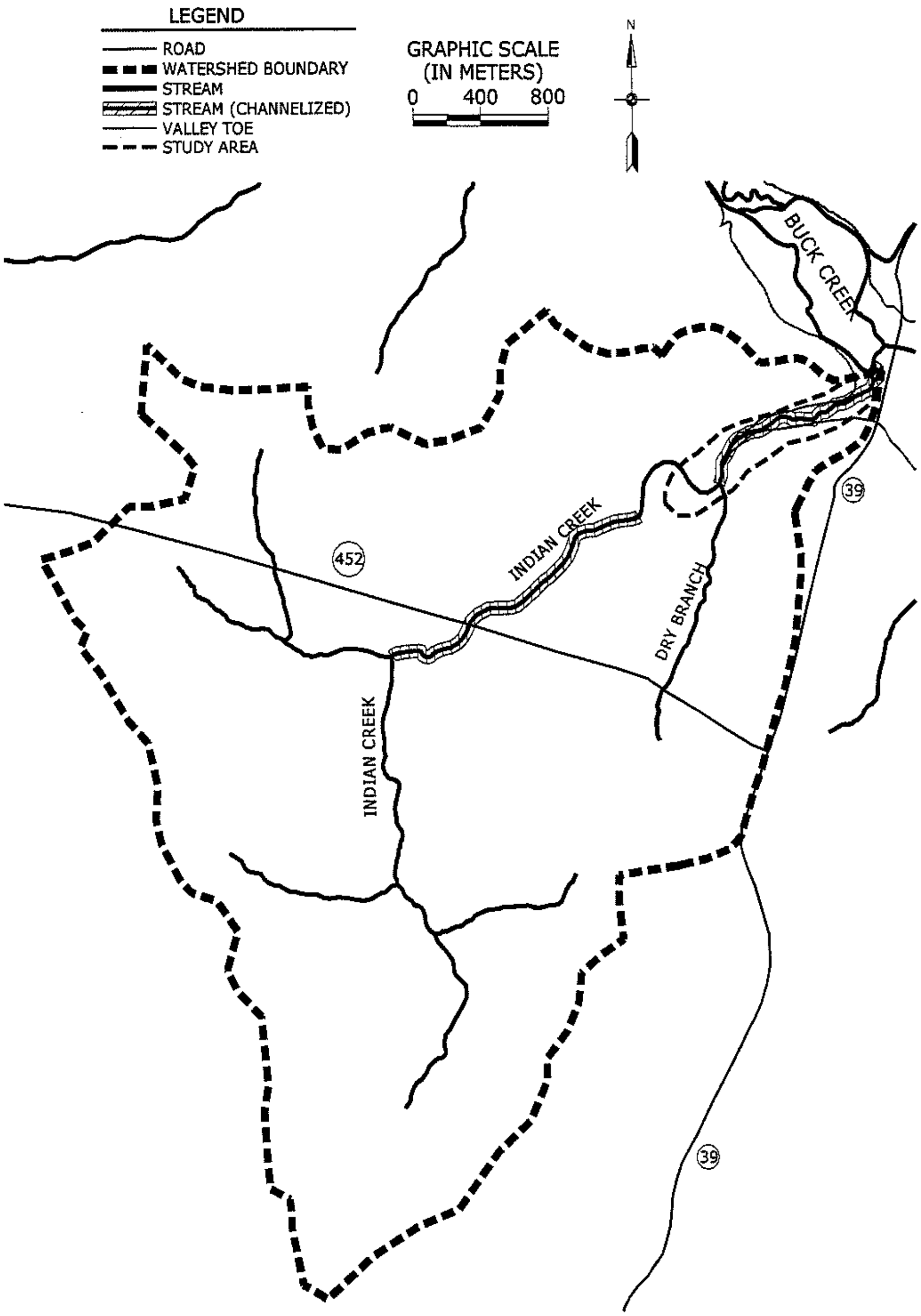

Figure 2.2. Watershed map of Indian Creek

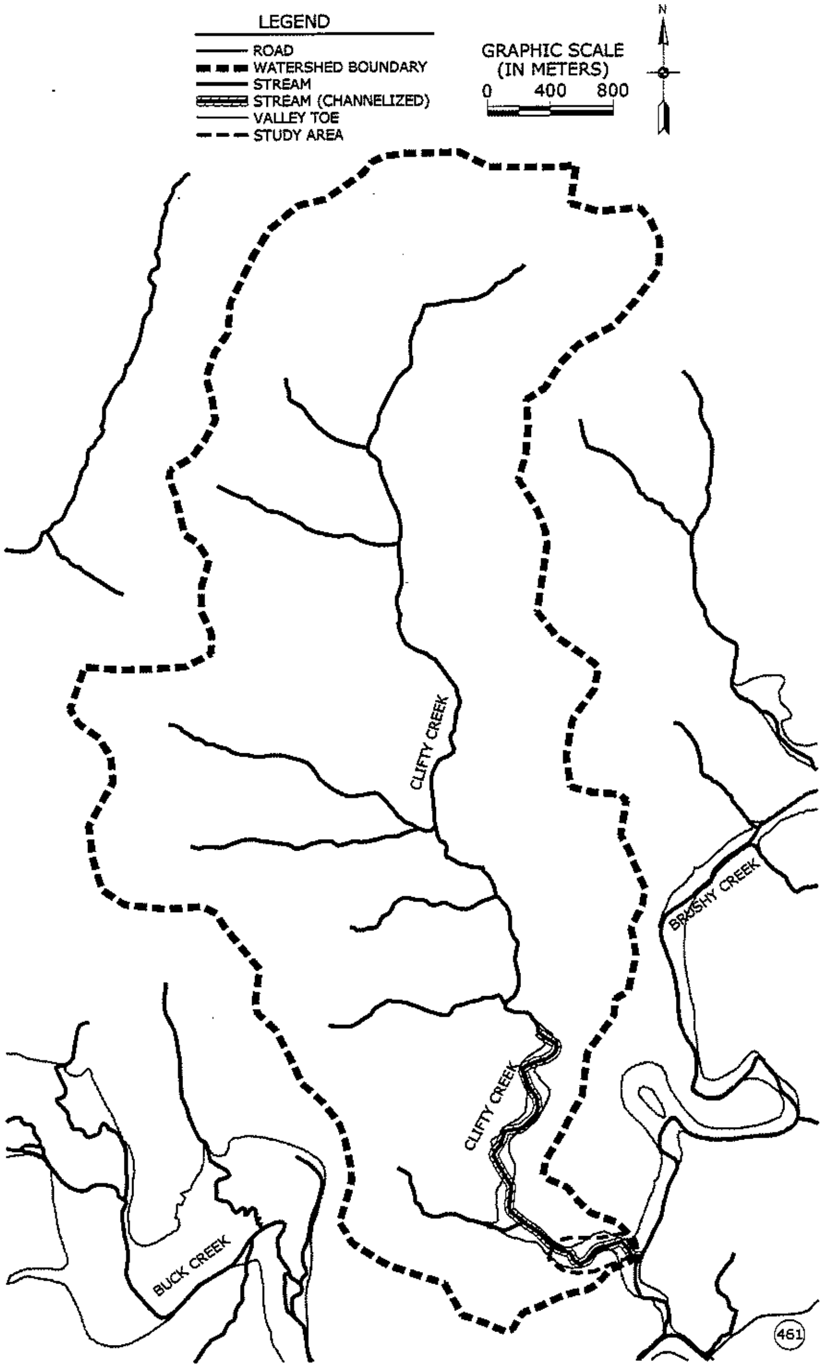

Figure 2.3. Watershed map of Clifty Creek

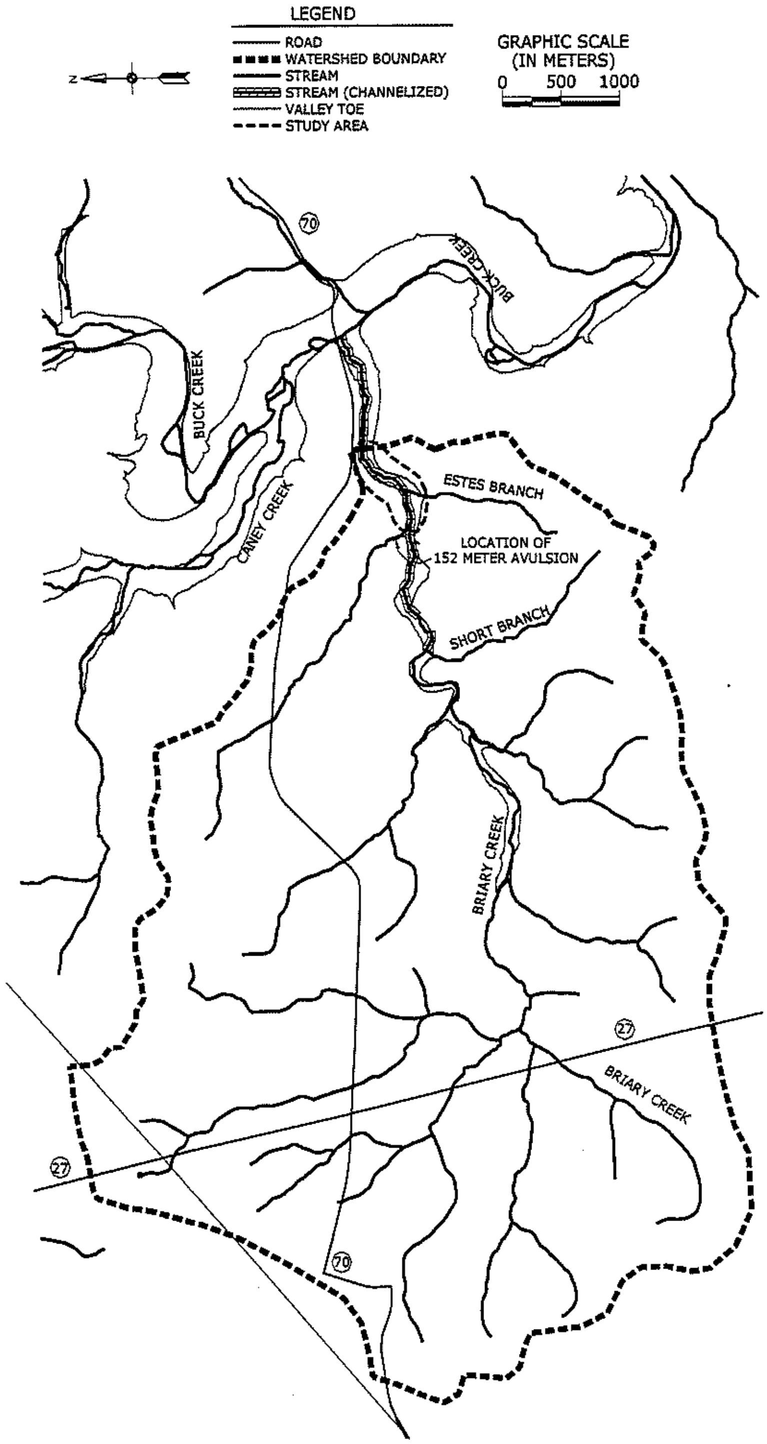

Figure 2.4. Watershed map of Briary Creek

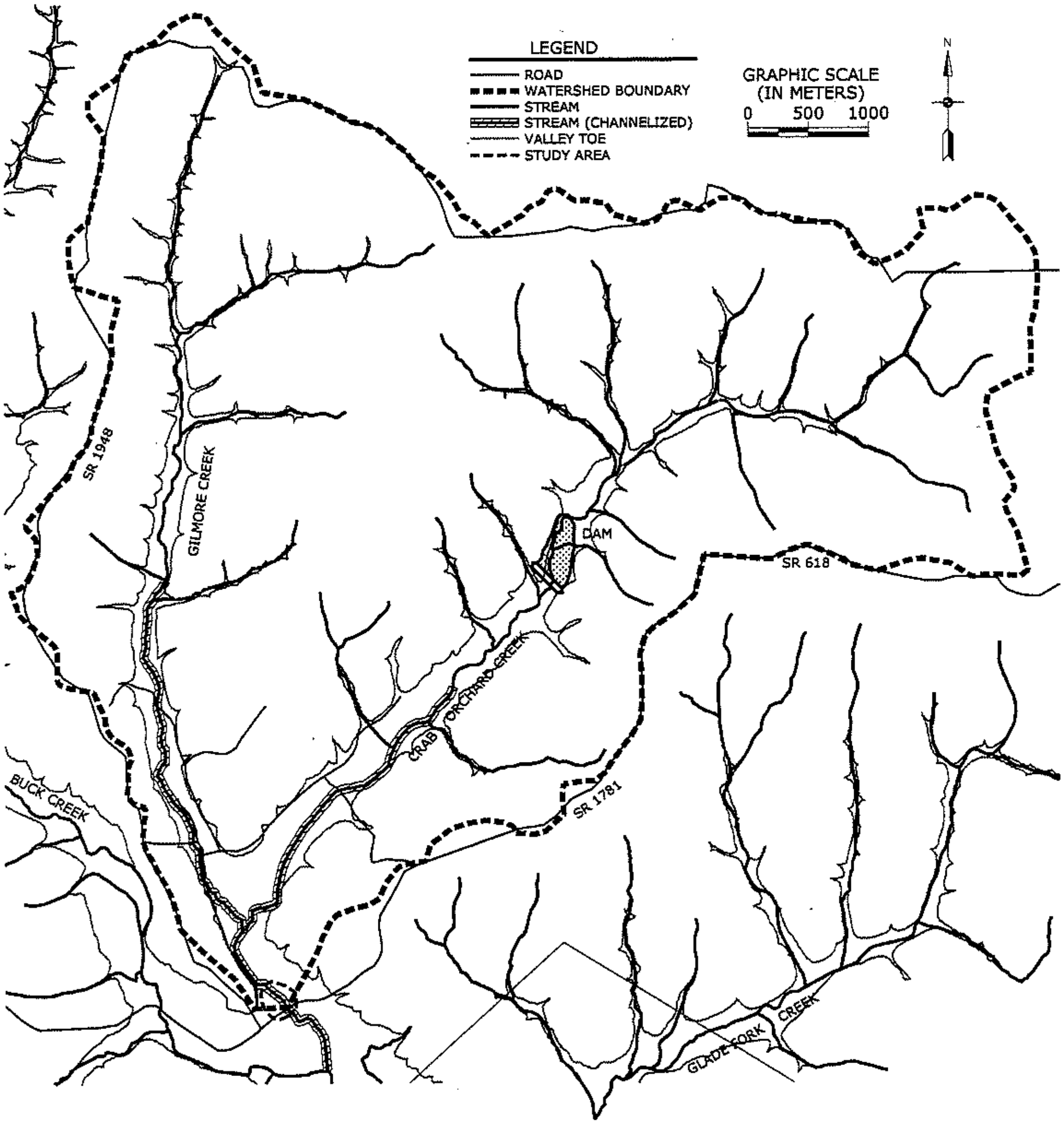

Figure 2.5. Watershed map of Gilmore Creek

Gilmore Creek is also unique in this study in that it is the only creek with a dam and reservoir along its course that intercepts sediment and impacts runoff from approximately 37% of the total watershed area. Despite these differences, this stream was still used as a reference for Briary because of a lack of other suitable candidate streams

2.2 Historical Impacts

The site descriptions above are primarily assessments of the current conditions of the creeks and their watersheds. However, impacts from the past contribute to the current conditions of the creeks as well. All of the study creeks show evidence of stream reaches being moved towards the valley walls to make room for agricultural activities. In addition, there are large sections of these creeks that have been straightened along much of their length (Figs. 2.2-2.5). All of these watersheds are responding to land clearance and other agricultural impacts as well as channel straightening. These "legacy effects" complicate the interpretation of gravel mining impacts on these streams. An attempt was made to determine the processes dominating the current morphological state of the study streams through detailed observations and morphological measurements. Larger scale maps of the stream reaches studied are provided in Appendix IV.

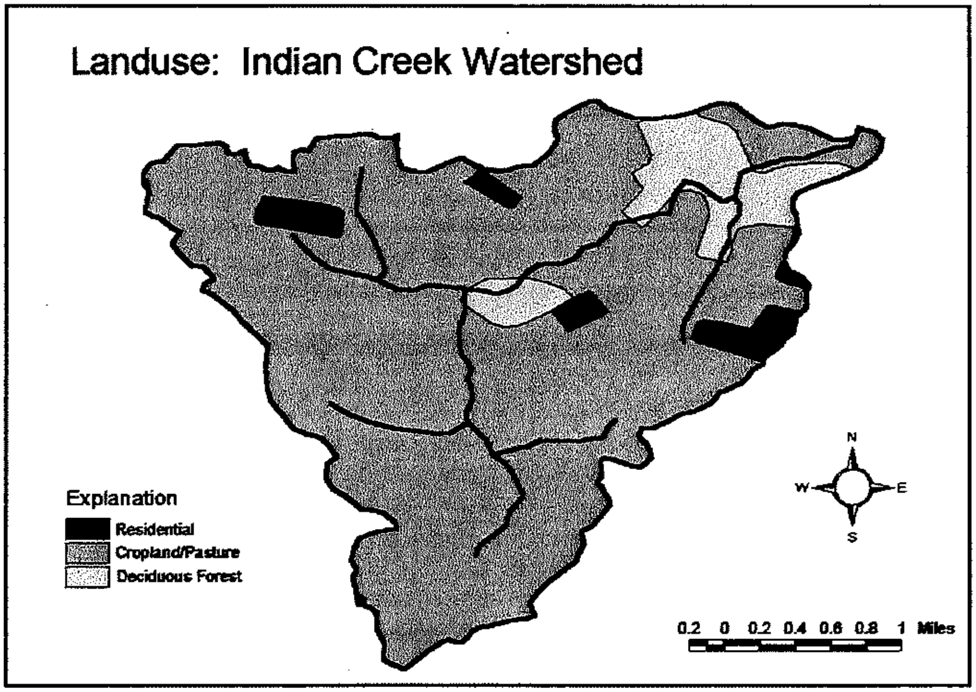

Figure 2.6 Landuse within the Indian Creek watershed.

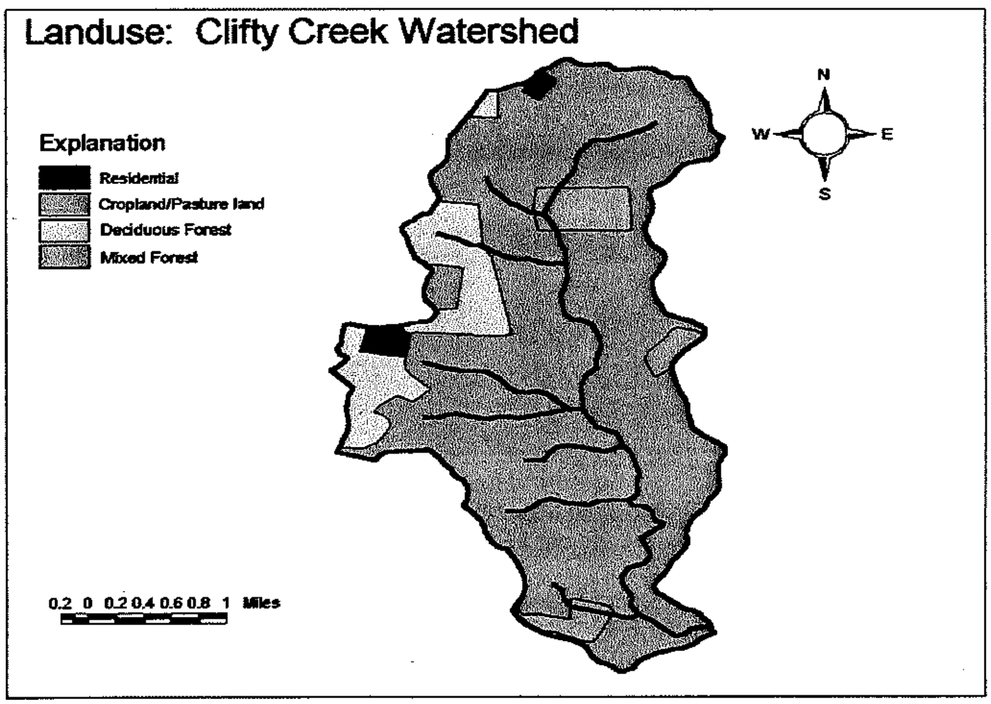

Figure 2.7. Landuse within the Clifty Creek watershed.

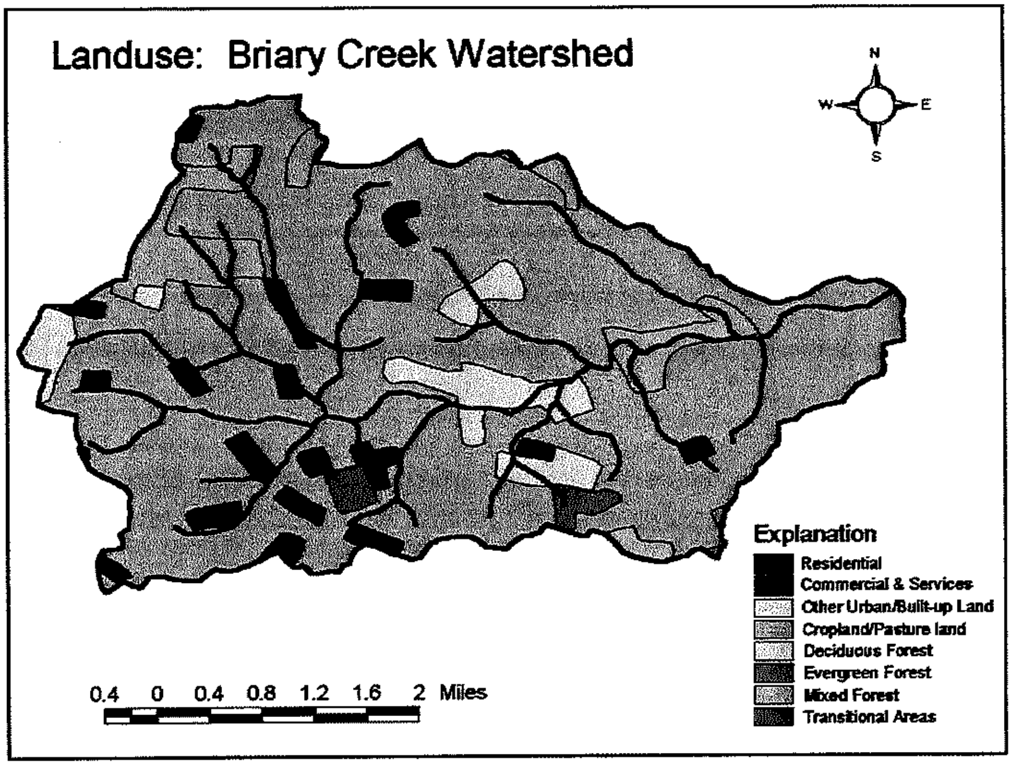

Figure 2.8. Landuse within the Briary Creek watershed.

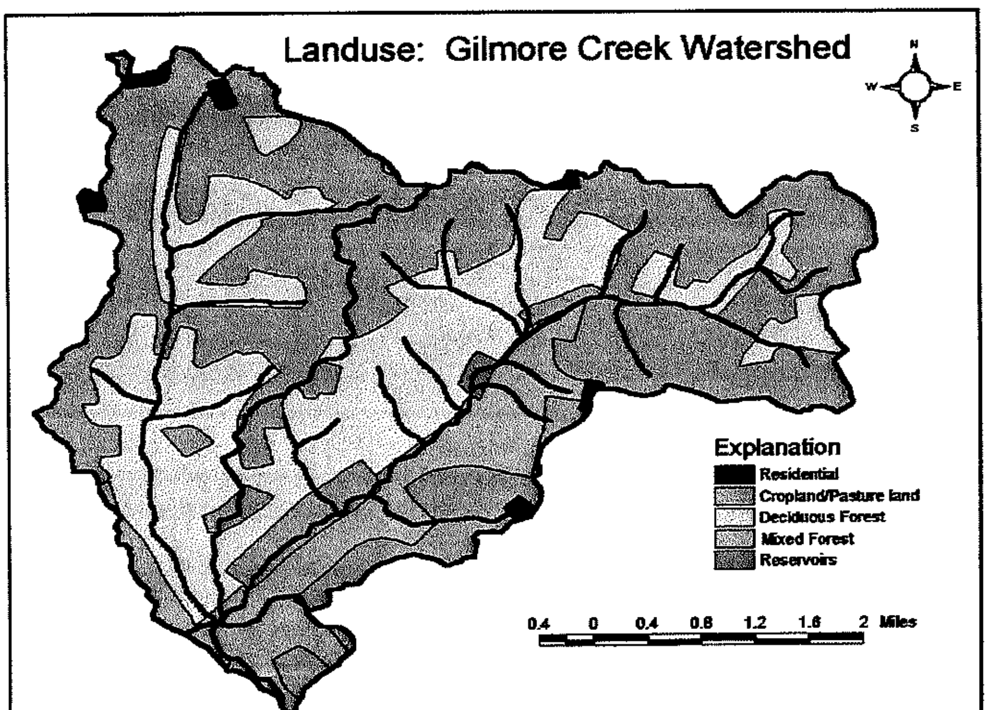

Figure 2.9. Landuse within Gilmore Creek watershed.

Table 2.1. Landuse types and percentages of the study watersheds.

Landuse Name	Study Creek			
	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
% Residential	3.87	1.25	5.27	0.99
% Commercial and Services	-	-	0.32	-
% Other Urban/built up land	-	-	0.24	-
% Cropland/Pasture	87.5	83.4	79.6	52.4
% Deciduous Forest	-	10.0	5.91	34.5
% Evergreen Forest	-	-	0.65	-
% Mixed Forest	8.62	5.3	7.29	11.7
% Reservoirs	-	-	-	0.40
% Transitional Area	-	-	0.65	-
Total Area (sq. km.)	**14.13**	**16.57**	**29.62**	**37.48**

*The value provided in this table is for the surface area of the reservoir. The run off from 13.95-km^2 area (37%) of the Gilmore Creek watershed is controlled by a small reservoir.

2.3 Previous bioassessment work in the watershed

Bioassessments of the lower and upper main stems of Buck Creek have been recently conducted (Compton and Shuster 1997; Moeykens and Shuster 1997) and the results suggest that water quality should be good in these watersheds. The upper mainstem of Buck Creek received scores for water quality in the "Excellent" category based on the Invertebrate Community Index (KDOW 1993) and the Hilsenhoff Biotic Index (Hilsenhoff 1987). The lower mainstem of Buck Creek scored slightly lower, but still in the "Good" to "Excellent" range.

2.4 Geomorphologic Assessment Methods

2.4.1 Examination of Topographic and Geologic Maps

United States Geological Survey (USGS) 7.5-minute topographic and surface geological maps were used for determining recent modifications to streams as well as identifying stream reaches that may have been straightened and relocated. Although use of these maps was initially considered to be an unreliable method for determining the location and general characteristics of stream channels, they represented an accessible and reasonably accurate means of examining stream planform characteristics and locations. Overlays of ground-based total station surveys of study stream reaches provided evidence that these maps could be useful in determining stream sections that had been straightened and/or relocated to the edge of valleys.

2.4.2 Hydrologic investigation

An assessment of the flood flow characteristics of Buck Creek was conducted to provide information on the frequency of flood flows in Indian Creek. The analysis used data from an abandoned gage station located on KY 461 on Buck Creek to estimate the characteristics of flow in Indian Creek. The flow rates estimated from this analysis were used in the modeling of specific characteristics of flow conditions and sediment mobility in intensively mined and other non-mined channel reaches. A summary of the hydrologic analysis procedures is provided in Appendix III. Based on this analysis, the peak discharge for a return interval of 1.5 to 2.0 yrs was estimated to be approximately 8 m^3/s (285 ft^3/s) for the Indian Creek and Clifty Creek watersheds. A discharge of 0.55-m^3 s/km^2 (50.5 $ft^3/s/mi^2$) for the 1.5 to 2 yr event was used in the analysis of Briary Creek and Gilmore Creek.

2.4.3 Site Surveys

Detailed channel topographic surveys were conducted on the study streams. These consisted of cross section surveys at distances from 10 m to 30 m spaced along the channels depending on the variation of channel or floodplain characteristics. At less frequent intervals, the topography of adjacent floodplains was measured. The stream thalweg was surveyed at distances required to detect subtle changes in streambed slope and channel substrate. The surveying was conducted using a Topcon APL-1 robotic total station. Detailed contour maps of the channels of the four study sites are provided in Appendix IV.

2.4.4 Sediment Data Collection and Analysis

Two methods of sediment assessment were used to evaluate the variation of sediment properties along the length of gravel mined streams and between gravel mined streams. The first method was focused on the sampling of bars as recommended by Yuzyk (1986). The second method involved the simple comparison of riffle surface particle size distribution using pebble-counting techniques (Wolman 1954, Bunte and Abt 2002).

2.4.5. Stream Geometric Characteristics

The data collected and geomorphological assessment procedures developed by Rosgen (1996) were used to assess stream channel incision, and entrenchment and to classify stream reaches. Since the original data were not collected according to the specific Rosgen protocols, some approximations were necessary; however, the errors in these approximations were not considered to significantly affect the results or the overall conclusions of the study.

2.4.6 Hydraulic Characteristics and Sediment Mobility Analysis and Comparison

The hydraulic characteristics of typical reaches of the study streams were modeled using the topographic data and cross sections obtained in the site surveys and the one-dimensional water surface profile program HEC-RAS version 3.1 (Brunner 2001). The water surface elevations and cross section averaged boundary shear stresses for flows ranging from well below bankfull to those that overtopped the banks and flooded low terraces were modeled. A simplified assessment of sediment mobility was conducted to make an indirect comparison of each channel's ability to mobilize its sediment load.

2.4.7 Hydraulic Modeling and Sediment Mobility Assessment

The mobility of riffle sediment was investigated in typical reaches of the four streams by 1) obtaining representative riffle surface particle samples, 2) one-dimensional modeling of flow and average channel boundary stress for four critical flow conditions, and 3) assessing the sediment relative mobility ratio (ratio of channel average boundary stress to sediment critical boundary stress). The modeling and assessment of sediment were conducted to examine the current conditions of the channel. The quantitative analysis of the current conditions of the channel provided a relative comparison of channel sediment stability rather than the rate of sediment supply, storage or export from the study stream sections. Riffle surface pebble counts (minimum of 200 samples) were obtained in sections 1, 3 and 4 of Indian Creek and in one riffle each of Clifty, Briary and Gilmore Creeks. The sediments were sampled in a grid pattern over the entire active streambed of each riffle. Cross-section surveys extended from at least a downstream pool, over the riffle to the next upstream pool. Boundary stress conditions were modeled for 12 flow regimes ranging from 10 percent of the 2 yr. event to 10 times the 2 yr. event. The 2 yr. (0.554 m^3s^{-1} per km^2) and 50 yr. (1.18 m^3s^{-1} per km^2) return interval events were determined from the hydrologic investigation described in Appendix III. Flows that overtopped the bank and provided relief to a wide flat area were also determined. For all streams except Briary Creek, the wide flat area was the pre-settlement floodplain (now a terrace in all streams).

Flows were modeled using HEC-RAS version 3.1 (Brunner 2001). Channel roughness was determined using the bed relative roughness (ratio of D_{84} of the riffle surface to the average flow depth) at the 2 yr return interval flow event and also by using the method developed by Limerinos (1976).

2.5 Biological Assessment Methods

2.5.1. Use of biometrics in gravel mining studies

In addition to the "standard" bioassessments, other metrics, such as functional feeding groups, may also be useful in the assessment of gravel mining impacts. The frequency and intensity of flow disturbances and substrate stability can have significant effects on the densities and composition of stream communities (Resh et al. 1988; Matthaei et al. 2000). Many insects that live in stream riffles are subjected to stress from the flowing water even under "normal" conditions. Insects in this habitat are often classed as "clingers", as opposed to burrowers, swimmers, sprawlers, etc. (Merritt and Cummins 1996). Clingers have either behavioral (fixed retreats) or morphological (claws, dorsoventral flattening, etc) adaptations to living on riffle substrate (Merritt and Cummins 1996). For example, several members of the family Hydropsychidae typically build net-like retreats directly within the stream flow, where flow is optimal for catching food. However, if the retreat is on cobble that moves frequently, the net opening may get turned in the wrong direction, or even worse, the cobble may be overturned and crush the inhabitant. Bond and Downes (2000) report that hydrospychid caddisfly densities were reduced to similar levels on different sizes of experimental bricks despite the fact that spates moved fewer large bricks than small ones. Even small movements of the substrate may misalign the net opening of a hydropsychid caddisfly enough to reduce or eliminate the food catching ability of the net. Gravel mine impacts may lead to more frequent substrate movements (see Fig

1.1a-c), so the percentage of clinger taxa may be reduced in streams with active gravel dredging or excavation.

While the percentage of clingers would be expected to decrease in gravel-mined streams, the percentage of "sprawlers" (Merritt and Cummins 1996) might be expected to increase. Sprawlers are insects that are described as "inhabiting the surface of floating leaves of vascular hydrophytes or fine sediments, usually with modifications for staying on top of the substrate and maintaining the respiratory surfaces free of silt" (Merritt and Cummins 1996). Insects with these traits should be more resistant to both destabilized substrate and the increased silt deposition that are associated with gravel mining operations within stream channels. Therefore the proportion of clingers was expected to decrease and the proportion of sprawlers was expected to increase in creeks with mining operations.

2.5.2. Macroinvertebrate Sample Dates and Site Locations

Synoptic samples were taken in May 1998, June 1999, April 2000, and in February and May 2001. Additionally, an event (spate) sample was taken in Indian and Clifty Creeks only in May 1999. All of the study streams were usually pooled by September so no fall samples were taken.

The mining site on Briary Creek relative to its confluence with Buck Creek was used to position the sampling sites at the reference streams Clifty and Gilmore. The mining site on Briary was approximately 1.5-stream km upstream of the confluence with Buck Creek. Previous work by Brown et al. (1999) indicated that mining impacts may travel upstream or downstream, so upstream and downstream stations were also established approximately 1.2 and 0.80 stream km from the confluence with Buck Creek, respectively. Sites were chosen on Clifty and Gilmore Creeks that were approximately the same distance apart and from their confluences with Buck Creek as the sites on

Briary Creek. There were no tributaries or other hydrological modifications such as bridges between any of the sites in these three streams or within 0.4 km of the upstream or downstream sites with the exception of a bridge just downstream of the Gilmore downstream site (Fig. 2.5).

Indian Creek's sites were more difficult to establish because it was regularly mined for much of its lower length (below Dry Branch, see Figure 2.2) down to its confluence with Buck Creek. A mining site and an upstream site approximately 0.4-stream km above the last active mining site were established at Indian Creek. These were the only two sites sampled on Indian Creek during May 1998, May 1999 and June 1999. In April 2000 an additional site above the landslide (about 0.8 stream km above the mined area) on Indian Creek was added to assess the macroinvertebrate communities in riffles that appeared to be less affected by the head-cutting and other impacts in Indian Creek (see above).

The May 1999 spate sample was performed during the end of a rain event that created a bankfull flow in Clifty Creek (estimated from debris lines). Sampling was completed during the rescinding part of the spate in Indian and Clifty Creeks to determine if there were differences in effects of the spate on stream macroinvertebrate community composition and densities in the mined vs. reference streams. After a one-month period community recovery was assessed in the two streams.

Macroinvertebrates were sampled via two methods following the rapid bioassessment protocol III (Plafkin et al., 1989). Three semi-quantitative traveling kick net (TKN) samples (Klemm et al., 1990) were taken from riffles with a 1/3-meter wide net with a mesh size of 250 μm. A one-meter length of substrate was kicked for a 1 minute time period. The second method was a qualitative composite sampling method (Comp) designed to sample multiple habitats (Klemm, et al., 1990). The composite sample was performed following Kentucky Division of Water guidelines (KDOW 1993) and focused on large substrate (boulders etc.) woody debris, leaf pack and undercut banks/root wads when these were present. All samples were sieved in the field with a 500 µm sieve and preserved in 70% ethanol. In addition to insect collection, basic physical and chemical water parameters, such as dissolved oxygen concentration, pH, conductivity, water temperature, and turbidity were taken.

Macroinvertebrate samples were cleaned and sorted in the laboratory. Insects were identified to the lowest practical taxonomic group using Merritt and Cummins (1996) Brigham et al.(1982) Westfall and May (1996) and Wiggins (1996). Identifications were compared to the KDOW Master Species List (KDOW, unpublished data). Representative individuals of each identified taxa were bottled separately for a voucher collection and taken to the KDOW for species-level taxonomic assistance and quality assurance/quality control of identifications. Insect densities were calculated for each riffle, and head capsule width was measured for selected taxa. Wet weight biomass of insects preserved in alcohol was also measured. Hilsenhoff Biotic Index (Hilsenhoff, 1987) scores were generated using tolerance values specific to the genus or species as determined by the KDOW (KDOW, unpublished data). The KDOW Kentucky Index of Biological Integrity (KIBI) was used to determine water quality scores for the four streams sampled (KDOW 1993; Table 2.2). Jaccard Coefficients and Evenness were also calculated from the taxonomic data as well. Functional feeding groups (FFG) were assigned to the taxa using Merritt and Cummins (1996) and relative proportions of each FFG were calculated for each sampling date. Finally the percentage of clingers and sprawlers from each riffle was calculated based on insect classification from Merritt and Cummins (1996). Following Maxted et al. (2000), only taxa where "clinger" or "sprawler" was the first functional habit listed were included in the analysis. Clinger and sprawler ratios were then calculated for the mined and reference creeks.

Table 2.2 Metric indices for the KIBI. TR = taxa richness, EPT = number of Ephemeroptera, Plecoptera, and Trichoptera taxa, HBI = Hilsenhoff Biotic Index, PCD-5 = percent composition of the dominant 5 taxa, and %EPT-tot = the percentage of EPT of the total number of individuals.

Percentile	**>90%**	**70-90%**	**40-70%**	**20-40%**	**<20%**
Score	5	4	3	2	1
TR	≥ 59	45-58	30-44	24-29	≤ 23
EPT	≥ 17	13-16	9-12	5-8	≤ 4
HBI	≤ 5.16	5.17-5.72	5.73-6.33	6.34-7.08	≥ 7.09
PCD-5	≤ 42	42.1-56.0	56.1-66.9	67.0-75.3	≥ 75.4
%EPT-TOT	≥ 59.3	46.4-59.2	30.4-46.3	19.8-30.4	≤ 19.7

2.5.3 Other Supporting Biological Data Collected

Fish, periphyton, surface water chemistry and hyporheos samples were also taken at various times throughout the study period. The sampling sites were located in the same areas with the exception that fish survey sites were much more extensive in the creeks than were the macroinvertebrate sites.

Fish were collected by seine (4.6 m, 0.45 cm mesh) using Kentucky Division of Water methods (KDOW 1993). Two runs, two riffles and two pools as were all subhabitat types present were sampled at each station (e.g., aquatic vegetation, exposed root systems, around logs). Each station was sampled for at least an hour and until no new species were collected. Fish were identified in the field and released, however voucher specimens were collected and preserved using a 10-percent formalin solution. The samples remained in the formalin for at least two weeks and were then placed in a 70-percent ethanol solution for curation. The fish specimens were identified to species, then taxa richness, relative abundance and the Index of Biotic Integrity (Karr 1981) was derived for each sample. Fish were identified using Burr and Warren (1998), Clay (1975), Page (1983) and Page and Burr (1991).

Periphyton samples were collected by gathering surface cobble substrate. Six rocks (approximately 10 cm in one dimension) were collected at each site, placed in Whirl-Pak bags and kept on ice in a cooler until they were frozen for later analysis. The presence or absence of any filamentous strands of algae and their length was also noted. Rocks collected for periphyton samples were scraped and surface area of each rock determined. Periphyton was analyzed for ash-free dry mass (AFDM), and Chlorophyll A, B, and C.

Surface water samples were taken in association with the periphyton collections. Grab samples were taken, kept on ice and immediately returned to the laboratory for storage following standard methods (APHA 1998). Hyporheic water chemistry samples were taken with stainless steel (1.8 m x 2.54 cm) piezometers at depths of 10 cm and to 40 cm in Gilmore and Briary Creeks and to 10 cm only in Indian and Clifty Creeks due to the close proximity of the bedrock to the riffle surface in Indian. Three piezometers were placed at the up- and downstream end of each riffle site (distance varied between 11 and 19.1 m) and were allowed to stand for a minimum of one hour before samples were taken to allow the zone around the piezometer to equilibrate. Water for chemical analysis was collected with 60 ml. syringes and drawn up slowly to prevent pulling in water from other depths or from the surface. Laboratory trials with stream substrate and dyed water in aquaria indicated that the withdraw rate used would not result in mixing of surface and subsurface water. Water samples were stored in acid washed containers and placed in an ice filled cooler for transport to the laboratory where they were processed as described for the surface water samples. Surface and hyporheic water samples were analyzed for nitrates/nitrite-N, NH_3, total nitrogen, soluble reactive phosphorous, total phosphorous, silicon, and chlorides; in addition, hyporheos samples were analyzed for alkalinity, dissolved organic carbon (DOC), and particulate organic carbon (POC). Samples were analyzed using standard methods and conditions (APHA 1996).

Organisms were sampled from the same depths and in the same locations as the water chemistry samples. Three liters of water was pumped through a 63 μm sieve with a steel piezometer and Bou-Roush pump (Bou and Rouch 1967). Organisms trapped within the sieve were fixed in 95% ethanol and preserved in 70% ethanol. Hyporheic organism samples were counted using a stereomicroscope and identified to order.

Sediment deposition samples were collected at the stream confluences and at sites upstream of the confluences using the methods of Brown et al. (1998.) Briefly, round plastic trays (diameter= 10cm) were filled with marbles to mimic the stream substrate. These traps were placed in depositional and scour areas during low flow and higher flow periods. For low flow samples, traps were placed at a site above the area of active gravel mining in Indian Creek, and in Buck Creek above and below the confluence with Indian Creek. Trays were left out for approximately 2 weeks. For the high flow samples, traps were placed in Indian and the Indian/Buck Creek confluence, Clifty and the Clifty/Brushy Creek confluence and in Gilmore and Briary creeks. Sediment trays and marble substrate were rinsed thoroughly to remove all sediment. All water used for rinsing and the removed sediment was poured into 1-liter beakers and allowed to settle 48 hrs. Most of the water was then decanted and the remaining water and sediment was filtered through a pre-ashed glass fiber filter (cutoff= 0.45 μm) dried, weighed and ashed to determine ash-free dry mass (AFDM).

2.6 Data Analysis

All biological data were tested for normality with a Kolmogorov-Smirnov one sample t-test calculating Lilliefors probabilities. Transformations were attempted for data not normally distributed. Non-normal data for which transformations were unsuccessful were analyzed for significance with a non-parametric Kruskal-Willis one-way Analysis of Variance or Mann-Whitney U tests. All normally distributed and transformed data were analyzed for significance by means of a parametric two-sample t-tests calculating Bonferroni adjusted probabilities (Wilkinson et al.1996). All statistical analysis was conducted with Systat 7.0.

3.0 RESULTS

3.1.1. Summary of Geomorphologic Data

As has been previously noted, most previous studies of gravel mining impacts were conducted in streams with deep alluvial valleys where several meters to more than 100 meters of alluvium (gravel and sand) overlay bedrock. In this study, however, bedrock was located within 1 m to 2.5 m of the top of the valley bottom soils in the sites investigated and was present as the streambed in the deep pools of all streams.

Historically the entire region has been logged and the land, including hillsides, has been cleared for agricultural purposes since settlement. The most prevalent impact since initial land clearing appears to be the extensive modification and management of the channel network along wide valley bottom areas. Channel relocation, straightening, and dredging to increase channel cross sectional area and to decrease channel length on each of the study streams were extensive. Figures

2.4 through 2.7 show the lengths of main channel stream that could be identified as "channelized". The identification of stream sections as channelized was determined through examination and comparison of aerial photographs, topographic maps and site observations. The evaluation was conducted for each of the four study stream main channels from the channel mouths to a point upstream where the valley flats narrowed as indicated on USGS 7.5 minute quadrangle topographic maps. Only main channel stream sections with relatively wide valley bottoms were considered. We believe that all sections of channelized stream were not identified and that more detailed study of the streams would reveal that channelization is more extensive than determined here. Table 3.1 illustrates the extent of stream channelization and is considered to be typical for the Buck Creek watershed. Summary characteristics of each of the studied stream's valley, profile, riffle and cross section are provided in Tables 3.2-3.6.

3.1.2 Buck Creek Channelization

Although a detailed investigation of Buck Creek was not conducted, several observations were made through examination of aerial photographs, USGS 7.5 minute quadrangle maps, and observations during flight reconnaissance in addition to site examinations at various points from the KY 80 bridge to the KY 1781 bridge. Examination of aerial photography indicated that large reaches of Buck Creek were transformed from a multi-thread channel system (Channel Type DA4; Rosgen 1994) anabranched stream to a single channel stream over most of its length (probably an incised C4 stream type using the Rosgen (1996) classification system). This transformation would have increased agricultural productivity of the floodplain by increasing tillable land (See Figure 3.1). Several sections of the channel still remain in an anabranched form.

Table 3.1 Extent of Stream Channelization

Stream	Length of Stream Examined (km)	Estimated Length of Stream Channelized (km)	Stream Length Channelized (%)
Indian (mined)	3.9	3.1	79
Clifty (unmined)	2.6	2.6	100
Briary (mined)	3.0	2.8	93
Gilmore (unmined)	4.9	4.9	100
Total	14.2	13.6	96

Table 3.2. Stream Channel and Valley Slopes

Stream	Section	Elevation Change (m)	Length (m)	Channel Slope (%)	Channel Sinuosity	Valley Slope
Indian	1	1.27	117	1.09		
Indian	2	2.63	158	1.66		
Indian	3 Upper	2.99	298	1.00	1.07	1.02
Indian	3 Lower	4.51	582	0.78		
Indian	4	3.10	375	0.83		
Clifty	1	4.82	669	0.72	1.14	0.82
Briary	1	4.30	793	0.54	1.08	0.58
Gilmore	1	0.74	218	0.34	1.14	0.39

Table 3.3. Stream Channel Cross Section Characteristics

Stream	Section	Bankfull Channel Width (m)	Bankfull Channel Area (m^2)	Bankfull Channel Depth (m)	Floodprone Width (m)	Depth of Incision* (m)
Indian	1	8.9	3.83	0.43	11.0	0.55
Indian	2	11.5	4.14	0.36	14.4	1.08
Indian	3	12.5	6.25	0.50	13.7	2.04
Indian	4	11.0	8.03	0.50**	12.5	1.87
Clifty	1	7.4	4.44	0.60	14.6	1.31
Briary	1	11.9	6.43	0.54	25.2	0.97
Gilmore	1	14.2	9.94	0.70	30.5	1.40

*Note that the depth of incision was measured from the pre-settlement floodplain elevation for all channels. Low bank heights close to the elevation of the bankfull elevation were present at Clifty, Briary and Gilmore Creeks.
**A bankfull depth of 0.5 m was based on the cross section in Section 3 because the stream cross sectional characteristics were modified by recent mining that removed gravel to bedrock in Section 4.

Table 3.4. Non-Dimensional Stream Channel Cross Section Characteristics and Channel Classifications

Stream	Section	Bankfull Channel Width/Depth	Bankfull Entrenchment Ratio	Degree of Incision*	Mean Surface Particle Size (mm)	Rosgen Channel Classification
Indian	1	20.7	>2.4	2.3	73	Incised C4
Indian	2	31.9	1.3	4.0	Bedrock/Boulder	Incised B1/B2
Indian	3	25.0	1.1	5.08	Bedrock/75	F1/F4
Indian	4	22.0	1.1	4.7	45	F4/1
Clifty	1	12.3	2.0	3.2	45-60	Incised C4
Briary	1	22.0	2.1	2.8	54	C4
Gilmore	1	20.3	2.2	3.0	26	C4

* measured from pre-settlement floodplain. Note that the degree of incision would be computed as 1.0 for Clifty, Briary and Gilmore if the low bank heights were used instead of the elevation of the pre-settlement floodplain.

Table 3.5. Study Stream Riffle Properties

Stream	Section	Stream Length as Riffle (%)	Riffles per Km	Average Riffle Length / Bankfull Channel Width	Average Riffle Spacing/ Bankfull Channel Width	Average Riffle Slope (%)	Number of Riffles
Indian	1	36	29	1.4	3.6	3.4	4
Indian	2	26	6	3.8	1.7	1.8	1
Indian	3	4	2	1.2	20.1	4.6	2
Indian	4	51	10	4.7	19.7	1.7	4
Clifty	1	29	13	2.9	10.5	2.5	11
Briary	1	26	16	1.4	5.6	1.9	13
Gilmore	1	10	28	0.3	2.7	4.7	6

Table 3.6 Characteristics of Riffle Surface Particles from Pebble Count Analysis

Stream Reach	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	D_{84}/D_{16}	t_{cr}+ (N/m^2)
Indian 1	24	75	163	6.7	47
Indian 3	11	77	171	16.2	24**
Indian 4	15	47	106	7.0	29
Clifty	14	45	134	9.6	29
Briary	16	57	117	7.4	35
Gilmore	12	28	56	4.6	17

+ Critical boundary stress for nominal rate of sediment transport based on a non-dimensional shear stress of 0.04.

** A critical boundary stress for nominal rate of sediment transport was based on a non-dimensional shear stress of 0.02 for transport of gravel over shale bedrock.

Channelization of the Buck Creek system would have initially caused incision of the main channel of Buck Creek and incision of some tributaries. Blockage and filling of some anabranches, deepening and widening of the main channel, and removal of woody debris increased the sediment transport capacity of the system that also contributed to this suspected initial incision. The channel modifications and the incision of the Buck Creek main channel may have changed the gradient of most tributary streams near their confluence with Buck Creek. Examination of aerial photographs near the KY 39 bridge indicated that many tributaries were relocated and straightened as they entered and crossed the Buck Creek floodplain, increasing channel gradient and maximizing available agricultural land.

The initial incision of Buck Creek would have propagated upstream and into tributary channels where bed degradation was observed during site visits. Currently Buck Creek, although incised by an estimated 1-1.5 meters, appears to be in a state of general widening and aggradation. Shale bedrock was observed in pools at all locations in the upstream part of the watershed. More resistant bedrock was observed in the shallower sections of the channel in the region of the KY 461 Bridge. Severe bank erosion and lateral channel migration, estimated to be in excess of 0.5 meters per year, on the outside of incised channel bends was observed at several locations both upstream and downstream of the Indian Creek confluence. Rapid reformation of mined point bars and riffles was observed after minor flood events. Erosion of high gravel content banks (estimated to be greater than 70% gravel) in the outside bends of the incised and partially channelized main thread of Buck Creek is suspected of being a significant source of gravels that contributes to the bar and riffle building of the generally aggrading main channel. Evidence of gravel mining in the main channel of Buck Creek was observed at four locations. Gravel at three of the mining sites was excavated from point bars to approximately the level of the low

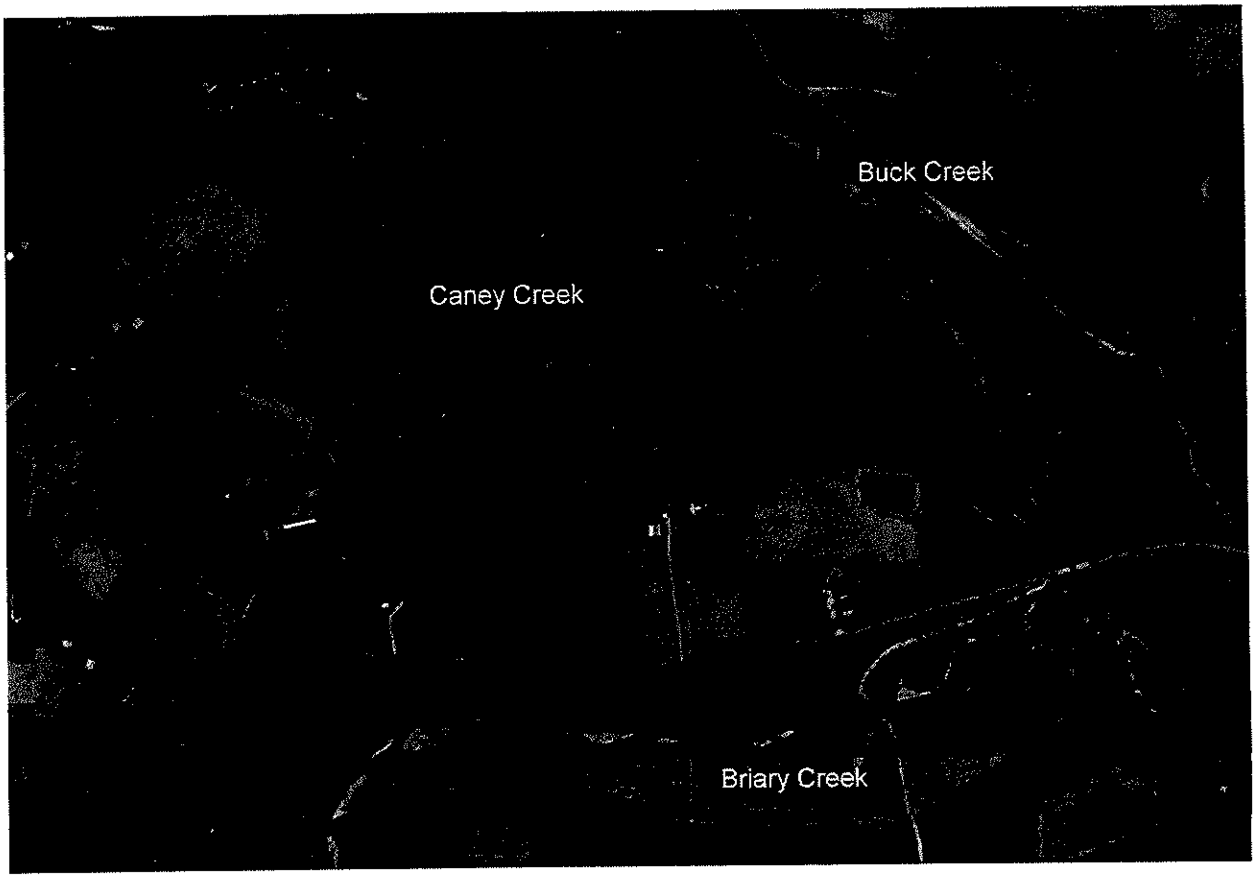

Figure 3.1. Existing primarily single thread channel system of Buck Creek and tributaries and evidence of previous anabranched channel networks. Current primary channel system is shown as thick lines and secondary and abandoned channel system is shown as thin lines.

water elevation at the time of examination. However, gravels were removed to within centimeters of the bedrock at and downstream of the Indian Creek confluence during periods of very low water. At some locations point bars were excavated and the material was placed along the toe of the outside of the bend bank in an apparent attempt to mitigate bank erosion.

3.2. Geomorphologic Assessment: Results for Study Reaches

3.2.1 Indian Creek

The current state of Indian Creek is representative of the physical conditions of many streams that have been straightened, enlarged and intensively mined in the Buck Creek watershed. In addition to channel straightening between 1958 and 1989, intensive gravel mining has occurred in a section near its confluence with Buck Creek. Gravel mining may have occurred in the early 1960s from the mouth of Indian Creek to the Dry Branch confluence (Skaggs personnel communication). Channel modifications prior to 1958 are not documented; however, channel dredging, debris removal and straightening along some reaches probably occurred prior to 1958.

Examination of the upland streams revealed that both straightening and deepening of tributary channels have occurred although the extent of channelization was not measured in these tributaries. In some cases, culverts at roadway crossings provided grade control that limited the upstream incision of the channel into the underlying bedrock and the thin layer alluvial streambed materials. Although all streams were gravel bed, there was no evidence of high gravel production tributary sources.

Indian Creek was the most extensively surveyed stream of this study. For this particular stream, the survey upstream extended from the confluence of Buck Creek to a location beyond what was known to be the extent of recent gravel mining along the main channel. Combined channel straightening and mining have occurred from the confluence of Buck Creek to the Dry Branch tributary confluence (Figure 3.2). The Indian Creek detailed study reach extended 1578 m upstream from the confluence of Buck Creek.

The stream was separated into four morphologic sections as characterized in Table 3.7. Figures 3.3 through 3.6 are photographs illustrating the conditions of each of the sections and Figures 3.7 through 3.10 are representative cross sections measured in each of the four reaches. Figures 3.11 through 3.16 show plots of the streambed (thalweg) profile through each of the sections. In addition, low flow pool depths and the measured elevation of the bedrock and estimated level of bedrock under gravel bed sections are shown. A histogram of pool depths was developed to compare pool depths in each section of Indian Creek and is provided in Figure 3.17.

Section 1 was the most upstream section studied in detail. Although this section had suffered past channel incision (about 0.55 m as indicated by Figure 3.7), siltstone boulders developed from fractured bedrock in the streambed and from hillslope failure debris (colluvium) have created a natural boulder grade control that has limited the depth of incision. The stream type according to the Rosgen (1996) methodology was classified as an incised C4 type channel although large woody debris (LWD) jams located in the upstream extent of Section 1 forced flow onto the adjacent floodplain several times during the period of the project. As shown in Figures 3.3 and 3.11, several deep pool and riffle sequences are present and tree roots extend to the low water elevation. Trees fallen across the stream obstruct and divert bankfull flows. A multiple channel section and island have formed from a partial channel avulsion (sudden shift and formation of a new channel) which has occurred because of LWD blockage. Bedrock is present in the deepest section of all pools as illustrated in the stream thalweg profile shown in Figure. 3.11. Evidence of direct gravel mining or channel straightening within Section 1 was not found; however, the upstream propagation of channel vertical degradation caused by downstream channel straightening and gravel mining (Sections 3 and 4) is considered to be a primary cause of channel incision in Section 1.

Two of the five deepest pools in the 1578 m long study area were found in Section 1 as shown in the histogram of pool depths (Figure 3.17). Bedrock is present only in the bottom of pools and appears to limit pool depth. The stream slope through Section 1 is approximately 1.09%, which is slightly steeper than the overall valley slope; however, the local valley slope may be steeper than the channel slope although it was not measured. Detailed information on the characteristics of the riffles

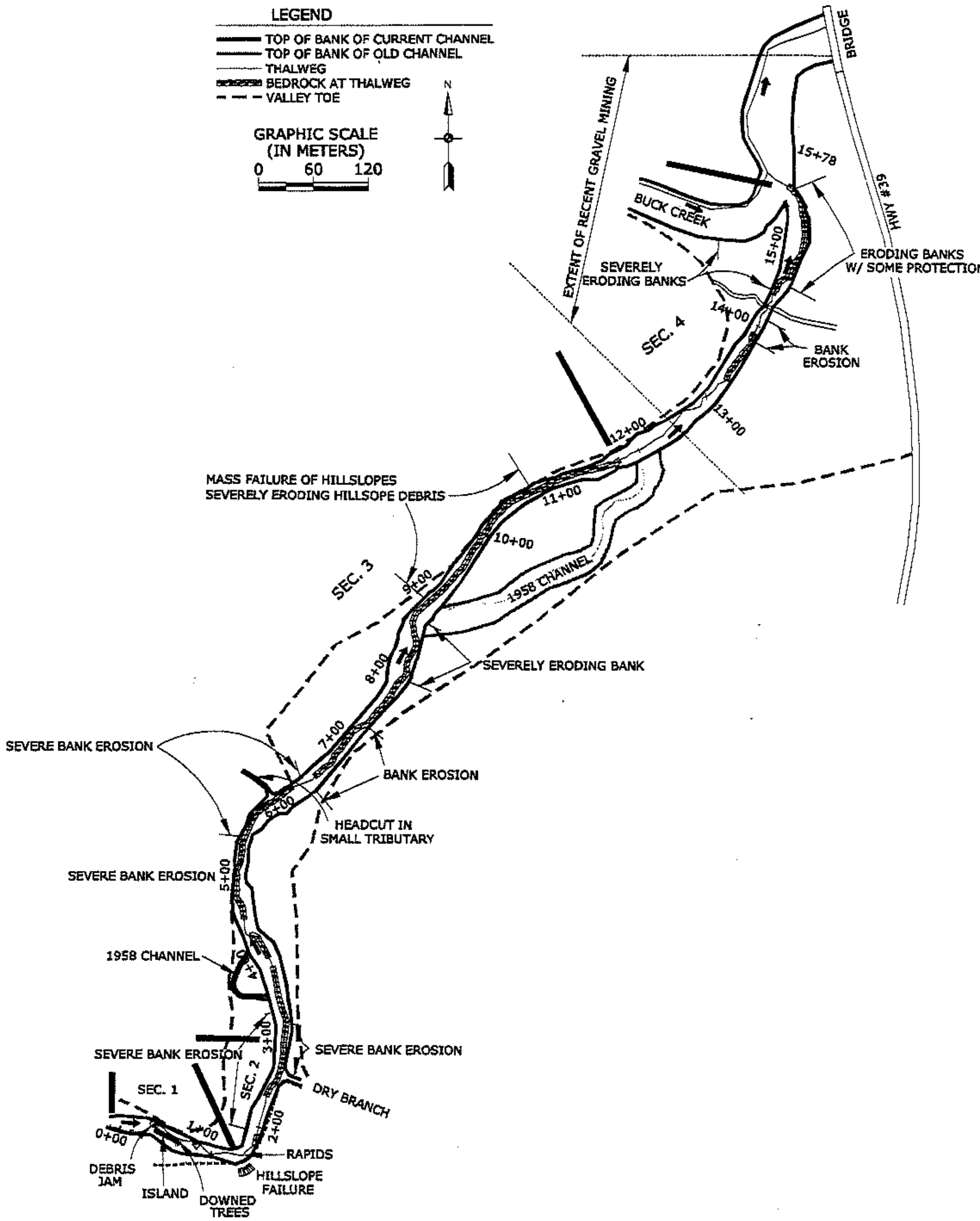

Figure 3.2. Indian Creek. Detail of study area

Table 3.7. Indian Creek Morphological Sections

Segment	Start Station (m)	End Station (m)	Description and Characteristics
Section 1 Upstream Reference	0+00	1+17	• Low entrenchment • Floods access floodplain annually • Debris interaction with channel • Bedrock only in deep pools and along valley wall • Well developed pools and riffles • Riparian tree roots in pools • Near equilibrium sediment transport/gradual incision with some lateral instability caused by interaction of debris (avulsion)
Section 2 Transition Reach	1+17	3+00	• Transition of low entrenchment at the upstream sections to high entrenchment at the low sections • Natural siltstone boulder grade control • Hill slope mass failure • Dry Branch tributary confluence • Bedrock bottom stream • Bank erosion and trees falling into stream on both banks of downstream end of reach • Transition in underlying bedrock from silt stone (upstream) to shale (downstream). • Large boulders from undermined siltstone streambed • Gradual incision into bedrock • No significant storage of gravels
Section 3 Shale Bedrock Reach	3+00	11+75	• Bed along thalweg composed primarily of shale bedrock • Channel incision into bedrock • Several sections of channel relocated since 1958 • Terrace with trees at approximately 1 m below upper terrace (pre-settlement floodplain) and above current apparent bankfull level (channel formative flow level) • Severe bank erosion at several bend locations • Mass failure of hill slopes along stream reaches that have been relocated to base of valley slopes • Development of bars along channel margins and inside of bends • Gravel extracted to maintain channelized conditions
Section 4 Deposition and Backwater Affected Reach	11+75	15+78	• Intermittent and intensive mining during the duration of this study • Backwater effects from Buck Creek extend to approximately station 11+50 for 1 m flooding of Buck Creek floodplain • Gravel riffles with shale bedrock in pools • Exposure of underlying shale bedrock substrate from mining operations • Aggrading and low rates of lateral migration

in Section 1 of Indian Creek is provided in Table 3.5. Riffles occupy about 36% of the channel length are relatively frequent (29 per km) and have a length equal to 1.4 times the channel width. The size distribution and characteristics of the riffle surface materials are shown in Table 3.6

Section 2 is called the transition section because of the rapid change in channel width, bed material properties, and channel incision. In addition, the confluence of the tributary Dry Branch Creek enters in this reach. One reason for the change in channel characteristics is the change in geologic conditions. A unit of relatively resistant siltstone overlays a much weaker unit of shale Vertical degradation of the downstream channel that would propagate upstream through this reach has been partially controlled by the siltstone. Although the underlying shale has weathered and eroded, large blocks of siltstone have armored the reach from approximately 1+60 to 2+50. Some larger fragments of siltstone were also found downstream as far as station 5+00. Figure 3.4 shows the steep section of large siltstone boulders. The initial incision that caused the exposure of the siltstone also caused the migration of the channel into the toe of the valley slope. A shallow slip failure in the colluvial material of the north valley slope has also contributed to the supply of gravel and large siltstone boulders (Figure. 3.4). The Dry Branch tributary has incised because of the base level change in Indian Creek. As a consequence the banks and bed of Dry Branch are eroding and are being transported to the confluence as shown in Figure 3.18. This transition section is the steepest section of Indian Creek. within the study reach with an average slope of 1.6%. One large riffle extends from the end of Section 1 into the upstream end of Section 2. The riffle should more properly be called a rapids because of the large boulders that armor its surface (Figures. 3.4 and 3.12) and slope of 1.8%.

Figure 3.3. Section 1: Upstream low entrenchment reach

Figure 3.4. Section 2: Transition and hillslope failure upstream of Dry Branch tributary to Indian

Figure 3.5. Section 3: Severely entrenched shale bedrock reach

Figure 3.6. Section 4: Backwater affected reach with recent deposition of gravels

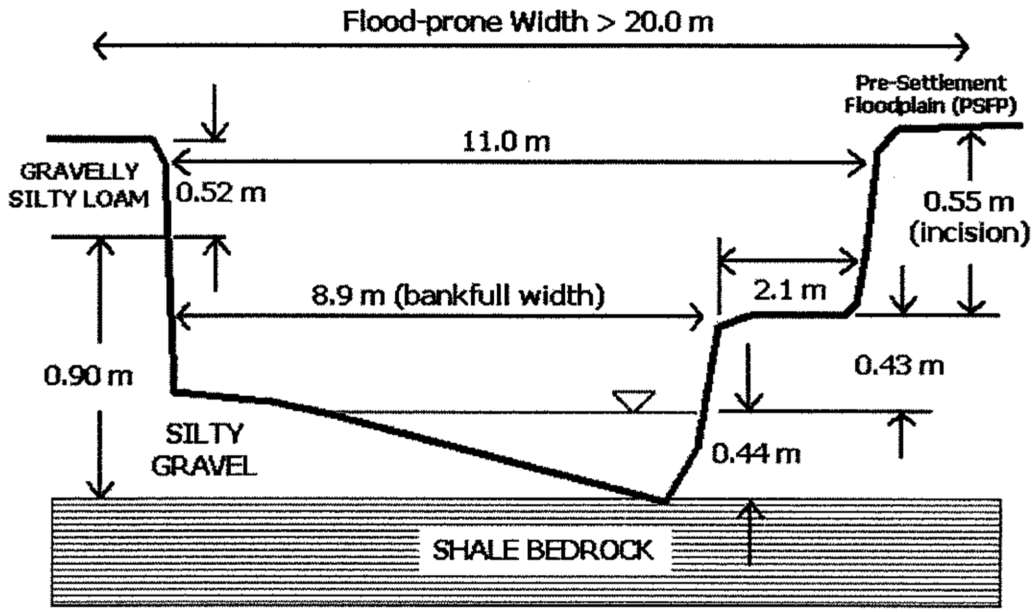

Figure 3.7. Section 1, Indian Creek: Upstream low entrenchment reach.

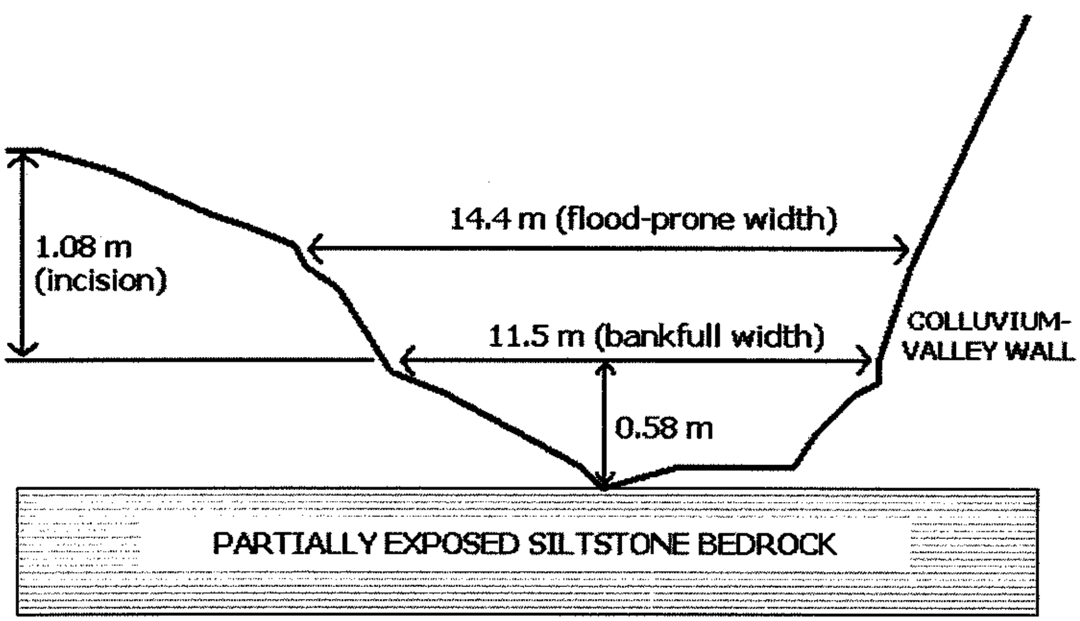

Figure 3.8. Section 2, Indian Creek, cross section: Transition reach.

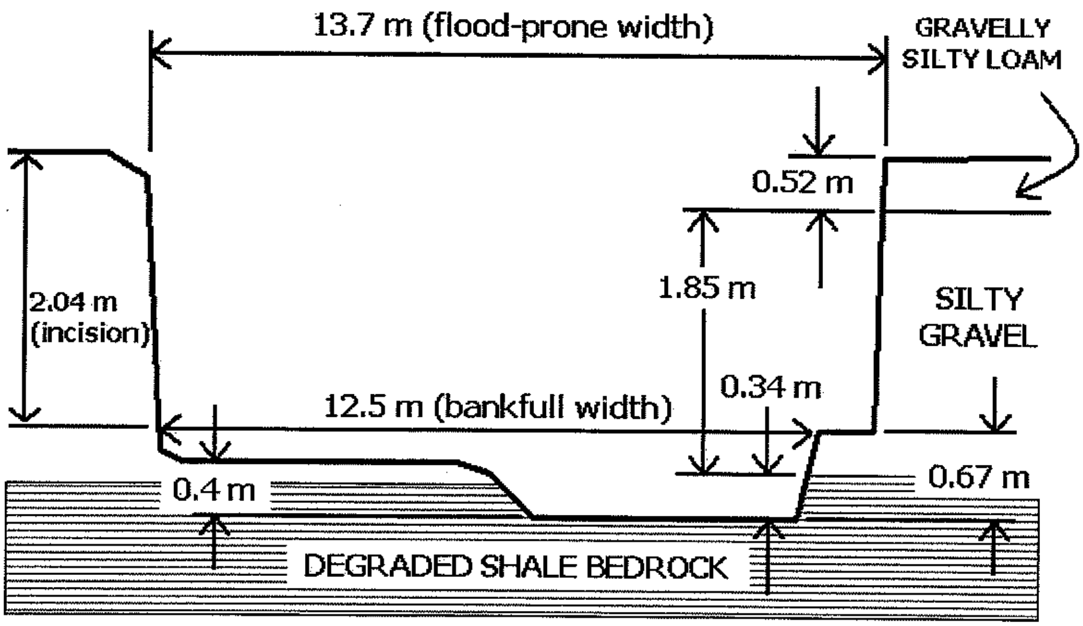

Figure 3.9. Section 3, Indian Creek, cross section: Severely entrenched shale bedrock reach.

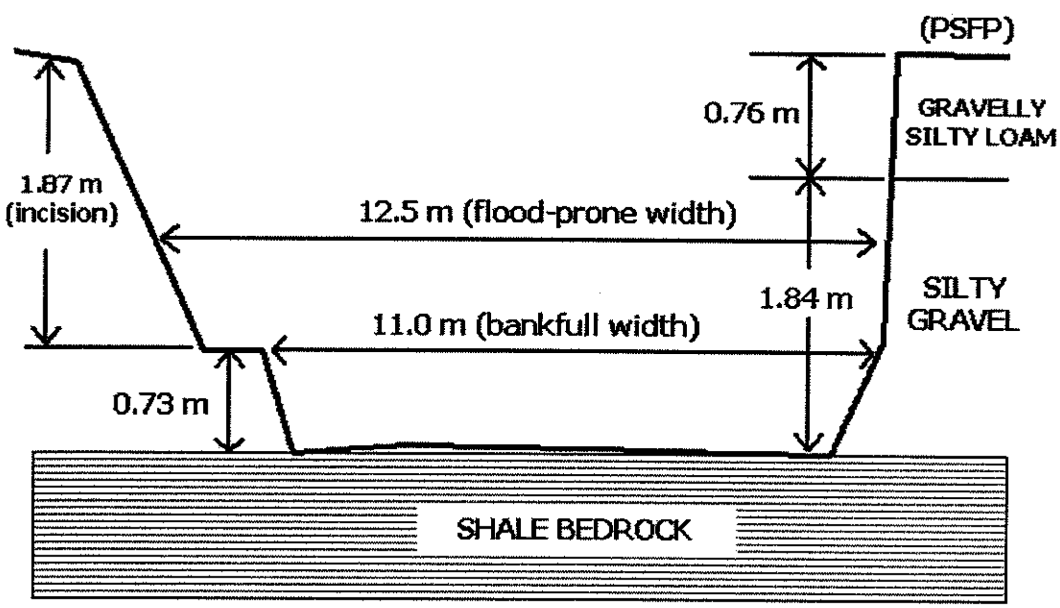

Figure 3.10. Section 4, Indian Creek, cross section: Backwater affected reach after gravel mining.

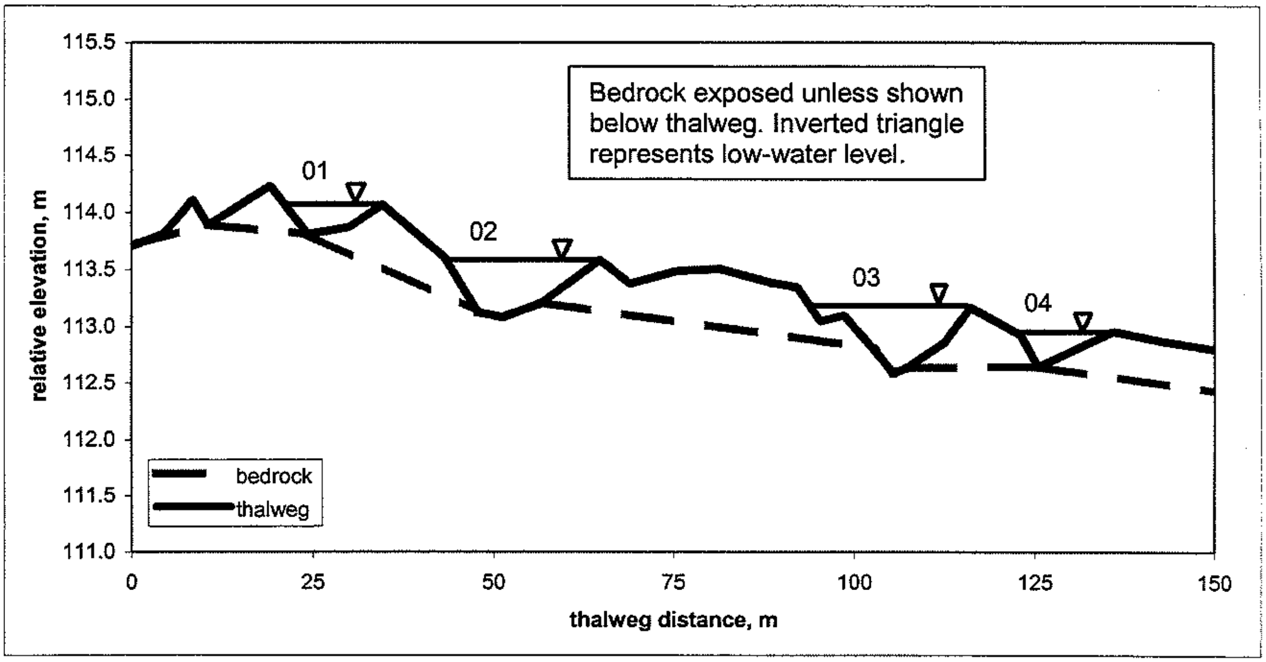

Figure 3.11. Section 1, Indian Creek: Streambed profile, pool location and bedrock elevation.

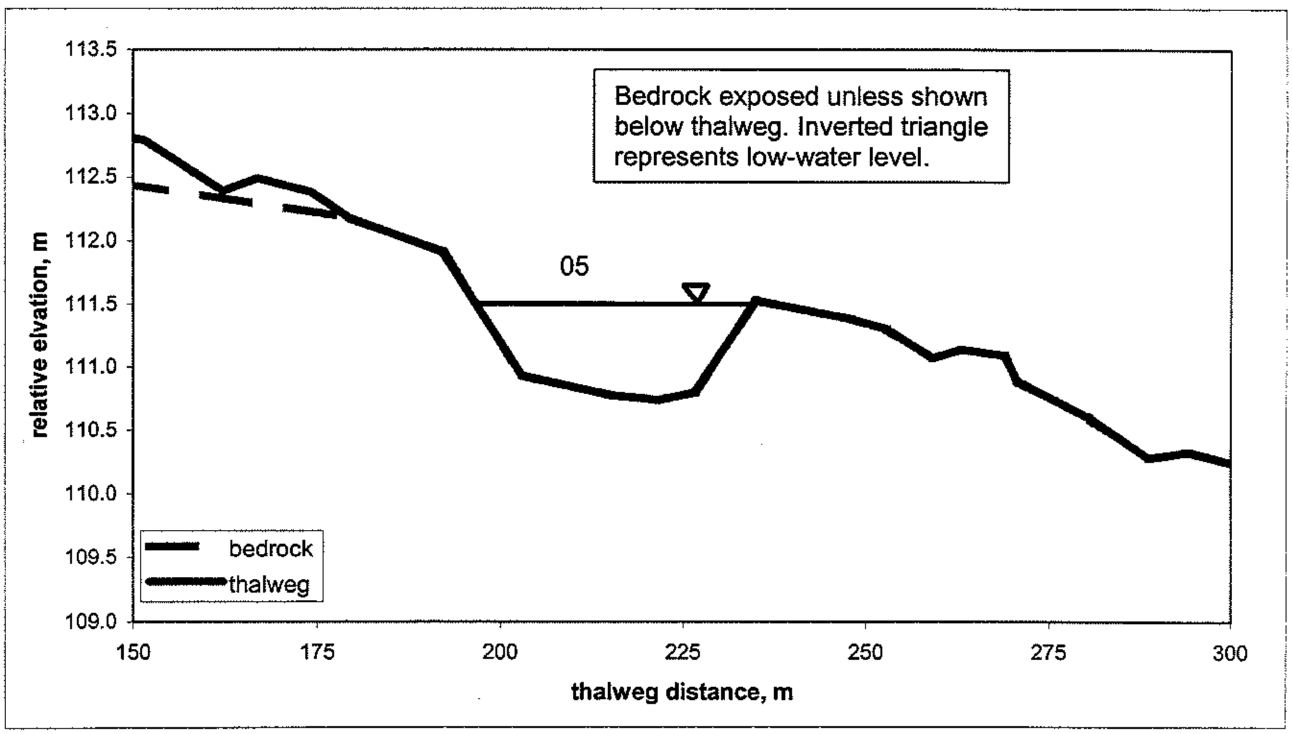

Figure 3.12. Section 2, Indian Creek: Streambed profile, pool location and bedrock elevation.

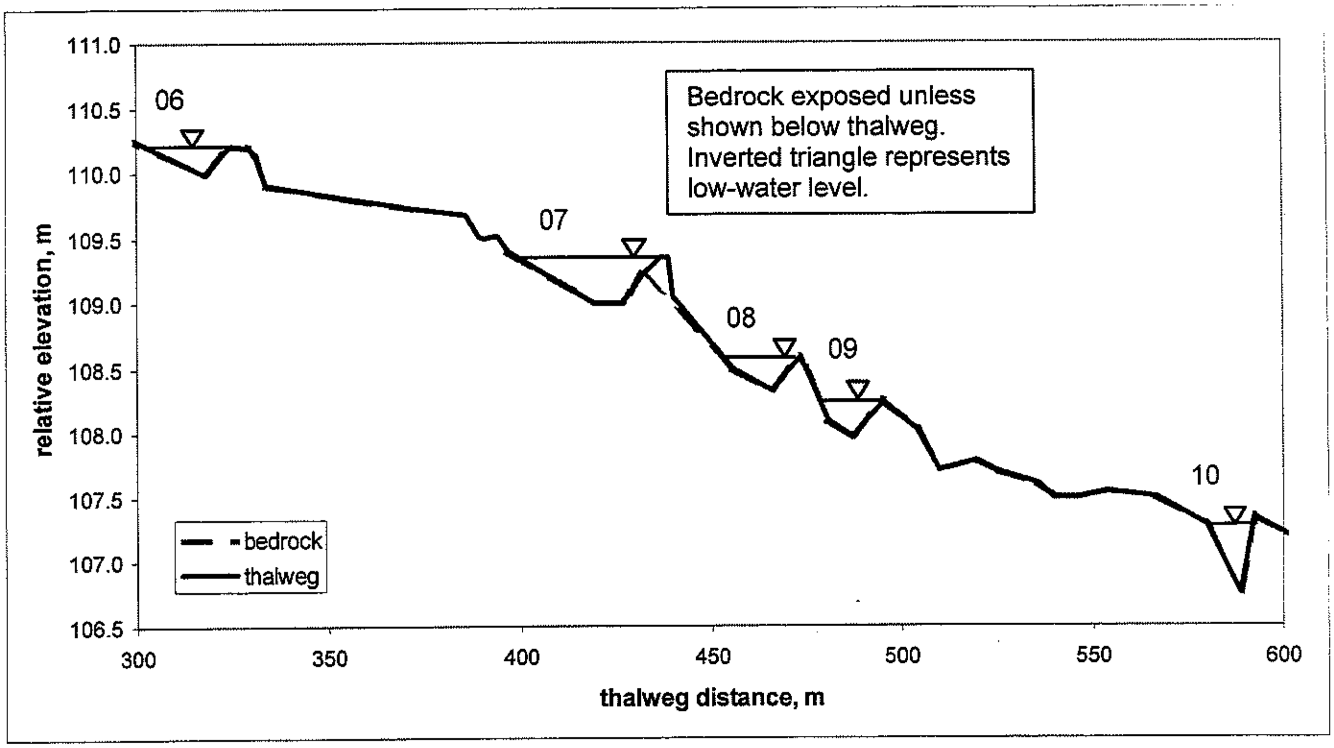

Figure 3.13. Section 3, Indian Creek (upstream): Streambed profile, pool location and bedrock elevation.

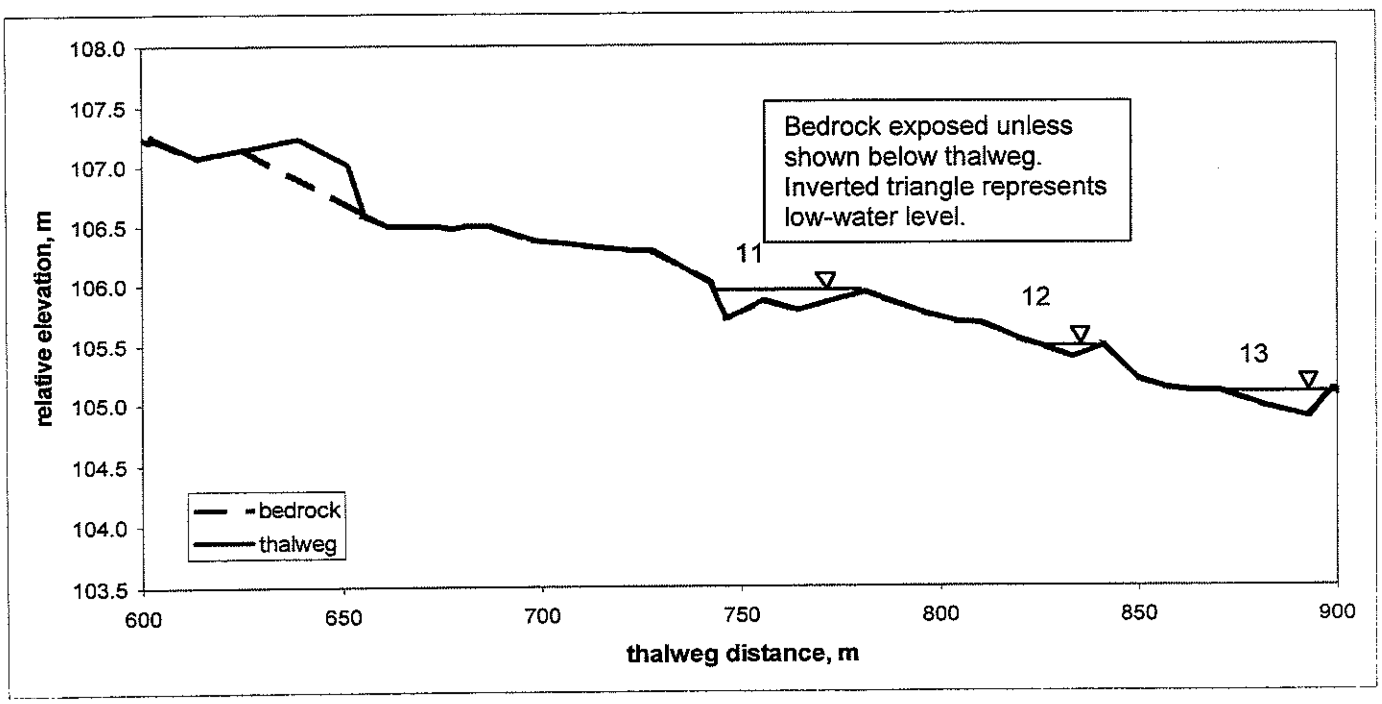

Figure 3.14. Section 3, Indian Creek (middle): Streambed profile, pool location and bedrock elevation.

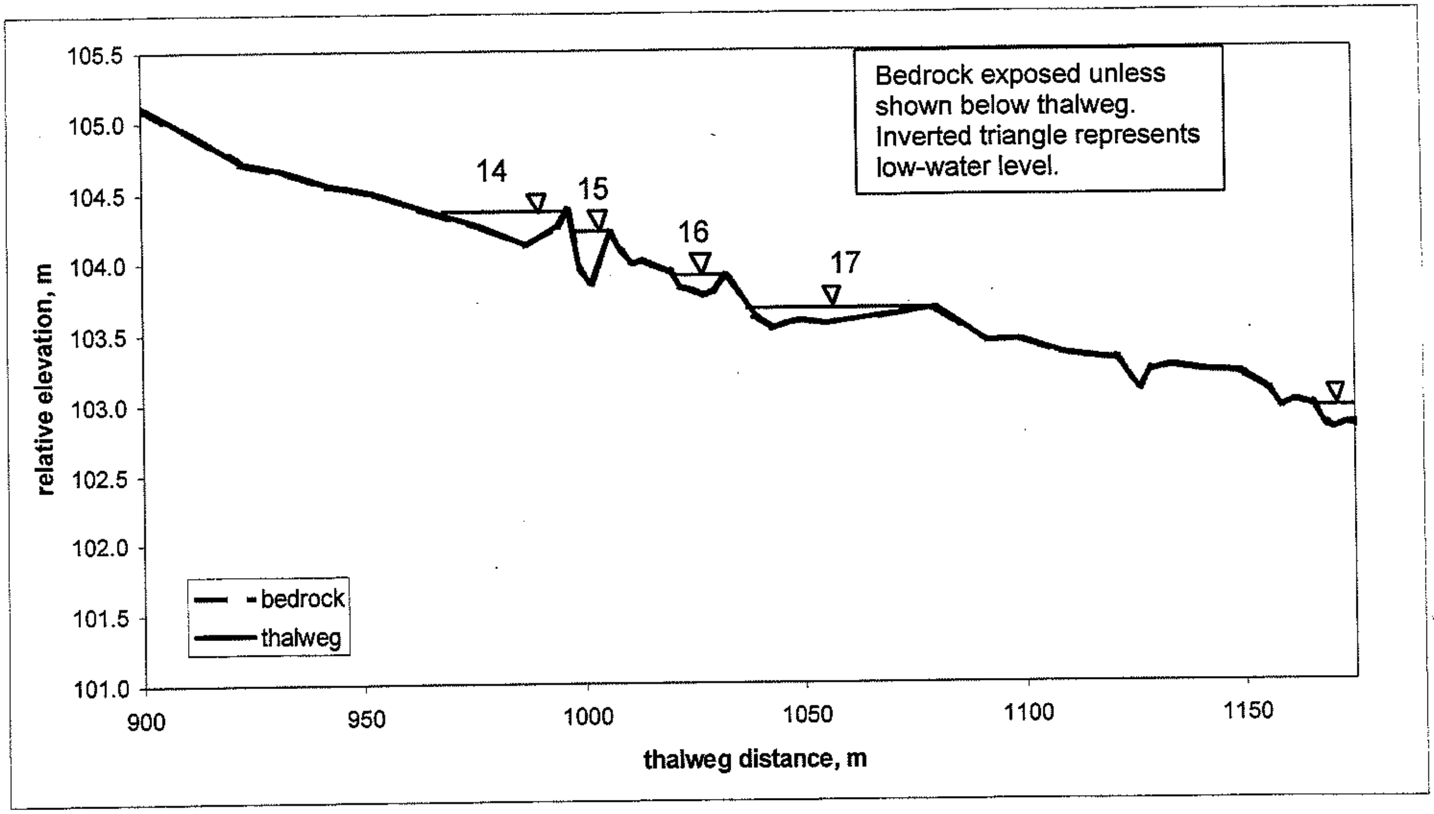

Figure 3.15. Section 3, Indian Creek (downstream): Streambed profile, pool location and bedrock elevation.

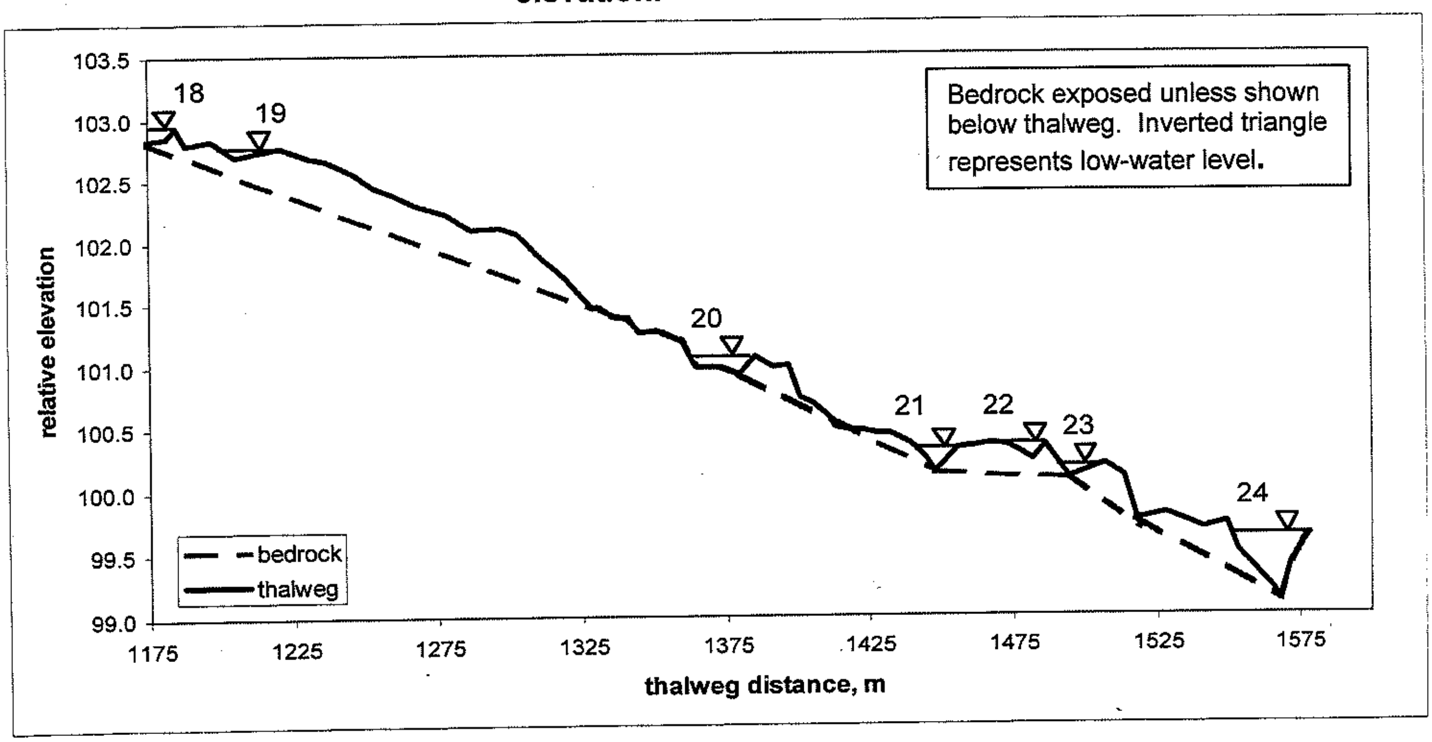

Figure 3.16. Section 4, Indian Creek: Streambed profile, pool location and bedrock elevation.

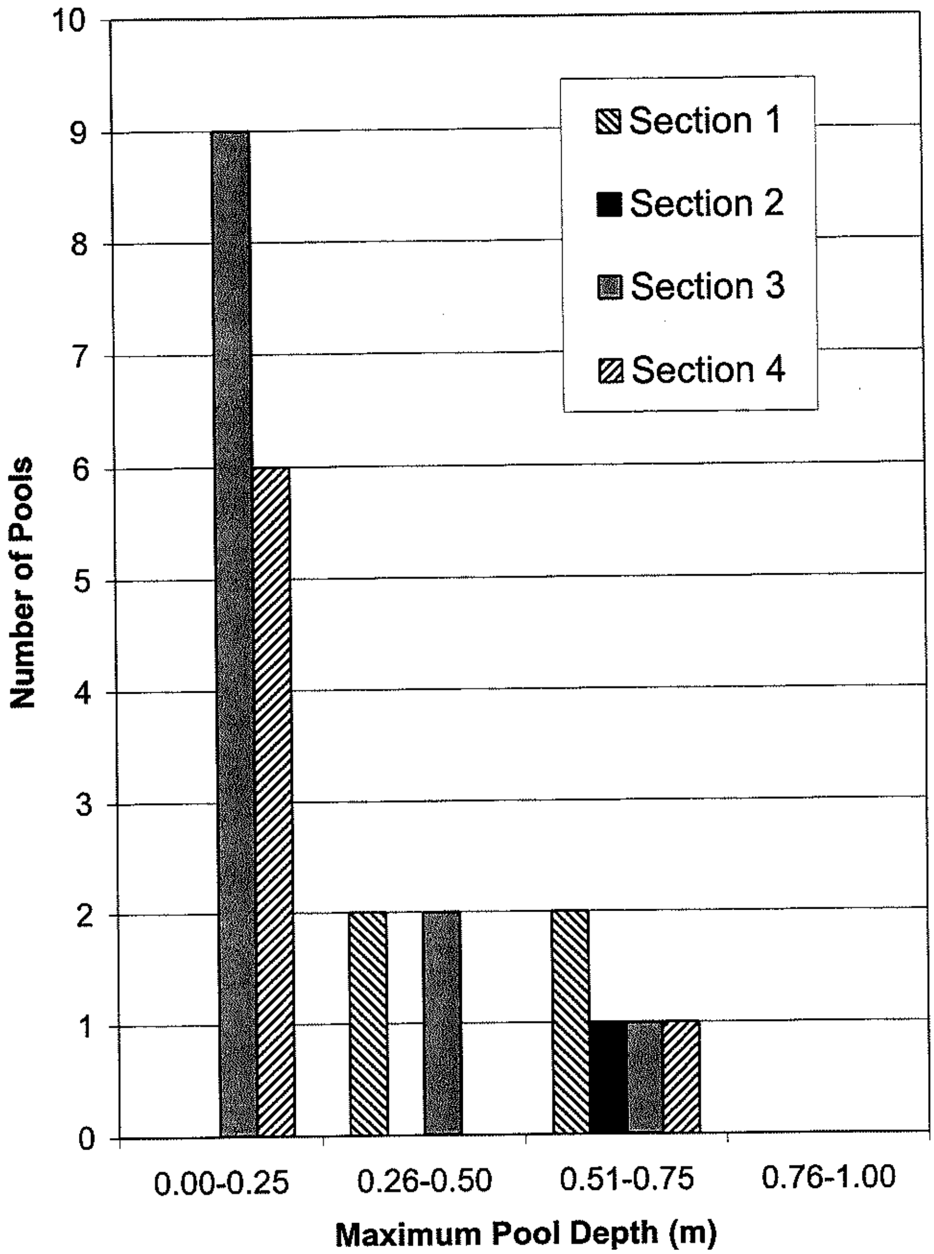

Figure 3.17. Histogram of pool depths for the morphologic sections of Indian Creek.

Figure 3.18. Sediment deposit at the confluence of Dry Branch and Indian Creek.

One relatively deep pool exists in Section 2. The pool depth is comparable to the pool depths in Section 1, the reference reach. The deepest part of the pool is lined with bedrock. Approximately 60 m of Section 2 is composed of siltstone and shale steps with scattered siltstone boulders. The bedrock steps transition from siltstone at the higher elevations to shale at the lowest elevations. According to the field measurements obtained for a cross section located in the region of boulder grade control (upstream portion of this Section 2, Figure 3.8 shows cross section) and the non-dimensional geomorphic parameters, Section 2 was classified as an incised B2 stream; however, the channel transitions into an F1 a short distance downstream. This section is in a state of gradual incision into siltstone by means of several headcuts. No significant storage of gravel is available in this reach.

Section 3 is characterized by channel incision into shale bedrock as shown in Figure 3.5 and as illustrated in Figure 3.9. Since 1958 at least 416 m, approximately 26% of the study reach shown in Figure 3.1, has been relocated. Since no levees are present and the pre-1958 channels do not appear to have been filled extensively, the gravel was either removed (mined) from the valley mechanically or transported by the stream after being eroded from the banks or the streambed. Severe bank erosion is apparent in several locations including banks along outside of bends and along the north valley wall throughout Section 3. These sediments form bars along the margins of the channel, on the inside of channel bends, and occasionally as very short riffles. Shale bedrock steps (headcuts) are also present along most of this section. These steps are more frequent in the steeper upstream reaches of Section 3. Figure 3.9 shows a typical cross section in the upper portion of Section 3 and Figure 3.19 shows erosion of the right bank at the same locations. At some locations the stream has incised into the shale bedrock as shown in Figure 3.20.

The lack of gravel on the bedrock severely limits the depth of pools in Section 3. The streambed profile plots shown in Figures 3.13- 3.15 show the extent of bedrock and its impact on pool development. The lack of gravel stored on the bedrock limits the number, length and size of riffles. Only 2 gravel riffles (less than 4% of the channel length) are present over the 875 m length of Section 3. This portion of Indian Creek has the smallest number of riffles per stream length (2 riffles/km) of all stream reaches examined. Section 3 is a severely entrenched high width to depth ratio channel that was classified as an F1 for most of its length. In a few locations, a thin layer of gravel covers large areas of the bedrock bottom and alter the classification to F4 in some reaches. The depth of incision from the pre-channelized floodplain was measured as approximately 2.0 m, making this section of Indian Creek the most severely incised reach.

Weathering of the exposed shale bedrock and the progression of headcuts in the shale are causing continued gradual incision into the bedrock. Bank erosion in the outside of channel bends is providing a large supply of gravel. Gravel is transported through this reach and minor amounts arestored along channel margins, in shallow point bars and in a few short riffles. Large siltstone boulders transported from Section 2 are present in the upstream reaches of Section 3. These boulders decrease in diameter with downstream distance. Occasionally gravels are moved from shallow point bars to the face or toe of eroding banks. Section 4 represents the region of channel that is affected by the backwater of Buck Creek. Flood events that fill the channel up to 1 m above the high bank would cause backwater to approximately Station 11+75 m (see Figure 3.2). This station corresponds to the transition from a mainly bedrock bottom channel observed in Section 3 to a primarily gravel bottom stream in Section 4. Gravels from the streambed of Section 4 were excavated to expose bedrock at least 2 times during the period of this study. The locally steep slope produced at the upstream extent of gravel mining is shown in Figure 3.16 at Station 13+25 m. The development of this steep slope reach at the upstream extent of gravel mining initiates a headcut that migrates upstream during bankfull and larger flow events. The removal of gravel, the development of the steep upstream slope, and the subsequent migration of headcuts reinitiate upstream streambed erosion and degradation upstream of the gravel mined location. Flow events subsequent to the channel survey redeposited sediments throughout Section 4, replaced mining-removed gravels, recreated a steep upstream slope, and reinitiated channel degradation upstream. As a consequence, gravels that may deposit on the bedrock upstream of Station 11+50 m.

Figure 3.19. Eroded stream bank at Station 3+00 in Section 3 (bed rock) of Indian Creek.

Figure 3.20. Eroded stream bank at Station 3+00 in, Section 3 (bed rock) of Indian Creek.

in Section 3 are eroded. Because of the continued gravel mining in Section 4, the gravel aggradation processes and the associated riffle and pool development cannot occur in Section 3. Consequently, continued weathering, slaking and eroding of shale bedrock is maintained because of the repeated mining of gravels in Section 4. Repeated intensive scraping of gravel to bedrock and subsequent gravel transport causes the streambed in this region to change rapidly. Gravel mining extended downstream of Indian Creek Section 3 into Buck Creek to KY 39. In at least one instance, gravels were scraped to the shale bedrock in both the mouth of Indian Creek and in Buck Creek between the Indian Creek Confluence and the KY 39 bridge. At the particular time of the stream survey 51% of the stream length of Section 4 was considered to be gravel riffle; however, the mining operations and subsequent gravel transporting flow events rearranged the streambed material of Section 4 frequently.

Although the gravel bed in Section 4 is aggrading, the repeated mining maintains incised (about 1.87 m) and entrenched conditions. The stream was classified as an F4/1 stream type (Figure 3.10) because bedrock was exposed over large regions of the mostly gravel streambed.

3.2.2 Clifty Creek

Clifty Creek has been channelized over its entire wide valley section as shown in Figure 2.5 and Table 3.1. Although Clifty Creek has been extensively relocated and straightened and gravels from the bed may have been excavated to increase flow capacity of the channel, evidence of recent mining activity was not found. Clifty Creek was surveyed from its confluence with Brushy Creek to a location approximately 750 m upstream as shown in Figure 3.21. During the period of this study, gravels were transferred from a point bar (Station 3+50 m to Station 4+50 m) to the outside bank of the bend. This transfer of gravels is a common practice throughout the Buck Creek watershed. Additionally, a bridge over Clifty Creek was replaced at Hazeldale Road approximately 6 months before channel surveying was initiated. A debris blockage was present at Station 4+60 m at the time of the channel survey. This blockage was removed after the survey. Since 1958, a bend located between Station 1+00 m and 2+00 m was removed to establish a straight channel reach. Bank erosion is active at locations along channel banks where the thalweg is in close proximity to the channel banks. The most active reach of erosion is located along the outside of a bend between Stations 3+50 m to 4+75 m. The cross section in Figure 3.22 shows a sidebar building to create a new floodplain level on which small sycamore trees were growing. Bank erosion has widened the high banks on both sides of the stream such that an inner channel has formed with one bank at approximately the bankfull elevation. The channel was classified as a C4 stream type in the particular reach characterized by Figure 3.22; however, other reaches upstream and downstream would have been classified as F4 channels. Given the current trend of channel widening in bends and bar building and assuming no additional channel disturbances, the stream is expected to aggrade and widen to build a floodplain typical of a C4 stream type. Approximately 29% of the stream length was considered to be composed of riffles. An average riffle length of 2.9 times the bankfull channel width was obtained for the study reach. The stream profile in Figures 3.23 and 3.24 shows accumulation of gravel over shale bedrock and long gravel riffles emptying into deep pools. The histogram shown in Figure 3.25 illustrates the differences between maximum pool depths in Indian Creek and those in Clifty Creek. The intensely mined sections of Indian Creek, Sections 3 and 4, have shallow pool depths while several deep pools are formed in the deeper channel gravel deposits of Section 1 of Indian Creek and Clifty Creek. Also bedrock steps are not present in both Sections 1 of Indian Creek

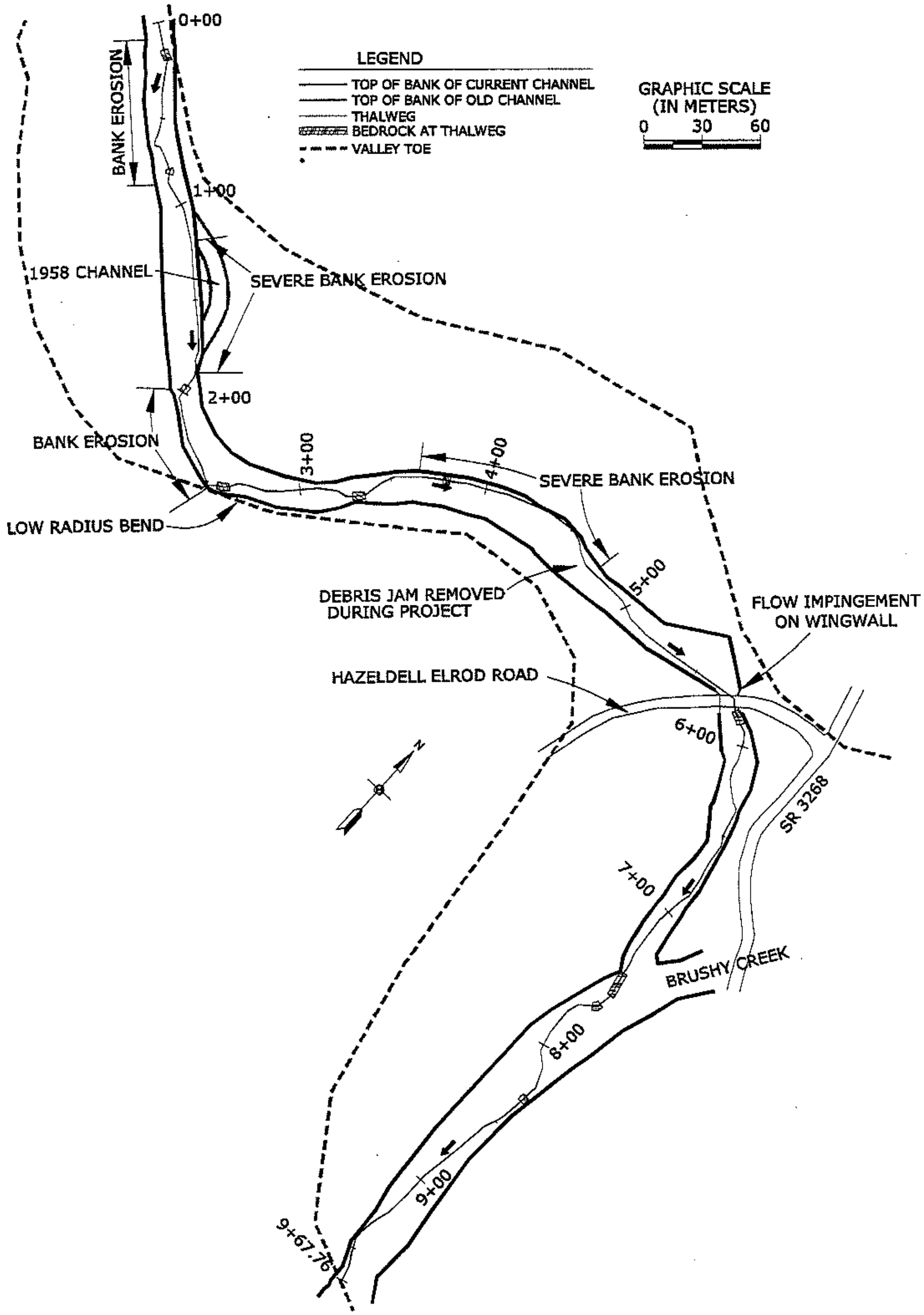

Figure 3.21. Clifty Creek detailed study area.

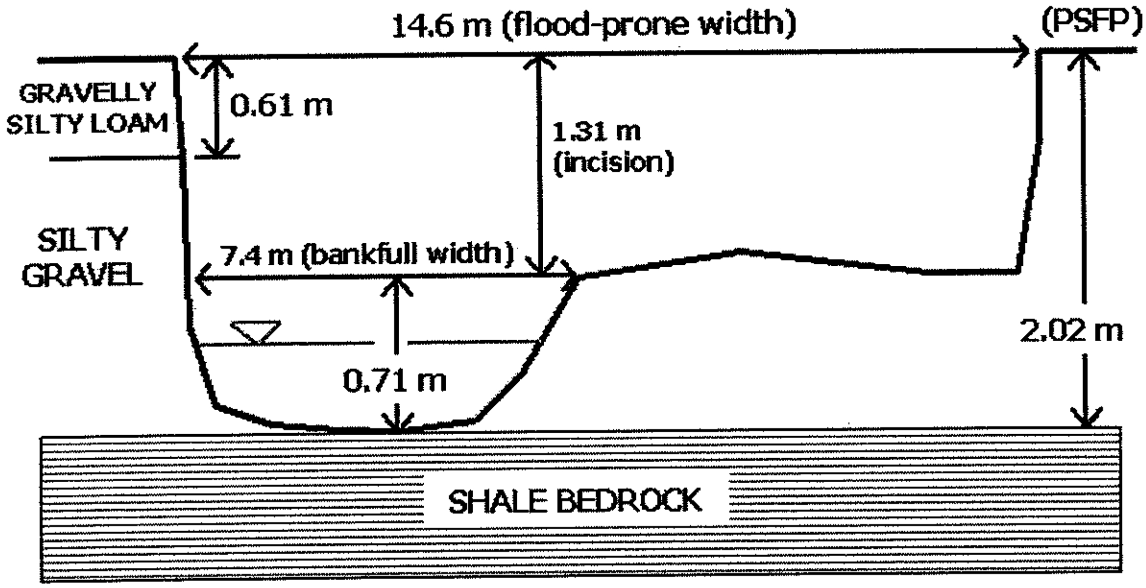

Figure 3.22. Clifty Creek cross section.

and Clifty Creek, whereas bedrock steps dominate the steep streambed regions in Sections 3 and 4 of Indian Creek.

3.2.3 Briary Creek

Large sections of the main stem of Briary Creek have been relocated and/or channelized. Figure 2.6 shows reaches that were examined downstream of Short Branch. Over 93% of the main stem of Briary was channelized (Table 3.1). Figure 3.26 shows the past locations of portions of channelized reaches within the study reach. The dynamic nature of Briary Creek is clear from the channel movement since 1958. Sections of Briary Creek have migrated more than 40 m (Station 5+00 m to 5+50 m). Recent gravel mining from the study reach has been primarily conducted through excavation of gravels from bars on the insides of two bends from Station 2+00 m to Station 2+72 m

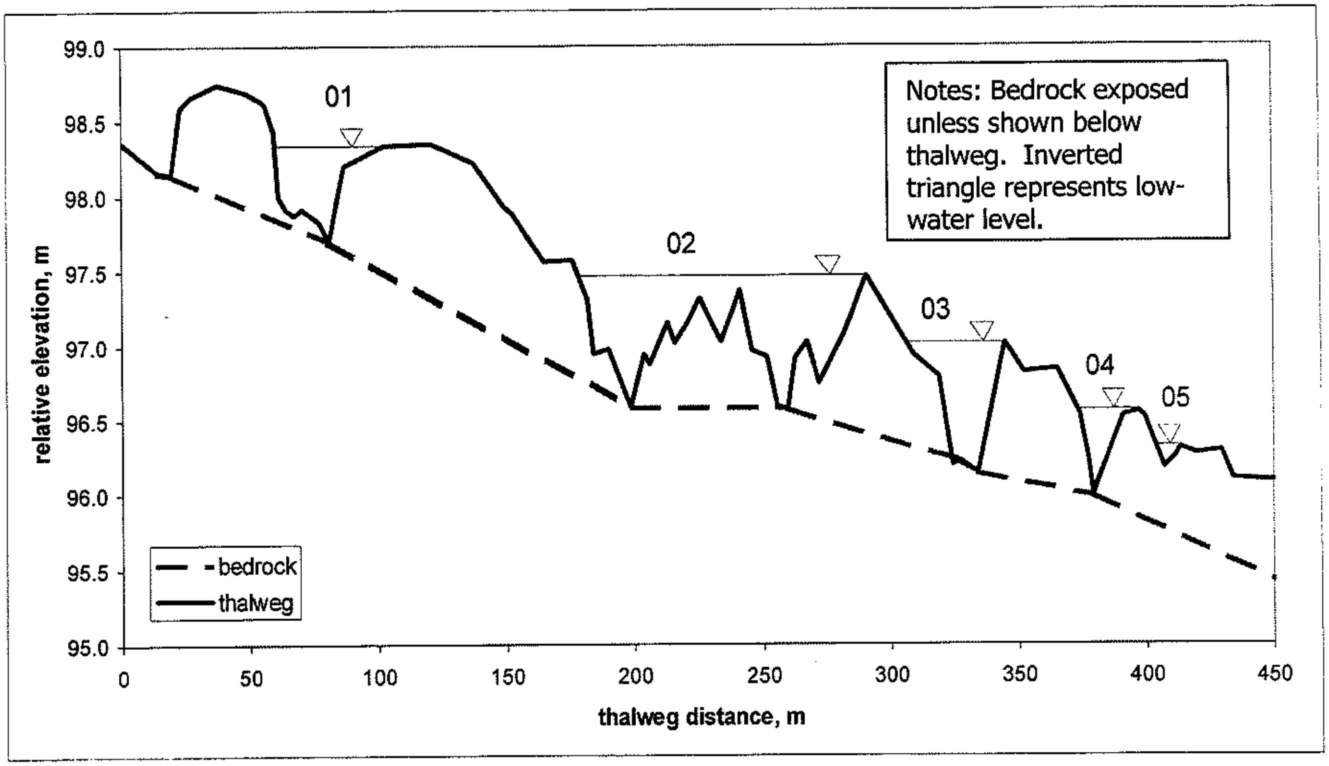

Figure 3.23. Upper Clifty Creek stream thalweg profile, bedrock surface profile and pools.

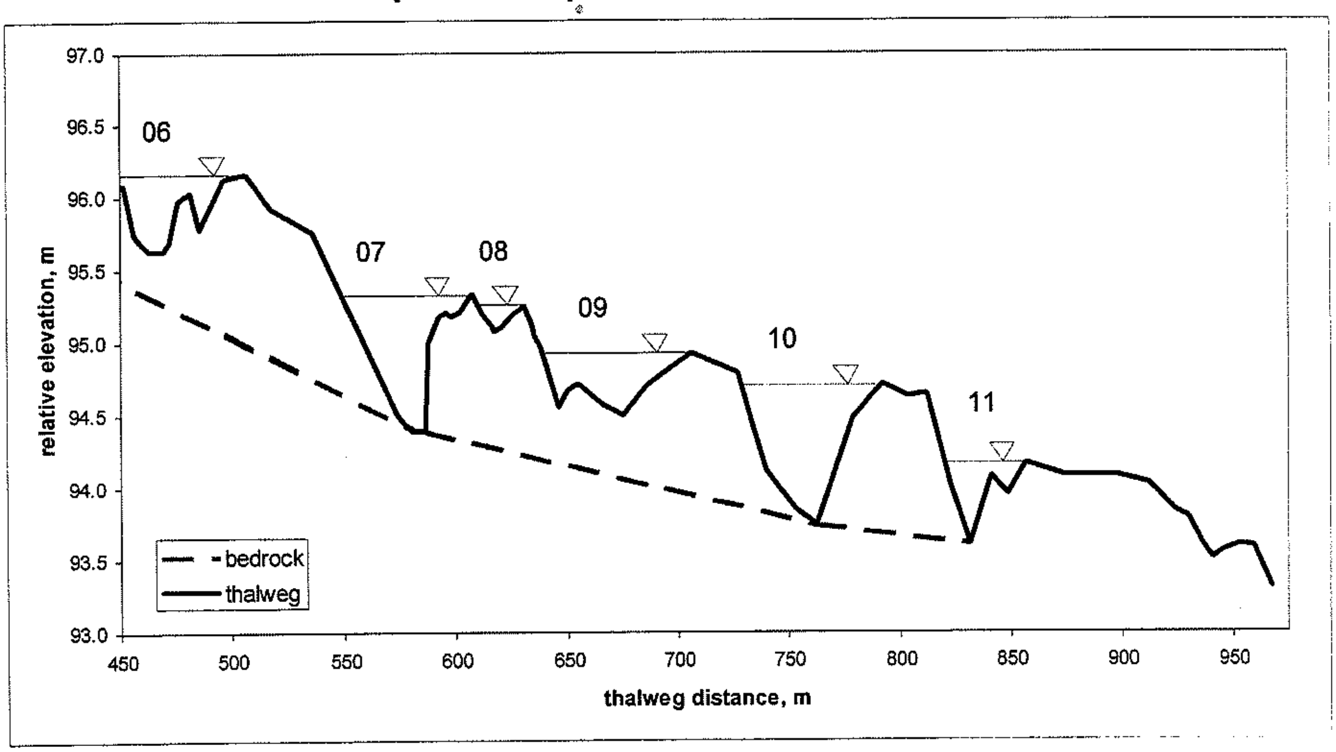

Figure 3.24. Lower Clifty Creek stream thalweg profile, bedrock surface profile and pools.

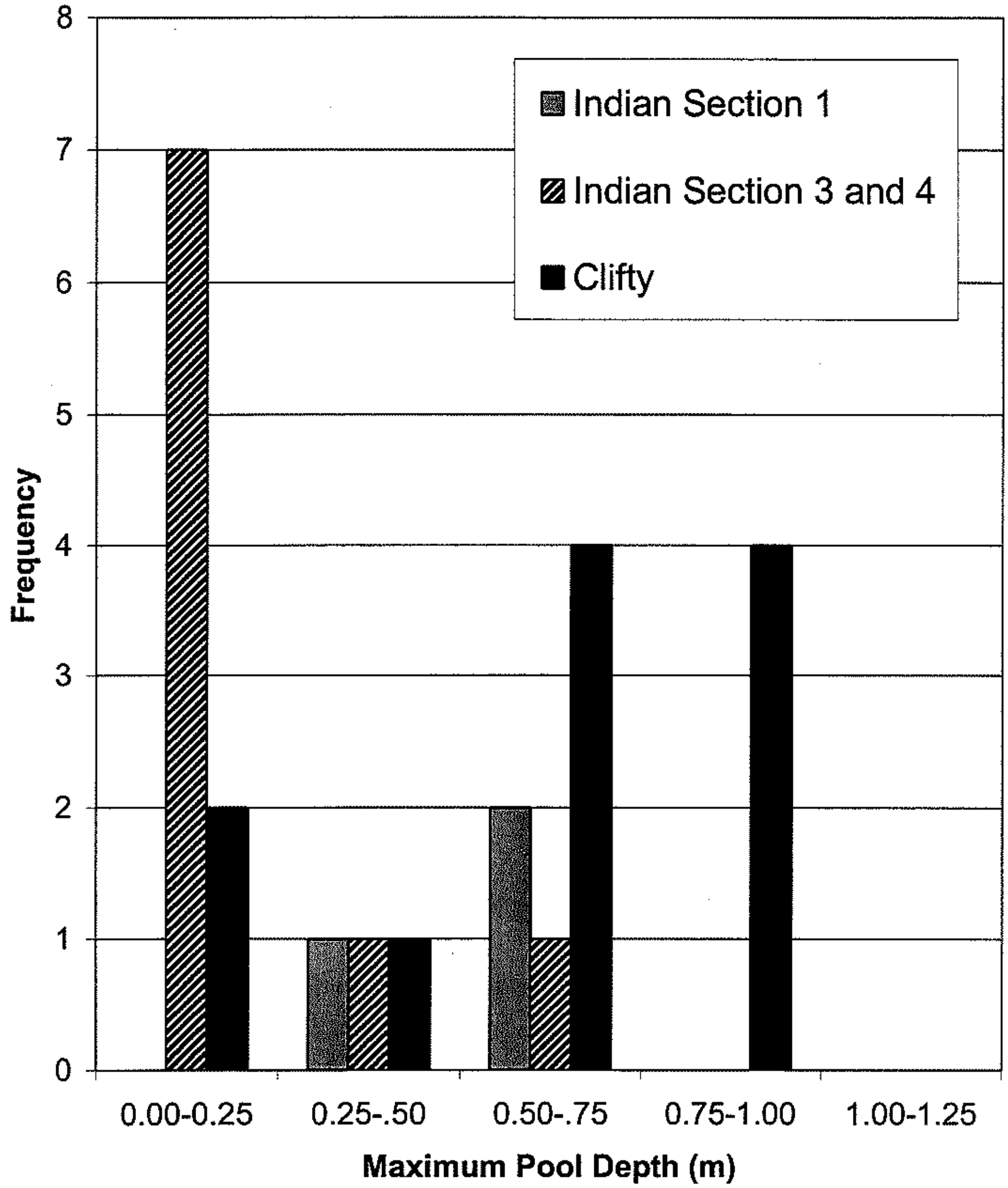

Figure 3.25. Histogram of pool depths for Clifty Creek, gravel mined reaches of Indian Creek (Section 3 and 4), and the morphologically stable section of Indian Creek (Section 1).

5+75 m as shown in Figure 3.26. Despite gravel mining, Briary Creek is the least incised stream of all the study streams as shown in Table 3.4 (depth of incision is less than 1 m).

A typical pool cross-section of Briary Creek immediately upstream of the mined area is shown in Figure 3.27 (Station 2+20 m). Figure 3.28 shows a region of exposed unvegetated gravel that extends approximately 30 m in the wide bend areas of the study reach. Although the apparent over-widened conditions in the channel bends may be attributed to excavations of the inside of bend bar materials, the rapid lateral migration and relatively low depth of incision are evidence of channel aggradation.

Bank erosion and at least one tributary channel avulsion (sudden change in the channel location, see Figure 2.6) are likely sources of the gravel causing aggradation in the gravel-mined reaches. Immediately upstream of the study reach a 1.3 km section of Briary Creek has shifted away from its channelized position. Bank erosion is prevalent along at least one side of the stream throughout this laterally active reach. Because the valley is sinuous through this section, the channelization created several bends and it appears that rapid channel migration was enhanced by bank erosion in the bends of these channelized reaches. Because channelization caused channel incision, the bank erosion of the high terrace is providing more sediment than is being used by the formation of point bars that are about 1 m lower than the top of the high bank.

Downstream of the gravel-mined reaches of Briary Creek, the channel is located against the valley wall and is straight. Banks on both sides of the channel are vegetated with mature trees. A quantitative assessment of the geomorphic characteristics was not conducted on this section of stream; however, based on the growth of mature woody vegetation on both streambanks and on the comparison of the aerial photographs from 1989 and stream locations on 1958 USGS quadrangle

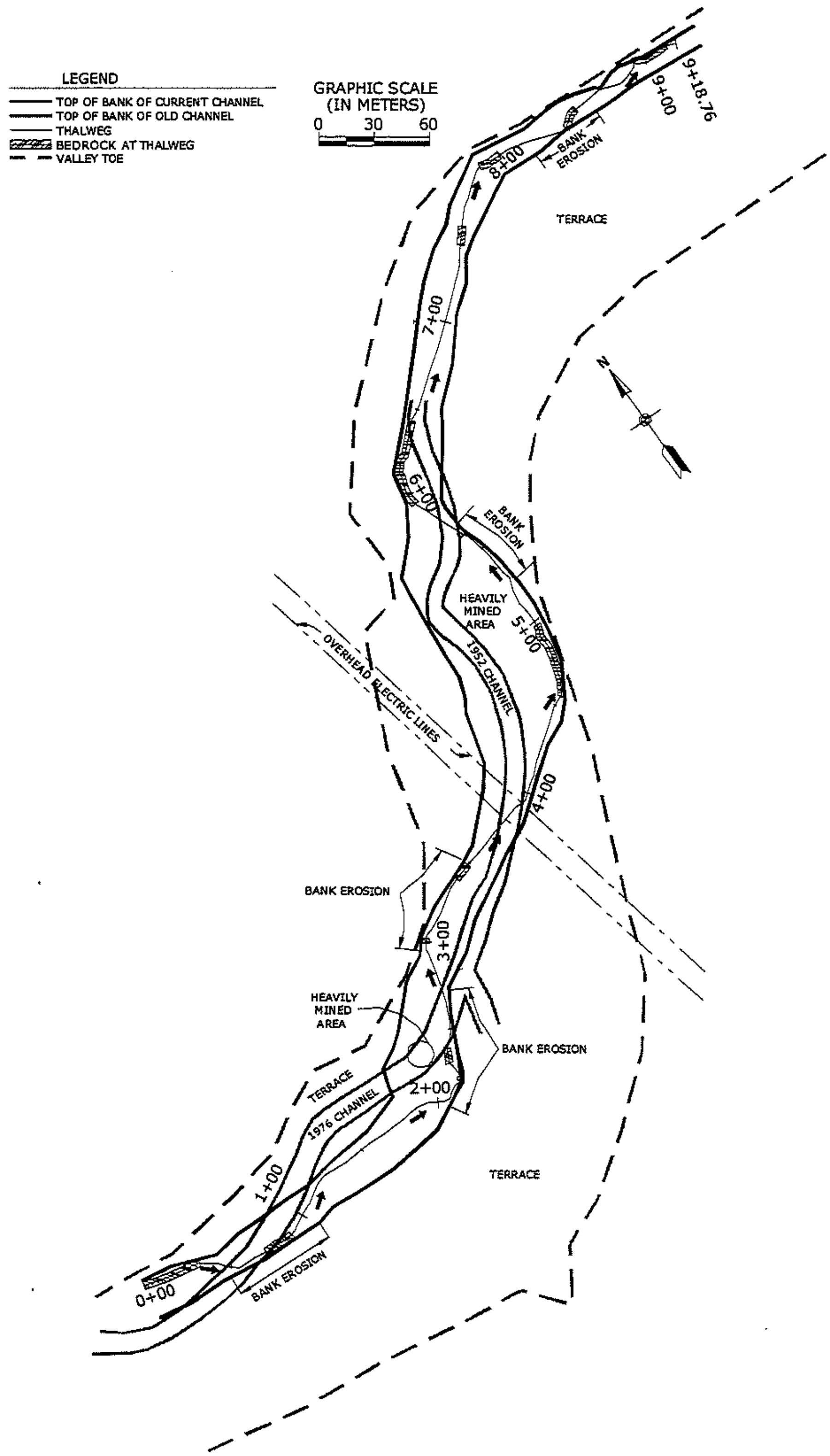

Figure 3.26. Briary Creek detailed study area.

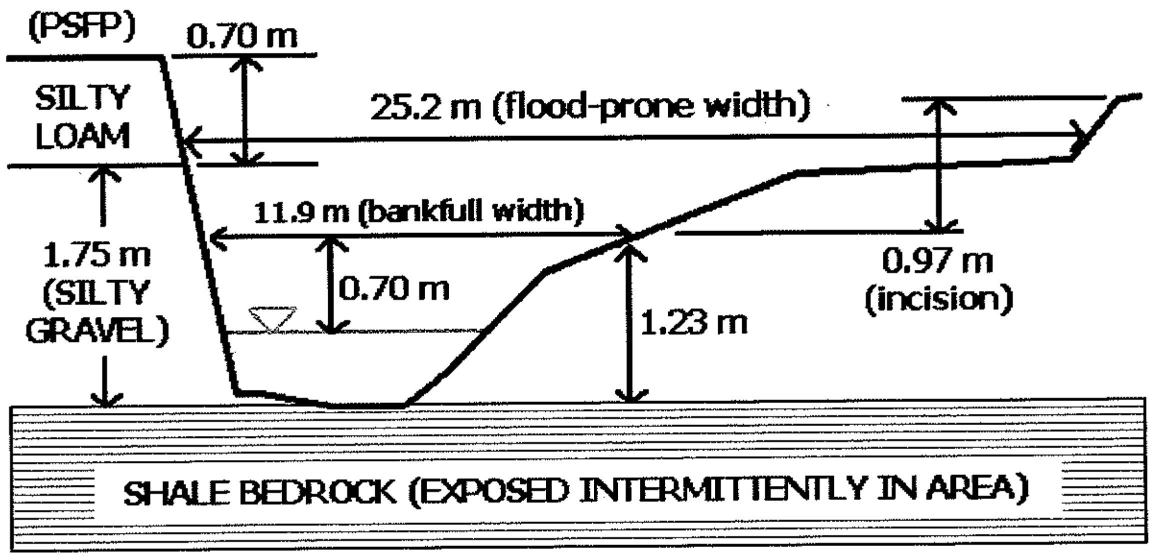

Figure 3.27. Briary Creek cross section (impacted).

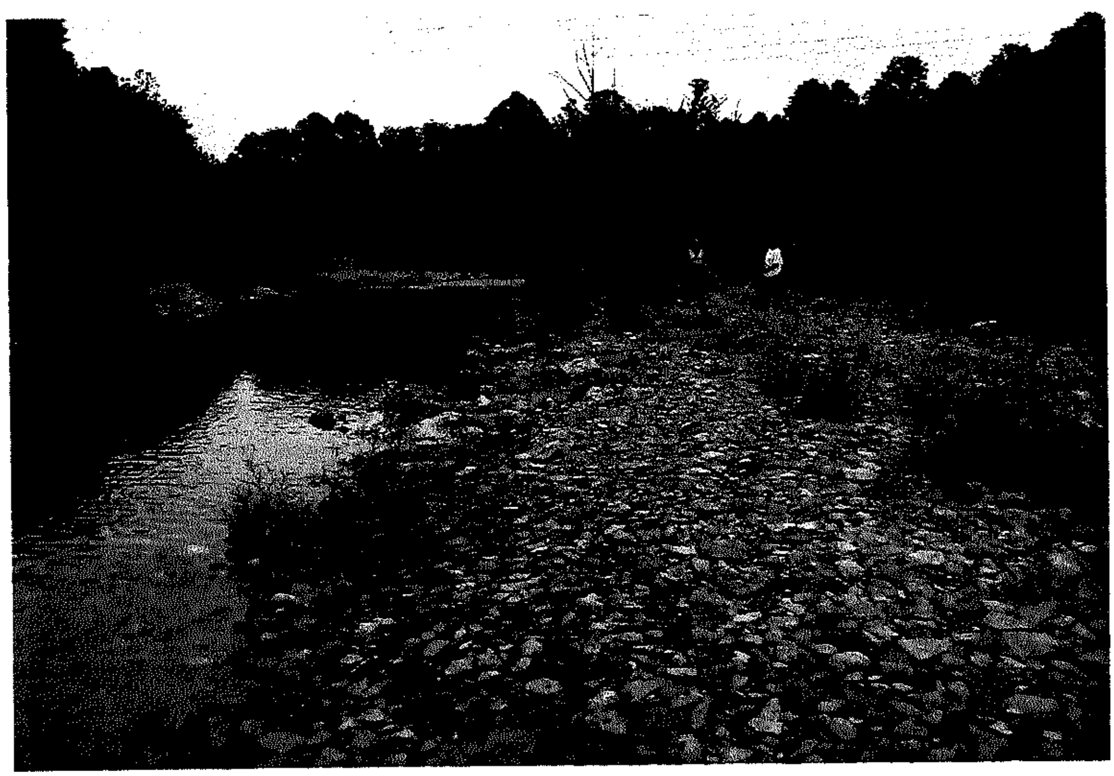

Figure 3.28. Area of gravel mining in Briary Creek. Cross-section shown in Figure 3.26 was obtained in the downstream region shown in photograph.

Figure 3.29. Tributary avulsion and incision upstream of Briary Creek study reach (pocket rod height 2.0 m).

maps, the stream section downstream of the mined reaches was determined to be not laterally active. A tributary avulsion contributed to past sediment loads to the study reach. Figure 3.29 shows the deeply incised tributary that confluences with the main channeled immediately upstream of the study reach. A 152 m-long reach of this tributary shifted from its original position in the tributary valley to a completely new position. A new channel was incised in the gravel floodplain of the tributary releasing a large volume of gravel to Briary Creek. The channel avulsion may have been caused by a debris blockage but the precise timing of the avulsion is unknown. Topographic maps dated 1958 show the tributary in a different location than the current location and the position of the pre-avulsion channel was field-verified. The supply of gravel from the vertical degradation of the avulsed tributary may been extreme in the past during the vertical degradation phase; however, the tributary has now incised through the gravel and is flowing over shale bedrock.

Briary appears to be aggrading within the study reach with channel lateral migration and rapid bank erosion as the main process of channel planform adjustment. The primary source of gravels from the tributaries is bank erosion of the steep, nearly vertical banks. Erosion and lateral migration of the main channel banks of Briary Creek are an important source of gravels in this system (see Figure 3.30). The banks also release fine sediment during bank erosion and mass failure that may contribute to turbidity downstream. Unlike most stream banks examined in this study, woody riparian vegetation was not present over large reaches of channel bank along the study reaches of Briary Creek. The absence of this vegetation may be a result of 1) land-owner removal of trees to maximize agricultural land, or 2) the undermining and falling of trees due to bank retreat.

Despite intensive gravel mining inside of bend bar areas, the stream profile of the Briary reach is similar to that of non-intensely mined streams such as Clifty Creek (Figures 3.31 and 3.32). Bedrock was exposed only in deep pools and long gravel riffles formed between the deep pools. Briary Creek has pool depths that are greater than its reference stream (Gilmore Creek; Figure 3.32). Briary Creek was classified as a C4 stream in the study reach based on bankfull flow conditions provided in Tables 3.3 and 3.4. The high supply of sediment to the region of gravel mining is sufficient to maintain a pool-riffle stream morphology over the bedrock. The disruption of channel geometry through the development of gravel pits and gravel berms that surround the upstream edge of the pits significantly modifies the transport characteristics of mined reaches. The berms used to protect the point bar mining pits appear to concentrate flow in the thalweg at near-bankfull conditions. The concentrated flow eroded banks on the outside of bends. At higher flows the berms are overtopped and/or breached, dramatically increasing the cross section flow area and decreasing the sediment transport capacity of the flow. These changes result in a highly unstable stream planform that enhances sediment storage and associated lateral point bar development at some flood stages and bank erosion at others. The current state of Briary Creek in the mined reaches is one of aggradation and active lateral migration. While the impact of gravel mining within the area of gravel excavation may be having a detrimental impact on channel stability, the removal of excess gravel produced from upstream bank erosion and gravel deposition in the very wide sections created by mining appears to be enhancing channel stability downstream.

3.2.4 Gilmore Creek

The Gilmore Creek watershed (37.48 km^2) is located in the northern part of the Buck Creek watershed and was considered a reference for the Briary Creek watershed. Several impacts to Gilmore Creek limit its usefulness as a reference stream, however. First, although intense recent mining was not observed, landowners located downstream of the study site remove gravel to maintain flood flow capacity. Second, a bridge is located immediately downstream of the study site. Third, the stream flows along a roadway embankment immediately upstream of the study site. Fourth, several terraces exist below the pre-settlement floodplain terrace indicating that the stream may have been relocated several times. Fifth, a reservoir interrupts flow and intercepts coarse sediment for approximately 37% of the watershed. Last, over 46% of the Gilmore Creek watershed is forested, whereas approximately 80% of the Briary Creek watershed is considered cropland or pasture (Table 2.1). Despite these problems, Gilmore Creek was the closest fit to the Briary Creek watershed in terms of size and geology, so we continued to use it as a reference stream realizing the limitations of any results drawn by comparing the characteristics of Gilmore Creek and those of other creeks. Figure 2.7 shows that 100% of the stream reaches examined in Gilmore Creek and its main tributary

Figure 3.30. Bank erosion on outside of bend in area of gravel mining in Briary Creek.

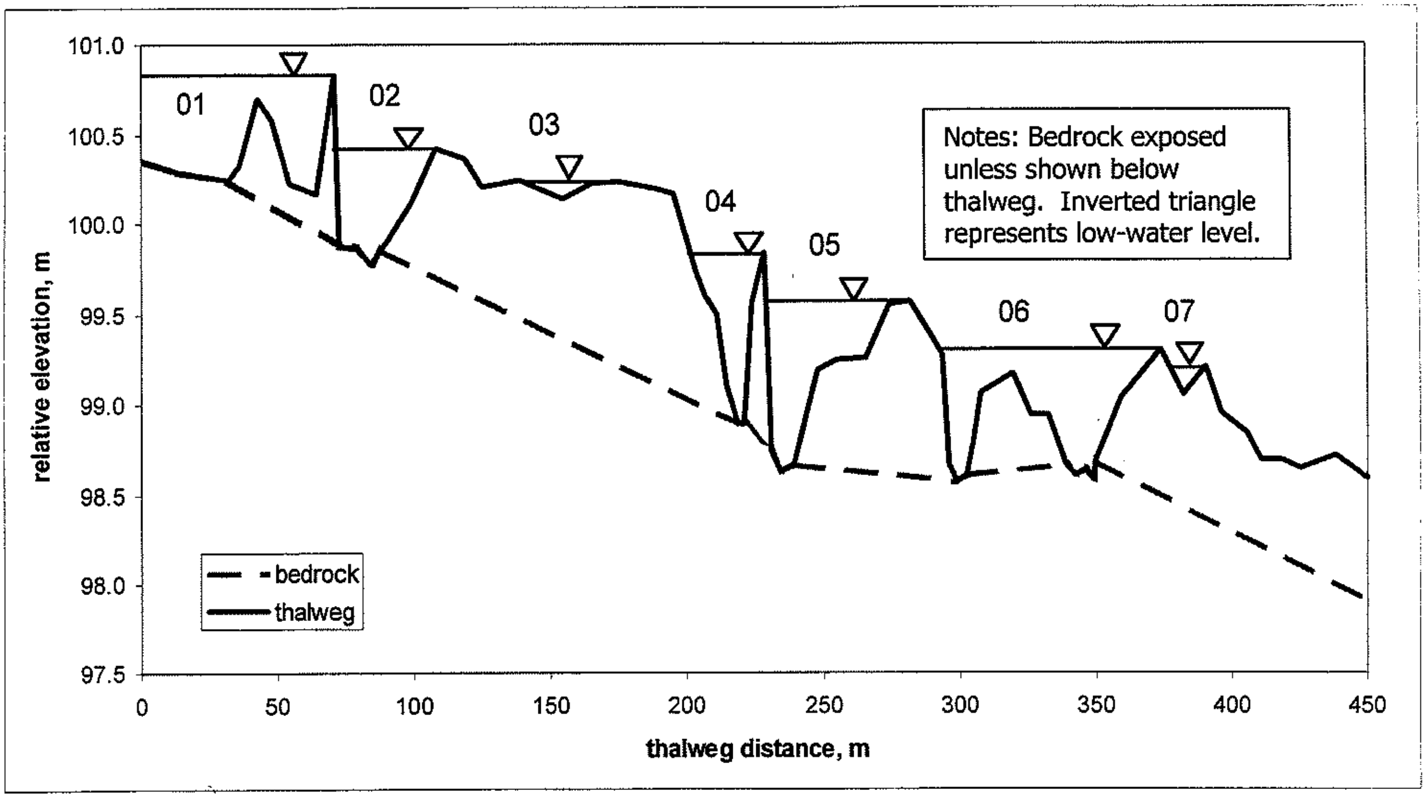

Figure 3.31. Upper Briary Creek stream thalweg profile, bedrock surface profile and pools.

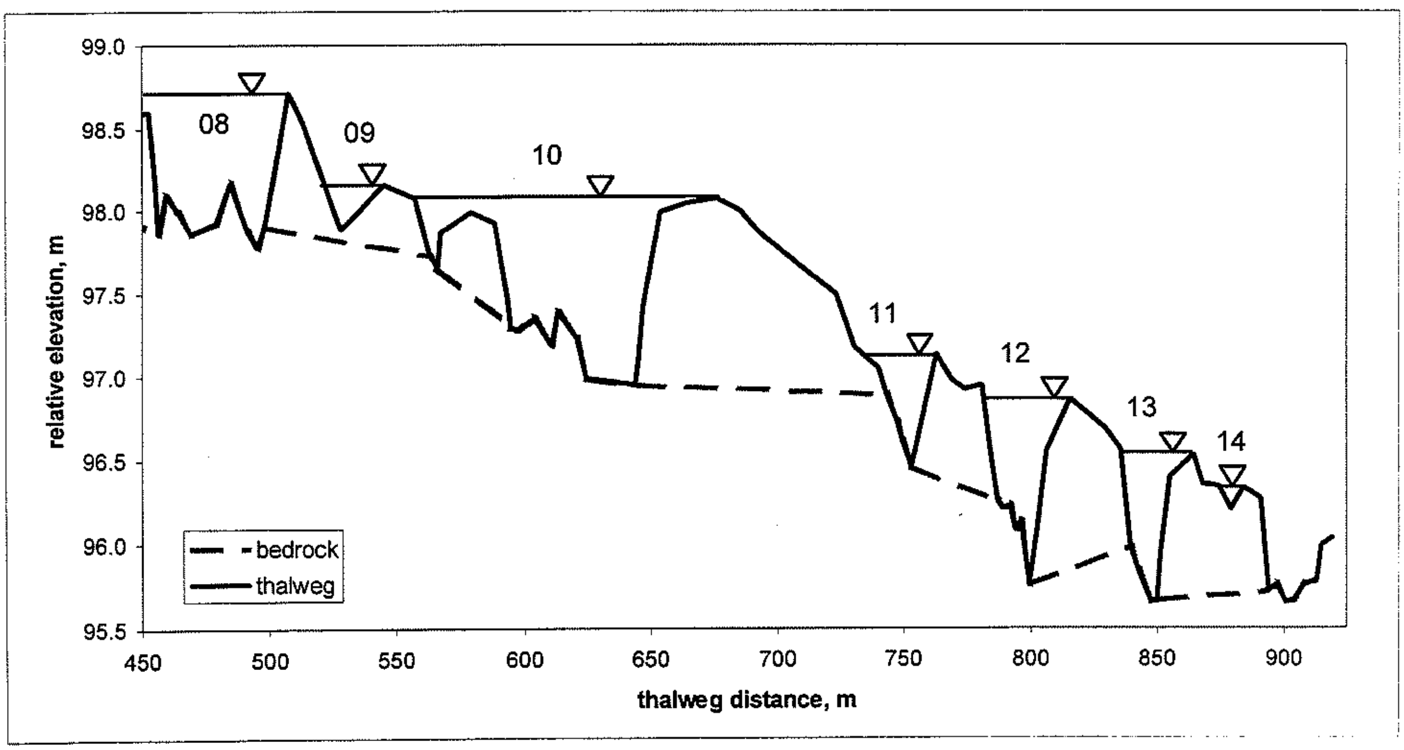

Figure 3.32. Lower Briary Creek stream thalweg profile, bedrock surface profile and pools.

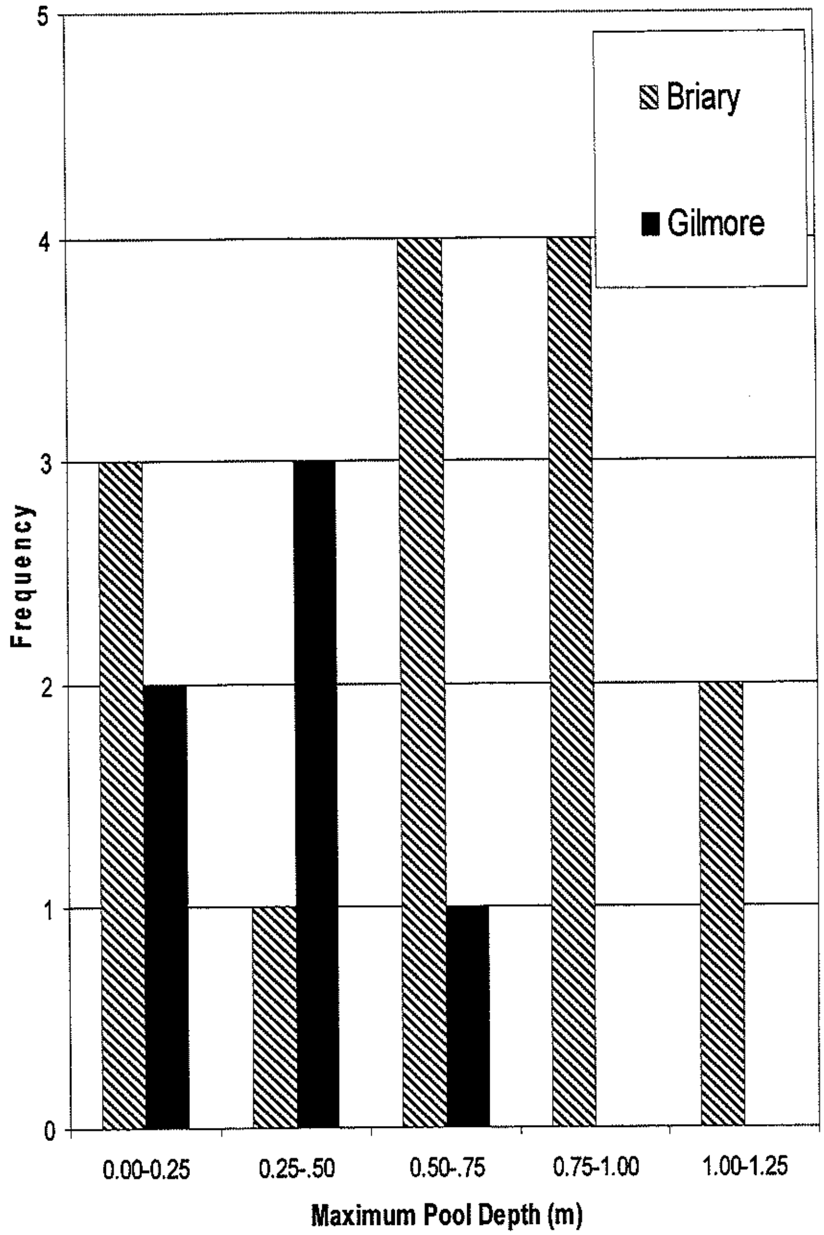

Figure 3.33. Histogram of pool depths for the morphologic sections of Briary Creek (intensely mined) and Gilmore Creek.

Crab Orchard Creek were relocated and/or channelized. Gilmore Creek upstream of its confluence with Buck Creek is positioned in a broad valley bottom with mild slope (0.29%; Table 3.2) as shown by the valley toe in Figure 2.7. Terraces and low level flats near current floodplain level indicate past channel migration. Consequently a wide low level floodplain exists to the east of the study reach shown in the left hand side of Figure 3.34. The contour map of Gilmore Creek provided in Appendix IV shows the low level floodplain north and east of the current channel position. Downstream of Station 1+00 m the study reach stream becomes confined by pre-settlement floodplain terraces and remains confined and entrenched to the end of the study reach at the KY 1781 bridge. Mature trees are present along the tops of both streambanks and on the floodplain along the entire study reach and provide a canopy over much of the stream channel in the study reach. Although the bank faces along eroding high terraces have little or no vegetation, the erosion rate appears to be gradual. The depth of gravel over bedrock (Figure 3.35) and the lack of rapid and extensive bar building indicate that the sediment supply may not be high in comparison to Briary Creek. The upstream reservoir may be a factor in the apparent low sediment supply. A second factor is the relatively high stability of the channelized reaches of Gilmore Creek. The very wide and straight valley in which Gilmore and its main tributary, Crab Orchid Creek, are situated allowed for the channelized streams to be relatively straight with few channel bends. Consequently, channel lateral stability initiated from bank erosion of high terraces in channelized reach bends is not as prevalent in Gilmore or Crab Orchard Creek.

The low sediment supply is a factor in the unusually large length of pools and short length of riffles found in Gilmore Creek. Less than 10% of the length of Gilmore Creek is composed of riffles although riffles are closely spaced (2.7 bankfull widths). The riffle lengths were extremely short (0.3 bankfull channel widths). Bedrock was prevalent over long reaches in pools. The combination of very short riffles and large areas of exposed bedrock in pools is an indication of the small amount of gravel storage over the shale bedrock. Although past incision is obvious from evidence provided by one high terrace, believed to be the pre-settlement floodplain, and at two lower terraces, there is no evidence of active incision. Based on the examination of aerial photographs and the abundance of mature woody vegetation in riparian zones and along both banks, the lateral erosion rates of high terraces are considered to be low. Based on this assessment, Gilmore Creek was considered to be in a state of gradual aggradation in the study reach.

Figure 3.36 shows the thalweg and pools of the study reach. Bedrock is present in all deep pools. The pool depths are relatively shallow when compared to those of Briary Creek as shown in the maximum pool depth histogram of Figure 3.33. The upstream section of the study reach was used for classification of Gilmore Creek and was classified as a C4 stream type because of the accessibility of the floodplain and the relatively wide width to depth ratio (Tables 3.3 and 3.4).

3.3. Stream comparisons

3.3.1 Upstream-Downstream Comparison - Indian Creek

We compared the four surveyed reaches in Indian Creek: the intensively mined reach (Section 4), an upstream reach impacted by the effects of mining (Section 3), a transition reach (Section 2) and a reach remote from the main impacts of gravel mining (Section 1). Section 1 was the least impacted by recent intense gravel mining because of the development of a natural bedrock and boulder grade control and downstream reaches that were intensively gravel mined during the study.

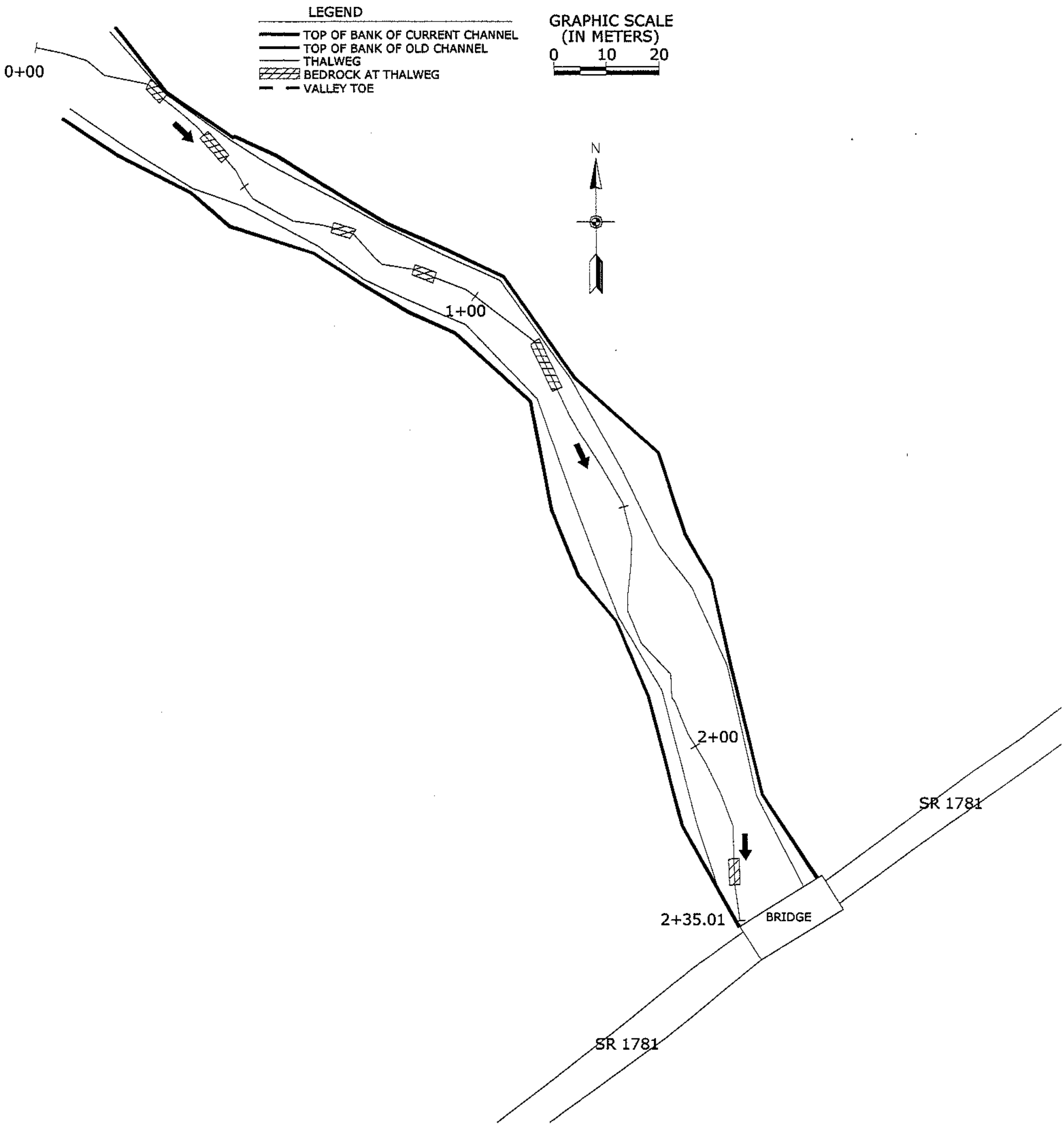

Figure 3.34. Gilmore Creek detailed study area.

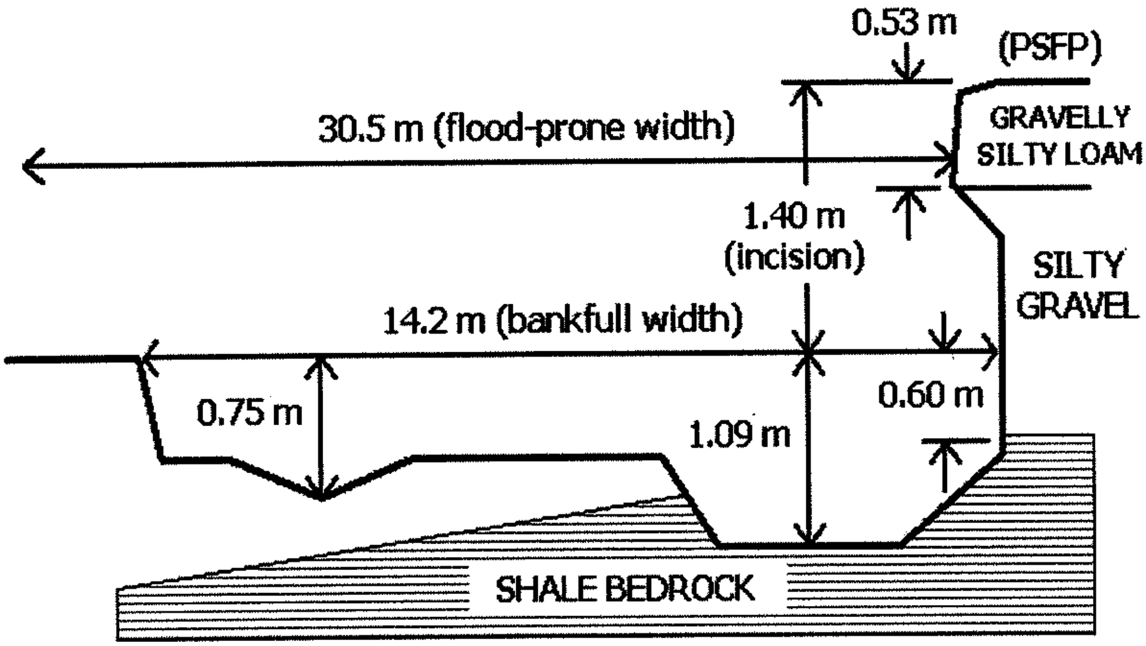

Figure 3.35. Gilmore Creek cross section.

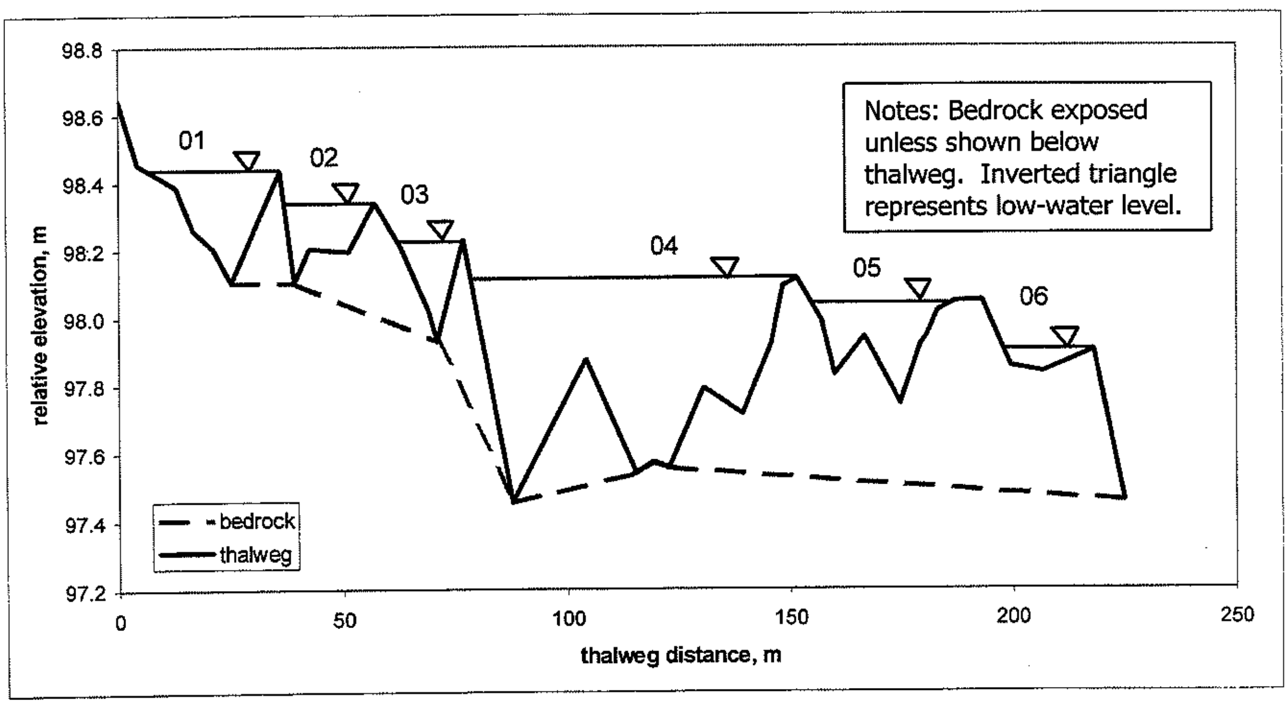

Figure 3.36. Gilmore Creek stream thalweg profile, bedrock surface profile and pools (reference).

Table 3.8 shows that two impacts in both the mined and upstream impacted reach are 1) the changes in pool morphology and 2) the change in channel substrate. The number of pools in the Section 1 is approximately 2 to 3 times more abundant (per channel length) and deeper than in the impacted reaches. The channel substrate in Section 3 is mainly bedrock while the substrate in the reference reach is coarse gravel. The substrate in Section 4 is medium gravel. The impact of channel straightening and other watershed and channel modifications has caused channel incision and entrenchment of all of the surveyed sections of Indian Creek such that all are classified as F type channels.

3.3.2 Indian Creek and Clifty Creek Comparison

Table 3.9 shows that the reference stream Clifty Creek is less incised, less entrenched (high entrenchment ratio is considered less entrenched) than the impacted reaches of Indian Creek. A notable difference is the width to depth ratio of the bankfull channel. Clifty Creek has a relatively narrow and deep active channel while Indian Creek in both affected sections is relatively wide and shallow. The bed materials in Clifty Creek are similar to those in Section 4 of Indian Creek. As shown in the stream profiles of Figures 3.11 through 3.16 for Indian Creek and 3.23 and 3.24 for Clifty Creek, bedrock dominates the substrate of Indian Creek while bedrock only appears as the substrate of deep pools in Clifty Creek. The average maximum depth of the pools in Clifty Creek is approximately 2 to 3 times that of Indian Creek. The absolute pool-to-pool spacing in Clifty Creek is between the spacing of Section 3 and Section 4 of Indian; however, the spacing in terms of the bankfull width is significantly larger in Clifty Creek than in both sections of Indian Creek. The impact of gravel mining on the stream substrate and on the formation of pools is supported by the comparison of reference streams in separate watersheds as well as upstream reference streams.

Table 3.8. Comparison of Intensely Gravel Mined and Affected Reaches with Upstream Reference Reach, Indian Creek			
Parameter	**Section 1 Reference Reach**	**Section 3 Upstream Affected**	**Section 4 Gravel Mined Reach**
Channel bankfull width to depth ratio	20.7	25.0	15.1
Degree of incision	4.0	5.8	3.6
Entrenchment	1.2	1.1	1.1
Bed material size (mm)	73	Bedrock/75	45
Channel type	F4	F1/F4	F4
Average maximum low flow pool depth (m)	0.43 (1.0 bankfull depth)	0.26 (0.5 bankfull depth)	0.20 (0.3 bankfull depth)
Pool spacing (m)	37.5 (4.2 bankfull width)	97.2 (7.8 bankfull width)	67.1 (6.1 bankfull width)

Table 3.9. Comparison of Intensely Gravel Mined and Affected Reaches of Indian Creek with Clifty Creek as Reference			
Parameter	**Clifty Reference Reach**	**Indian: Section 3 Upstream Affected**	**Indian: Section 4 Gravel Mined Reach**
Channel bankfull width to depth ratio	12.3	25.0	15.1
Degree of incision	3.2	5.8	3.6
Entrenchment	2.0	1.1	1.1
Bed material size (mm)	45-60	Bedrock/75	45
Channel type	C4	F1/F4	F4
Average maximum low flow pool depth (m)	0.57 (1.0 bankfull depth)	0.26 (0.5 bankfull depth)	0.20 (0.3 bankfull depth)
Pool spacing (m)	82.2 (11.1 bankfull width)	97.2 (7.8 bankfull width)	67.1 (6.1 bankfull width)

3.3.3 Briary Creek and Gilmore Creek Comparisons

Bankfull cross-section characteristics of the intensively mined Briary Creek are similar to the characteristics of Gilmore Creek (Table 3.10); however, the pool depth and pool spacing characteristics are very different. Pool depths in Briary are similar to less impacted reaches of the smaller streams: Section 1 of Indian Creek (Table 3.8) and Clifty Creek (Table 3.9). Two factors may be account for this similarity: 1) the sediment supply is significantly larger than the quantity of gravel mined, and 2) the elevation of the active streambed is sufficiently deep to allow deep pools to form. As stated previously, many potential watershed and channel impacts may be affecting the morphology of Gilmore Creek, confounding the gravel mining impacts with other activities in the watershed.

Table 3.10. Comparison of Intensely Gravel Mined Briary Creek with Gilmore Creek as Reference

Parameter	Gilmore Creek Reference Reach	Briary Creek Gravel Bar Mining
Channel bankfull width/depth ratio	20.3	22.0
Degree of incision	3.0	2.8
Entrenchment	2.2	2.1
Bed material size (mm)	26	54
Channel type	C4	C4
Average max. low flow pool depth (m)	0.31 (0.45 bankfull depth)	0.66 (1.2 bankfull depth)
Pool spacing (m)	39.2 (2.8 bankfull width)	65.6 (5.5 bankfull width)

3.3.4 Hydraulic Modeling and Sediment Mobility Assessment

Table 3.11 provides the characteristics of riffle surface sediment determined from analysis of the pebble count data on representative riffles. Table 3.12 shows the flow conditions modeled.

Table 3.11 Characteristics of Riffle Surface Particles from Pebble Count Analysis

Stream Reach	D_{16} (mm)	D_{50} (mm)	D_{84} (mm)	D_{84}/D_{16}	t_{cr}+ (N/m^2)
Indian 1	24	75	163	6.7	47
Indian 3	15	47	106	7.0	29
Indian 4	15	47	106	7.0	29
Clifty	14	45	134	9.6	29
Briary	16	57	117	7.4	35
Gilmore	12	28	56	4.6	17

+ Critical boundary stress for nominal rate of sediment transport based on a non-dimensional shear stress of 0.04.

Table 3.12. Modeled Flow Rates

Stream Section	Q_{2yr} (M^3/s)	$Q_{bank\ top}$ (M^3/s)	Q_{50yr} (M^3/s)	*10 X* Q_{2yr} (M^3/s)
Indian 1	6	14	20	60
Indian 3	8	>80	17	80
Indian 4	8	13	17	80
Clifty	9	30	20	90
Briary	16	120	34	160
Gilmore	21	44	44	210

The computed reach averaged boundary shear stress (**t**) over the riffle sections for each flow condition modeled is shown in Table 3.13, with the flow conditions are noted in the subscript of the column heading. The relative mobility of surface sediment was investigated for each flow condition and riffle reach by examining the ratio of reach average boundary stress to the critical estimated boundary stress required for sediment mobility (**t_{cr}**). Table 3.14 shows the ratio of modeled reach average boundary stresses (Table 3. 11) to critical boundary stress for the reaches modeled (Table 3.13).

Table 3.13. Modeled Average Boundary Shear Stress over Riffle Reach

Stream Section	t_{2yr} (N/m^2)	$t_{bank\ top}$ (N/m^2)	T_{50yr} (N/m^2)	$t_{10XQ2yr}$ (N/m^2)
Indian 1	60	83	96	130
Indian 3	35	n/a	45	85
Indian 4	20	23	26	59
Clifty	44	65	55	93
Briary	86	38	86	36
Gilmore	25	34	34	29

Table 3.14. Relative Mobility of Riffle Armor Layer

Stream Section	t_{2yr}/t_c	$t_{bank\ top}/t_c$	t_{50yr}/t_c	$t_{10XQ2yr}/t_c$
Indian 1	1.3	1.8	2.0	2.8
Indian 3	1.2	n/a	1.6	2.9
Indian 4	0.7	0.8	0.9	2.0
Clifty	1.2	1.7	1.5	2.5
Briary	2.4	1.1	2.4	1.0
Gilmore	1.5	2.0	2.0	1.7

Except for the backwater section of Indian Creek (Indian 4), Table 3.14 shows that the riffle sediments in all of the stream sections examined appear to be mobile (shear to critical shear ratio greater than 1.0) for flow conditions of an approximately 2-year event or greater. Another important factor is that the maximum boundary shear to critical shear ratio is less than 3.0 for all sites and for all flow conditions investigated. One weakness of one-dimensional models such as HEC-RAS is that they do not represent losses at bends well and they provide little information to incorporate these important factors into roughness factors. Consequently Indian 1, located upstream of a sharp valley bend, shows a relatively high boundary stress and mobility at the largest flow levels. In actuality, the backwater effects of the downstream bend would likely make these values significantly lower. Similarly, the riffle examined in Clifty Creek was upstream of a sharp bend that would decrease boundary stresses significantly over what is provided by the one-dimensional model during high flow events.

Despite the modeling inaccuracies, Upper Indian Creek (least impacted by gravel mining) and Clifty Creek show similar relative mobility characteristics throughout the range of flows. At the estimated 2-year return interval condition both show relatively mobile riffle sediments. The top of bank condition for both Indian and Clifty Creek have relative mobility ratios of 1.8 and 1.7 respectively. Both show very similar relative riffle sediment mobility at the very high flow rate conditions (flow onto the wide adjacent terraces).

The modeled results for Section 3 of Indian Creek, bedrock streambed, show boundary stresses (Table 3.13) that are much lower than those of Section 1. One reason for the low average stress is that almost the entire bed in this reach is composed of shale bedrock that has very low roughness except for small isolated falls and a few small riffles where the width to depth ratio of the channel expands locally. Sediments rolling on this bedrock are likely to be mobile at relatively low average boundary stress because of small pivoting angles and high relative protrusion of the particles into the flow. Consequently, the sediments are expected to be highly mobile through this bedrock reach despite the low shear stresses and the computed relative mobility shown for Indian Creek Section 3.

The backwater effect of Buck Creek can be seen in the low shear stresses of Indian Creek Section 4 (Table 3.13) and sediment mobility ratios less than 1.0 (Table 3.14). The low shear stresses are an indication of this reach's lack of capacity to transport the load delivered by Section 3. Consequently, bed material transported to Section 4 is deposited and Section 4 can be considered to be an aggrading reach from approximately Station 12+00 m to Indian Creek's mouth at Buck Creek. The aggradation condition has been created through channel deepening and widening associated with channel gravel mining. The reduced bed elevation and increased channel width have reduced the energy slope of the flow upstream of the confluence of Buck Creek. Although this condition causes deposition of gravels that are available for future mining, it starves the downstream section of Buck Creek of historic gravel load from Indian Creek. One consequence of the reduced load may be the rapid channel migration upstream of the confluence of Buck and Indian Creek. The rapid migration of this bend toward Indian Creek will cause major changes in both channel planforms as it erodes land between the two streams. The changes in channel planform pattern will have an impact on flow and bank erosion from the confluence to the Highway 39 bridge.

Stress levels at the 2-year flow interval levels of both Briary and Gilmore Creeks are relatively high for their riffle sediments (Table 3.13 and 3.14). The relative mobility of 2.4 in Briary Creek is the highest relative mobility of all stream reaches modeled at the 2-year flow conditions. This high relative stress level at a low flow level is in part a consequence of the floodplain and channel berms that were constructed to prevent flow from entering gravel-mining pits. At higher flow conditions, the flow overtops the berms and enters the pits. Boundary stresses at higher flow levels decrease because of the large increase in flow area associated with the gravel-mined pits. Although flow may have access to the pits, bedload sediments do not have access because of the configuration of berms. The reduced channel stress causes deposition on point bars and migration of the channel into stream banks. The development of large pits adjacent to the main thalweg in Briary Creek appears to be enhancing the lateral migration of the stream during flood events higher than the estimated 2-year flood level.

Although Gilmore Creek has relatively mobile riffle sediments at the 2-year level ($t_{2yr}/t_c = 1.5$), the boundary stress does not increase significantly for higher flow levels. This is a consequence of access to a wide, flat floodplain in the reach examined. Although the sediments are mobile at lower level flood flow (2-year event), the bank height and entrenchment are low, which causes only small increases in boundary stress for large flood conditions.

The examination of riffle mobility has shown that in regions of gravel mining in which the channel bed is excavated, as is the case for Section 4 in Indian Creek, a depositional environment is created which leads to increased sedimentation in the mined reach during small and large flood events. In cases where gravel pits are created in point bars and berms are constructed to prevent low level flood flows (2-year return interval and less) from entering the pits, high mobility conditions (possible erosive) can result; however, highly depositional conditions may result from flood levels that overtop the berms. This highly depositional environment can cause bar building, bank erosion and lateral channel migration.

3.3.5. Groundwater and Hyporheic Zone Impacts

The shale bedrock, with thickness in excess of 5 m below the valley alluvium, provides a highly non-porous aquitard to prevent vertical flow of groundwater. The incision of the streams into the alluvium has lowered the inflow and outflow boundary conditions along the interface between the stream and the aquifer that exists in the alluvial gravels over the shale bedrock. In addition, the portion of the aquifer that is directly under the streambed has been reduced in thickness by the depth of incision in each of the channels. In some cases, such as the bedrock reach of Indian Creek (Section 3), the aquifer has been eliminated below the streambed. The hyporheic zone (aquifer surrounding the stream channel) has been impacted by channel straightening and to the extent that gravel mining depletes the storage of gravel over the bedrock, gravel mining also impacts this zone.

3.4 Biological Results from Study Reaches

3.4.1. Fish Data

The numerically dominant taxa (pooled over all samples) in the streams are listed in Table 3.15. Reference creeks had higher mean taxa richness and total numbers (17.45 and 424.1 respectively versus 15.12 and 334.7 for mined creeks) but the differences were non-significant (P> 0.05; Figure 3.37). The pooled IBIs of the reference streams were significantly higher than those of the mined streams (53 vs. 46.4; Mann-Whitney U statistic = 359.5, p = 0.0026). When the streams are examined as reference and mined pairs, similar trends were evident. Both species richness and IBI scores were generally

Table 3.15. Five dominant fish species (numerical) in the study streams

	Indian Creek	**Clifty Creek**	**Briary Creek**	**Gilmore Creek**
1	*Campostoma oligolepis*	*Campostoma oligolepis*	*Campostoma oligolepis*	*Campostoma oligolepis*
2	*Etheostoma caeruleum*	*Lythrurus fasciolaris*	*Fundulus catenatus*	*Etheostoma caeruleum*
3	*Luxilus chrysocephalus*	*Etheostoma caeruleum*	*Lythrurus fasciolaris*	*Etheostoma spectabile*
4	*Cyprinella galactura*	*Luxilus chrysocephalus*	*Etheostoma caeruleum*	*Semotilus atromaculatus*
5	*Lythrurus fasciolaris*	*Notropis telescopus*	*Luxilus chrysocephalus*	*Cyprinella galactura*

higher in the reference than in the mined streams although there were some exceptions to this trend (Figures 3.37-3.40). There were also differences in the species composition of the stream fish communities that may reflect the impacts of gravel mining on the streams. For instance, many fish species associated with pool habitats, such as the *Lepomis* species, were absent or not as common in mined streams as they were in their unmined references. Fish species considered to be omnivores or tolerant of degraded environmental conditions in the Kentucky Master List (KDW 2002), such as *Pimephales notatus,* were more common in Indian Creek than in Clifty, while Clifty had intolerant species such as *Notoris telescopis* which were likewise absent from Indian Creek. In addition, piscivorous fish such as *Micropterus dolemeiu* and *Micropterus punctalatus* were some times collected in Clifty Creek but were not found in Indian Creek. The absence of these "top predators" is reflected in the lower over-all IBI scores for the mined streams and may reflect poorer ecological conditions for fish community.

There were *Lepomis* sp. and predator fish species present in both Gilmore and Briary but densities of these taxa were usually higher in Gilmore. For instance, in the June 2000 collection, up to 94 *Lepomis* were collected from Gilmore stations compared to a maximum of 35 individuals collected at Briary stations. Similar trends were noted for the *Micropterus* species; for instance, the Gilmore community was dominated by *Micropterus salmoides*, while the Briary community was dominated by the smaller *Micropterus punctulatus.*

The suckers were another group showing differences in distributions among streams. These species are good examples of simple lithophils, fish requiring clean gravels for spawning. For example, hog suckers (*Hypentelium nigricans*) were found in Gilmore, but were not found in Briary. Another group of simple lithophils, the darters (genus *Etheostoma*) are insectivores commonly found in the riffles of good quality streams. These taxa were found in all streams although darter densities tended to be at least 20% higher in Clifty Creek than in Indian Creek.

3.4.2 Macroinvertebrates

Across all sampling dates and sites, the pooled mean density of insects in the reference streams was significantly higher than densities in the mined streams (676.5 inds./m^2 vs. 332.4 ind/m^2; $t = 2.977$, $df = 54$, $p = 0.004$; Fig. 3.41) and Kentucky Index of Biotic Integrity scores (KIBI) were higher for most dates in the mined streams (Fig. 3.42). Wet weight biomass over all dates was higher in reference than in mined streams (521 mg/m^2 vs. 401 mg/m^2; Mann-Whitney U = 916.5, p= 0.009). Mined creeks always had lower wet weights per area than their reference creeks for individual dates with the exception of April 2000 when Indian Creek had 10.90 g/m^2 and Clifty Creek had 7.48 g/m^2 (Fig. 3.43). During this sampling date, Indian Creek had comparatively large numbers of *Tipula* sp. (Appendix V), which made up 64.1% of the total wet biomass. Removing *Tipula* sp. from all datasets resulted in significant higher wet biomass in the reference streams compared to the mined streams for all dates (488 and 254 mg/m^2 respectively; Mann-Whitney U test statistic =769.5, P=0.000; Fig 3.44). This would suggest that there are fewer good refuges from high flow impacts in Indian than in Clifty but the rapid recovery of the densities in Indian by June 1999 indicate there must be effective source population to recolonize this reach after such events.

While the pooled data supports the hypothesis that the macroinvertebrate communities are different between mined and reference streams, examination of the IBI trends over the study period seems to suggest that the "quality" of the streams, as expressed by their macroinvertebrate

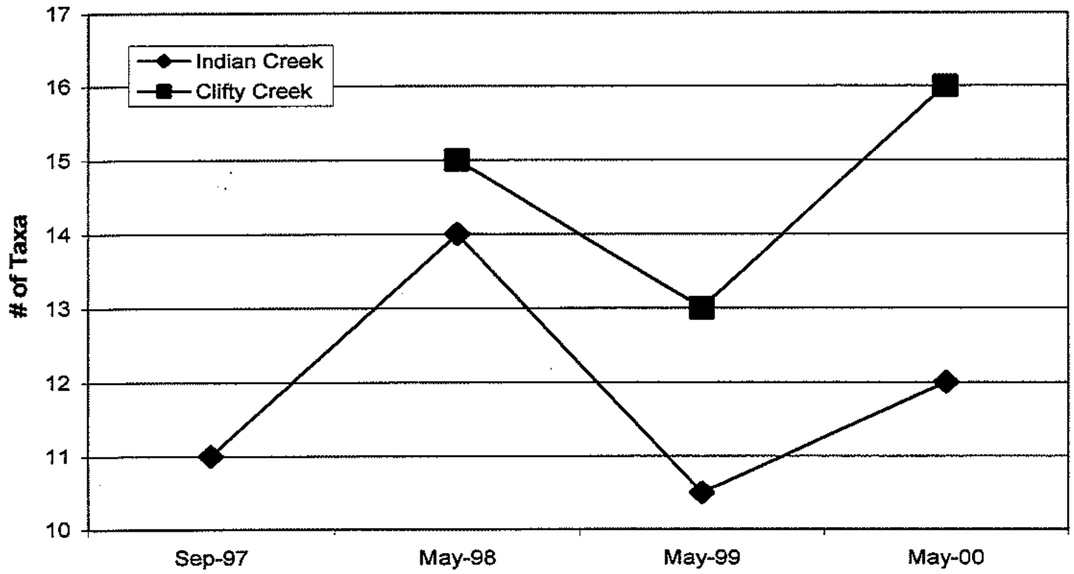

Figure 3.37. Taxa richness, Indian and Clifty Creeks

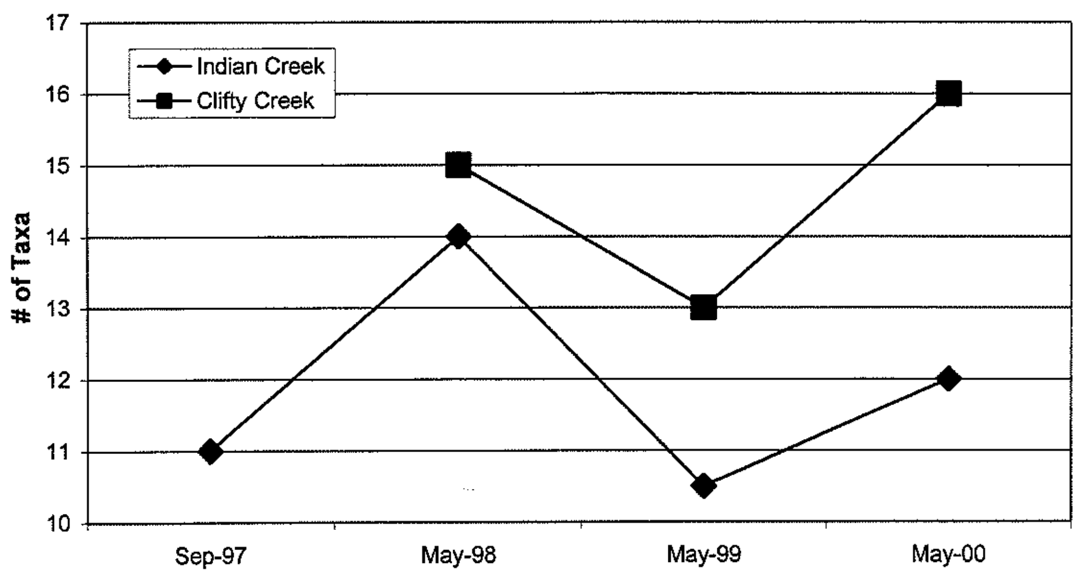

Figure 3.38. Taxa richness, Briary and Gilmore Creeks

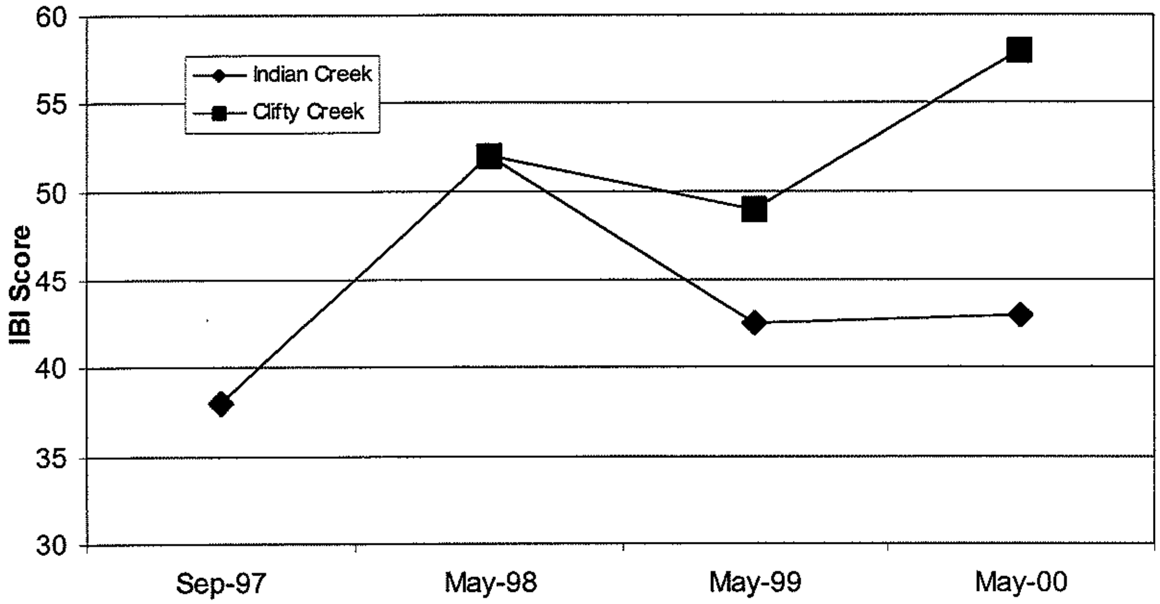

Figure 3.39. Fish IBI for Indian and Clifty

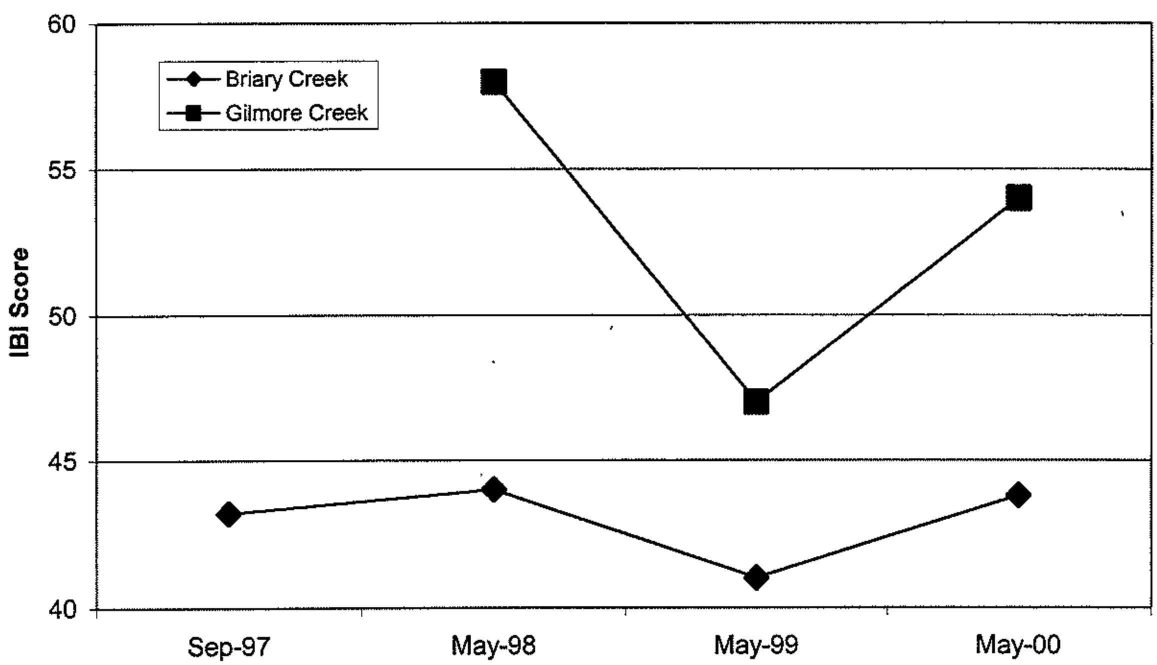

Figure 3.40. Fish IBI for Briary and Gilmore

communities, was initially very different but became less so over time. This may reflect changing physical conditions in the streams; there was very little rainfall in the study area during 1998-1999 period and the streams were dewatered early, while local precipitation was closer to normal in the following two years (Skaggs, personal communication). A similar trend was seen for the fish, although fish sampling did not continue past April 2000 (see above).

3.4.3 Functional Feeding Groups

Analysis of the percent composition of the functional feeding groups (FFG) over all sampling dates showed there was a higher percentage of collector gatherers in the mined streams (25% vs. 11%; Mann-Whitney U test statistic = 84.0; p=0.010) but a lower percentage of collector filterers (16% vs. 28%; Mann-Whitney U test statistic = 23; p=0.041) compared to reference streams (Figs. 3.45-3.46.) The proportion of predators was higher in non-mined creeks on the first three sampling dates, but lower on the last three sampling dates.

3.4.4 Community Similarity Indices

The Jaccard coefficients of similarity using data from Composite and traveling kicknet samples comparing reference streams to mined streams for Indian/Clifty changed very little even though other factors such as density changed dramatically. Indian Creek always had the lowest evenness score for each of the synoptic samples. Values ranged from a minimum of 31 to a maximum of 63; most scores were between 40 and 60 (Tables 3.16 and 3.17). The percent composition of insects that are classified as clingers (Merritt and Cummins, 1996; Maxted et al. 2000) was significantly higher in the reference streams than in the mined streams (66% vs. 45% respectively; Mann-Whitney U test statistic = 593.5, P=0.001, Figure 3.47.)

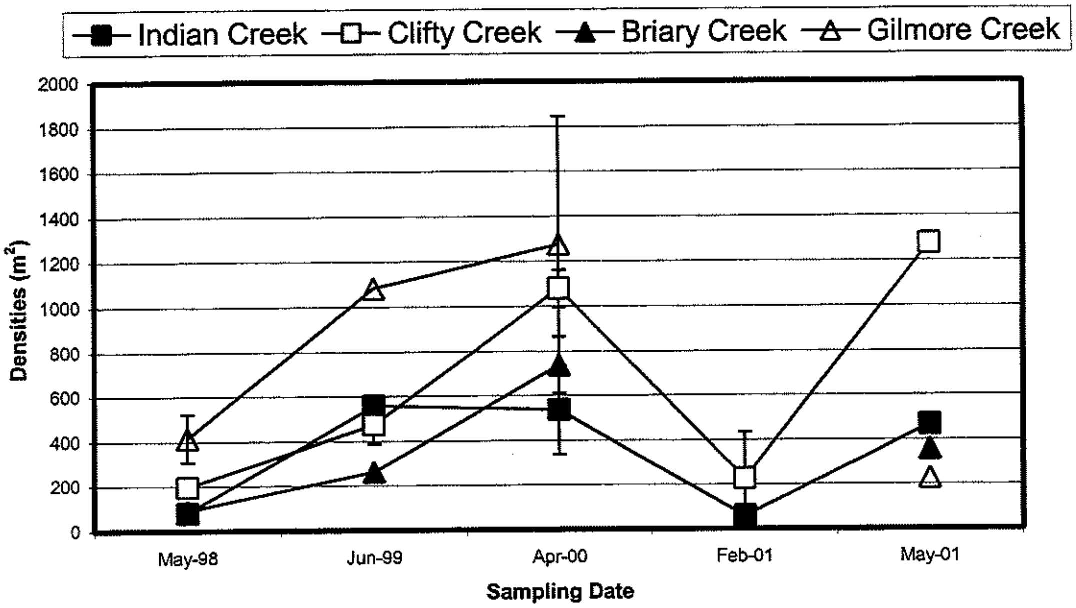

Figure 3.41. Insect densities (means ± standard errors) in synoptic samples over all sampling dates. Open symbols are reference streams, closed are mined streams. Bars show standard errors.

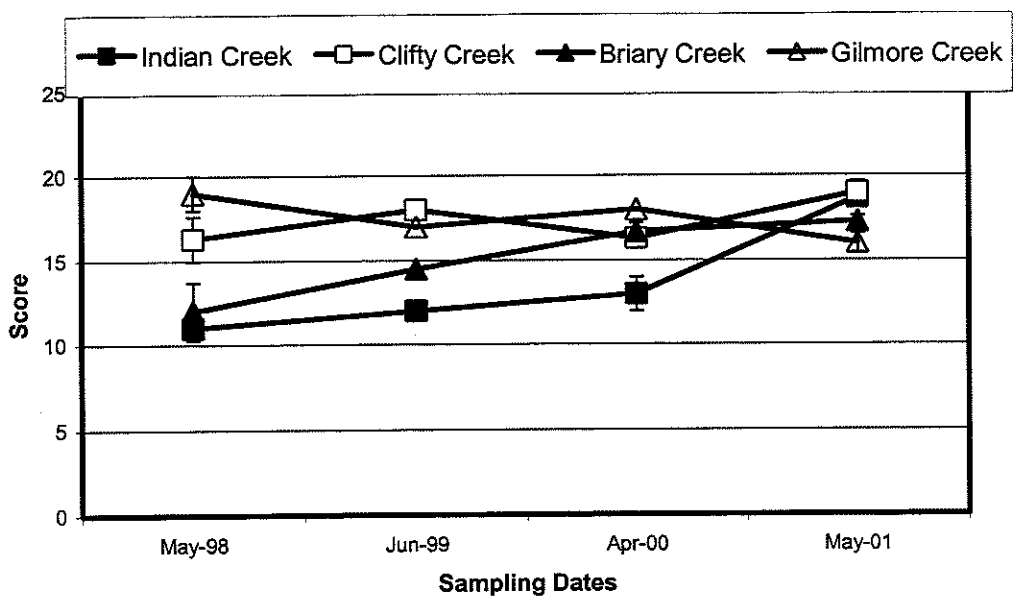

Figure 3.42. Kentucky Index of Biotic Integrity Scores. Mined streams are indicated by solid symbols, reference streams by open symbols. Bars show standard errors.

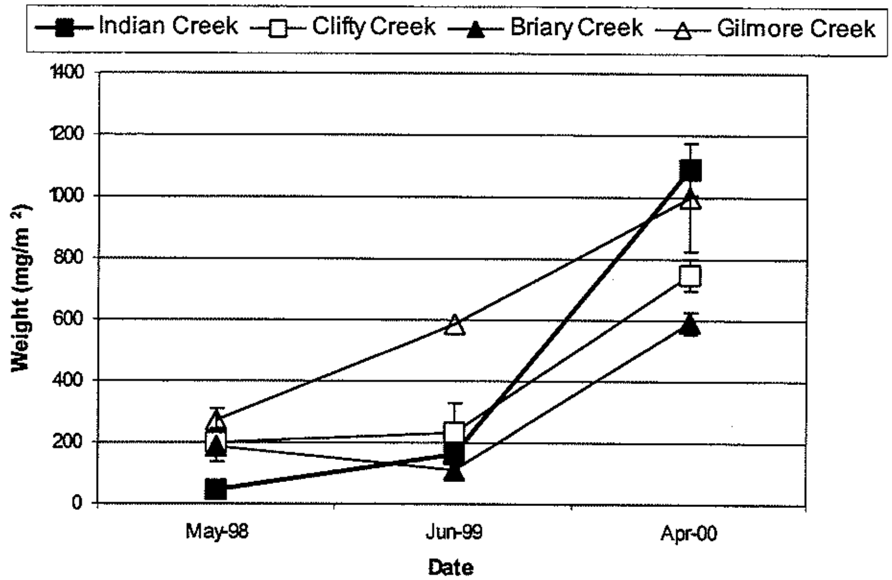

Figure 3.43. Wet biomass (means ± standard errors) across three sample dates. Mined streams are indicated by solid symbols, reference streams by open symbols. Bars show standard errors.

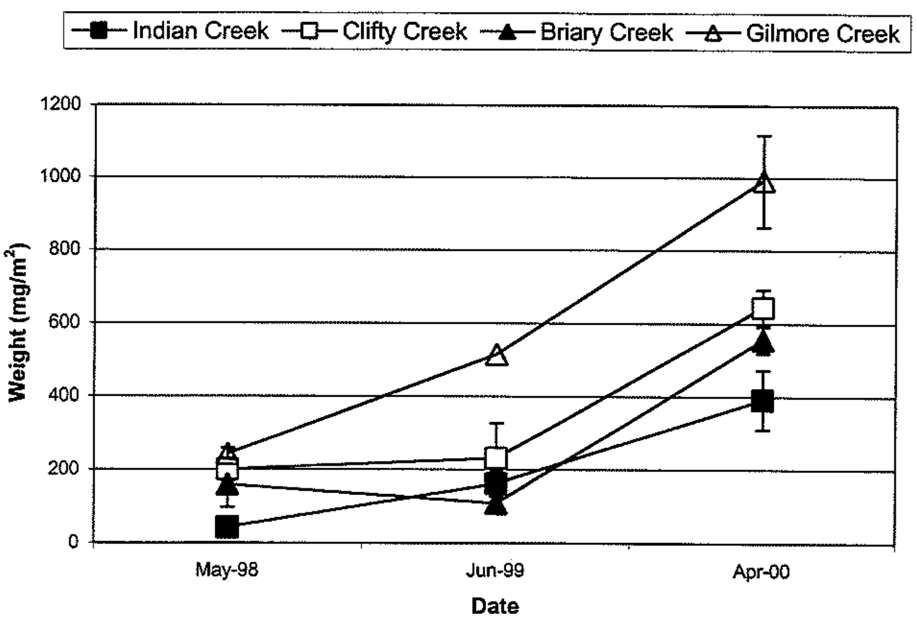

Figure 3.44. Wet biomass (means ± standard errors) minus *Tipula* sp. Mined streams are indicated by solid symbols, reference streams by open symbols.

The percent composition of insects classified as sprawlers (Merritt and Cummins, 1996) was significantly higher in the mined creeks (26.4% vs. 14.4% respectively, Mann-Whitney U test statistic = 297. P=0.001, Figure 3.48). Reference creeks from this study had a clinger/sprawler ratio of 4.58 while mined creeks had a ratio of 1.69.

3.4.5 Periphyton

Analysis of periphyton showed that there were no significant differences in periphyton chlorophyll levels (pooled) between mined and reference creeks. However reference creeks had a significantly lower periphyton AFDM than mined creeks (0.357 mg/cm^2 vs. 0.631 mg/cm^2; Kruskal-Wallis One-Way Anova, $p = 0.000$) between mined and reference creeks.

3.4.6 Sediment Transport

During high flows in October 1999, sediment traps below the Indian/Buck Creeks confluence contained a larger mean amount of sediment (3403.4 mg/cm^2) than the traps above the confluence (303.0 mg/cm^2; Fig. 3.49). During low flows, similar patterns were noted with the downstream traps (Fig. 3.50; Mann-Whitney U statistic = 35.0, p =0.000; Mann-Whitney U statistic = 38.0, p = 0.000, respectively). Traps in the downstream (Section 4) area of Indian typically contained the most sediment and the traps in Buck Creek downstream of the confluence contained more sediment than the upstream traps. Traps in the downstream of Briary Creek captured up to three times more sediment downstream of the mining site than at the downstream site in Gilmore during low flow (April 2000 0.75 vs. 2.0 g cm^2; June 2000 1.1 vs. 3.2 g cm^{-2}), even when deposition in Gilmore in the upstream sites was higher than in Briary's upstream sites (April 2000).

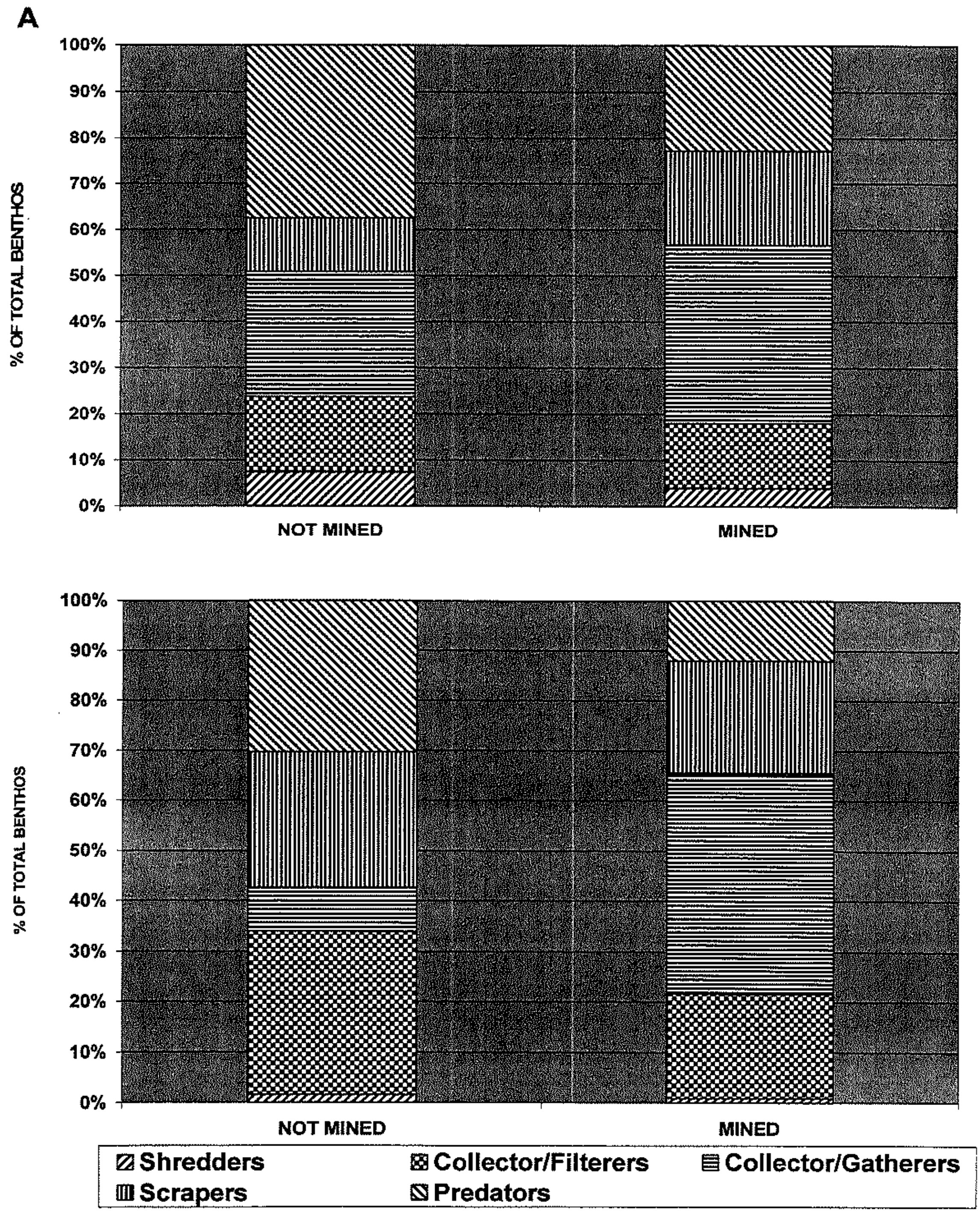

Figure 3.45. Macroinvertebrate functional feeding group representation for mined and unmined streams (pooled data). A= May 1998, B=June 1999.

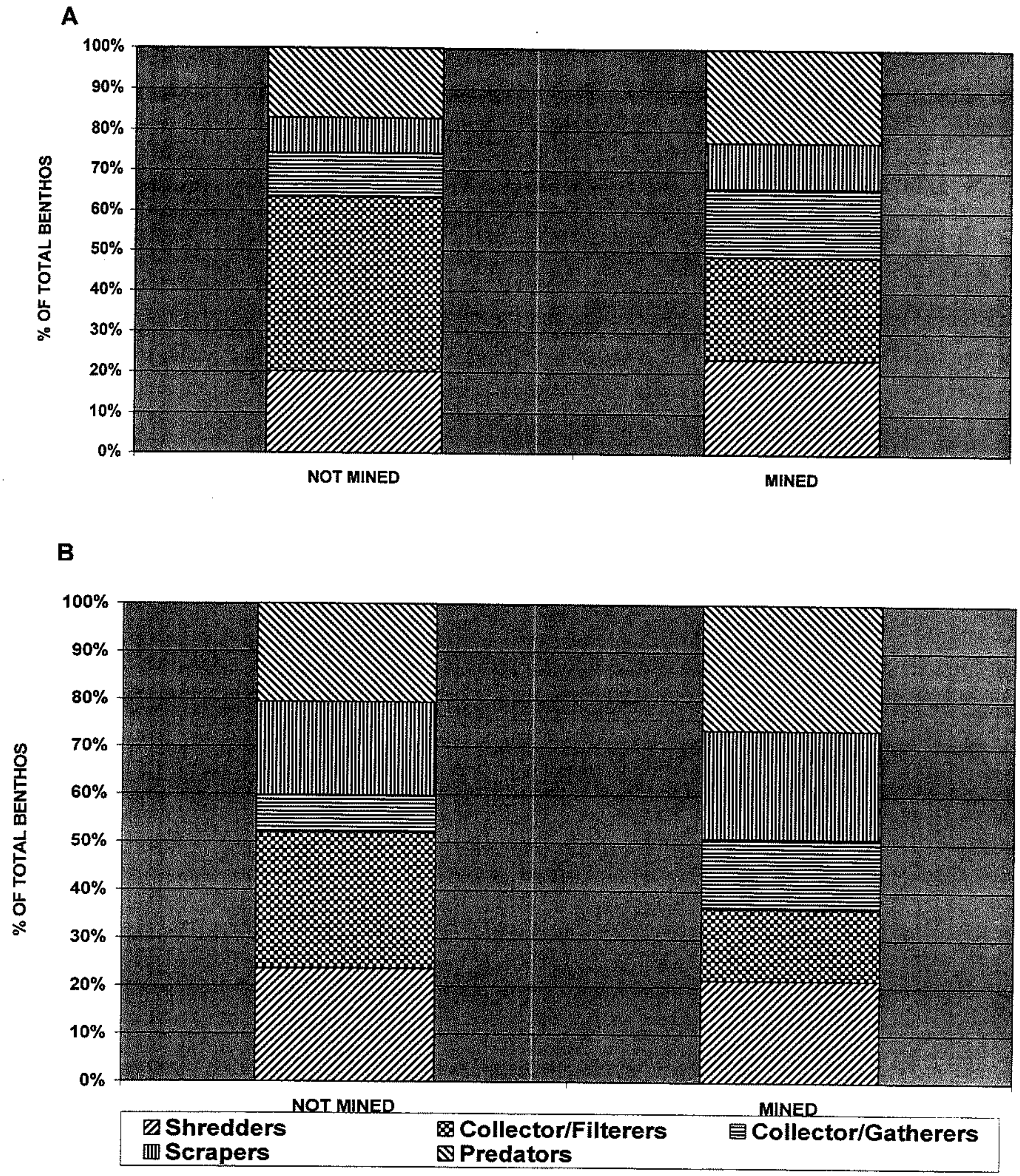

Figure 3.46. Macroinvertebrate functional feeding group representation for mined and unmined streams (pooled data). A= April 2000, B=May 2001.

Table 3.16. Evenness for study creeks at each date.

	Indian	Clifty	Briary	Gilmor e
May 1998	.595	.738	.663	.731
June 1999	.499	.705	.614	.572
April 2000	.568	.586	.627	.516

Table 3.17. Jaccard Coefficients comparing mined creeks to their reference creeks using data from composite and traveling kick net samples.

	Briary/Gilmore	Indian/Clifty
May 1998	.43	.55
June 1999	.43	.53
April 2000	.57	.54

3.4.7 Hyporheos

Mean pooled NO_x (1042.313 μg/l versus 822.2 μg/l; Mann-Whitney U statistic = 427.5, p = 0.000) and alkalinity (61.77 mg/l versus 43.54 mg/l; Mann-Whitney U statistic = 530.5, p= 0.000) values were significantly higher in the mined creeks than in the reference streams (Fig. 3.51). Briary Creek showed no significant differences of any water chemistry parameter tested when analyzed for up/down variation and up-down/depth interaction. However, there was a significant difference in Total Nitrogen (Bonferroni pooled p = 0.035) when analyzed for variation between depths. Gilmore Creek showed no significant differences for any parameter under any analysis. Indian Creek showed no significant up/down differences for any parameter. However, Clifty Creek showed significant up/down differences for NH_3 (Bonferroni pooled p = 0.049), POC (Bonferroni pooled p = 0.031), DOC (Bonferroni pooled p = 0.007).

Indian Creek had slightly higher total numbers of invertebrates in the hyporheic zone than Clifty, and Gilmore had higher total numbers than Briary Creek (which had the lowest numbers of the steams sampled). Copepods were the most numerous organisms found (309 total) and the only group found at all sites, Diptera was next (83), followed by Oligochaetes (79), Ostracods (51), and Plecoptera (50). Members of the order Trichoptera (Mann-Whitney U Statistic = 38.5, p = . 0.025) and Ephemeroptera (Mann-Whitney U statistic = 42.00, p = 0.009) were found in significantly higher abundances in reference streams.

3.4.8 Physiochemical Data and Surface Water Chemistry

Physiochemical parameters measured during the field sampling showed that all creeks had similar characteristics for most parameters measured. The most notable difference was in the turbidity measurements taken in May 1999 during the spate event. The turbidity of Indian Creek was measured at 50.35 NTU's while Clifty Creek's turbidity was 7.00 NTU's. The only other parameter that was significantly different between mined and reference creeks were chlorides (Mann-Whitney U statistic = 250.0, p = 0.000). The surface water chemistry data for each creek over all dates is presented in Table 3.18.

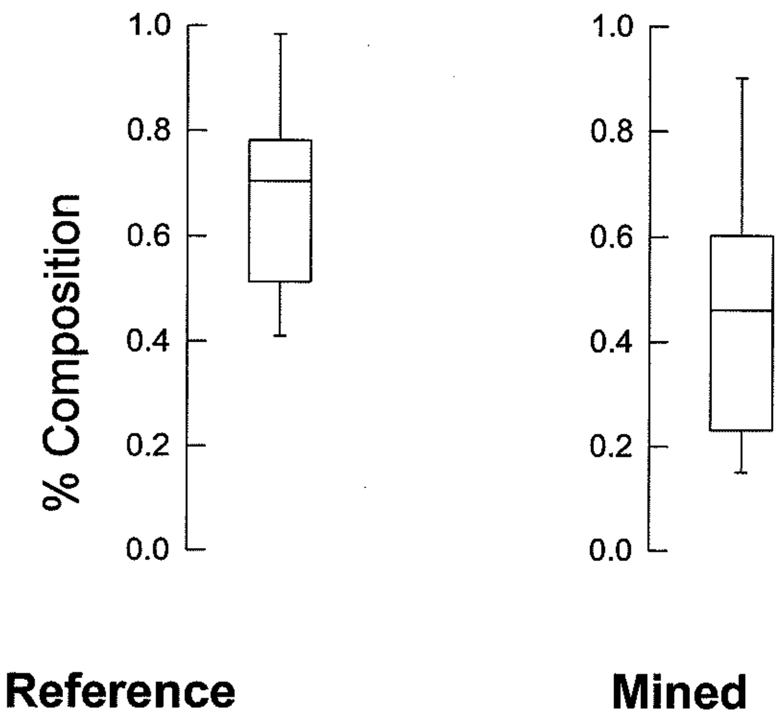

Figure 3.47. Percent composition of clingers in non-mined and mined creeks (p= 0.0000, Mann-Whitney U test statistic = 321). Boxes represent central 50% of the values.

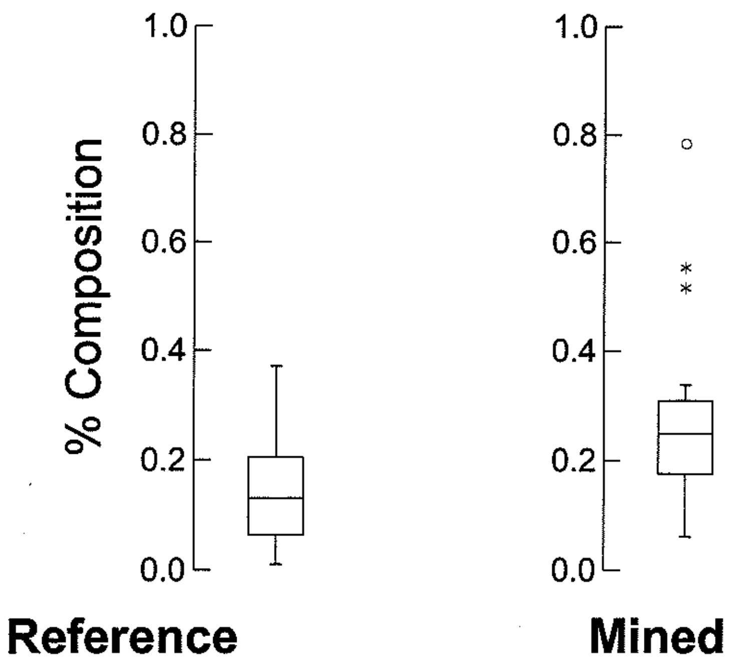

Figure 3.48. Percent composition of sprawlers in non-mined and mined creeks (p= 0.0000, Mann-Whitney U test statistic = 321). Boxes represent central 50% of the values.

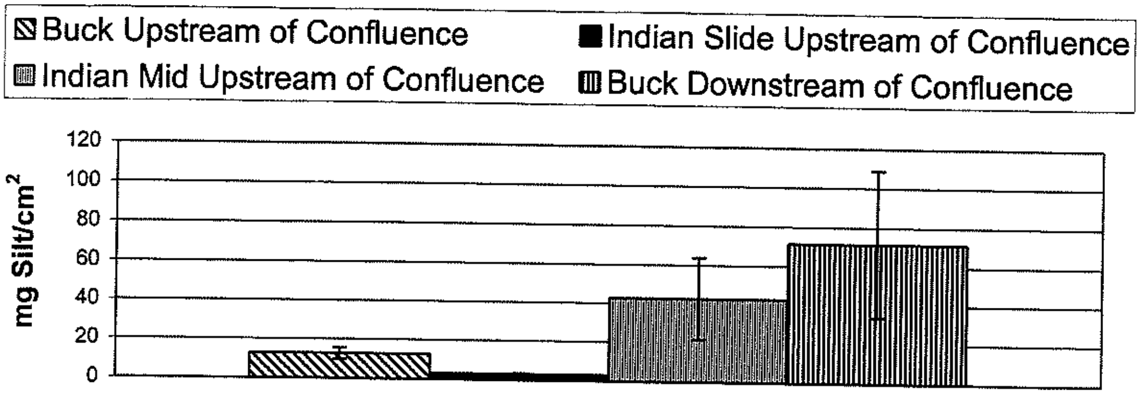

Figure 3.49. Mean weights of sediment trap contents at the Indian/Buck Creek confluence, high flow, October 1999. Bars show standard errors.

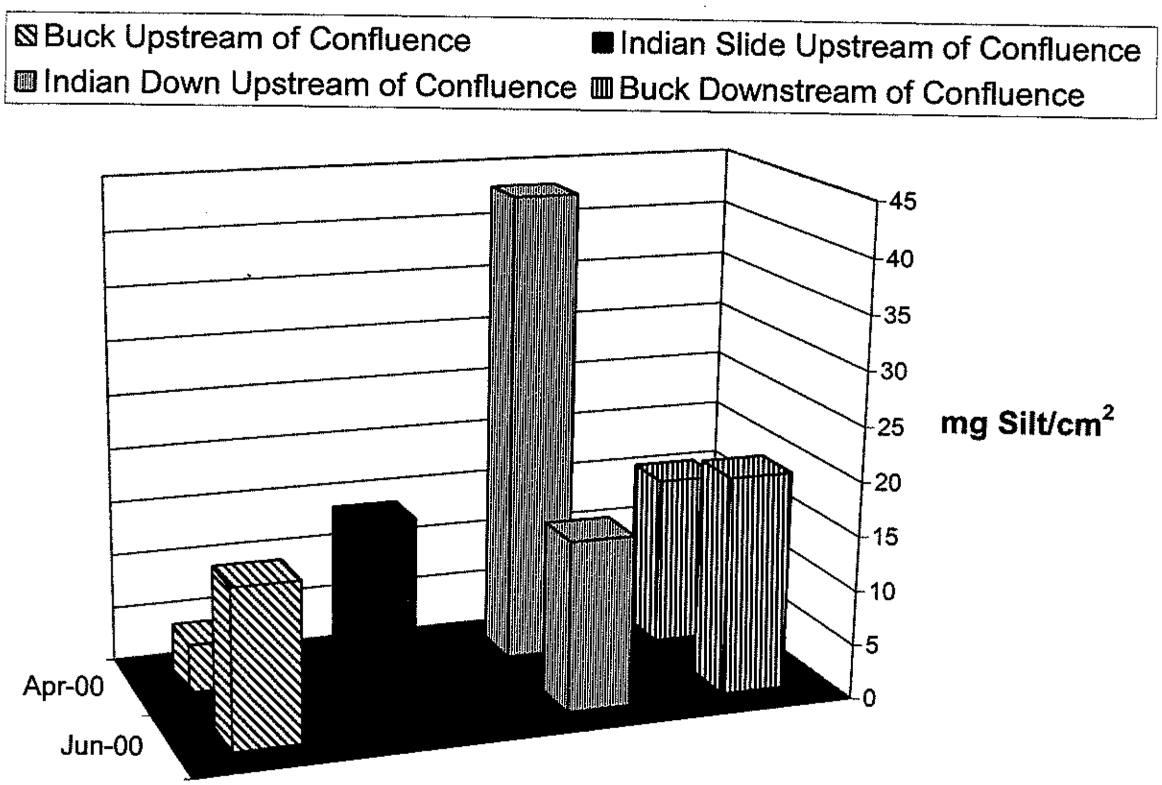

Figure 3.50. Mean weights of sediment trap contents above and below the confluence of Indian and Buck Creeks (Low Flow).

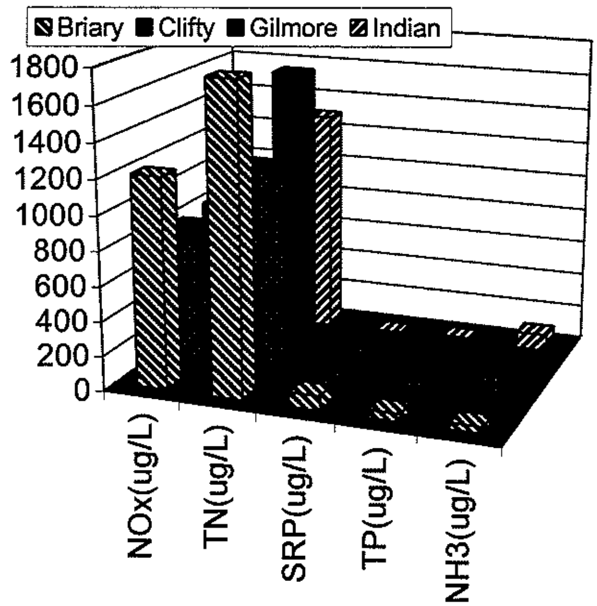

Figure 3.51. Mean hyporheic water chemistries at 10 cm for mined (bars) and reference (stippled) streams

Table 3.18. Selected physiochemical water parameters.

	D.O mg/l	pH	Turbidity, NTU's	Specific Cond. μMhos cm^{-1}	Temp.°C
MAY 1998					
Clifty Cr.	3.58	7.82	2.2	557	18.8
Indian Cr.	5.69	8.52	6.8	505	20.3
Gilmore Cr.	5.72	7.8	5.13	458	20.4
Briary Cr.	3.10	8.15	2.53	576	23.0
MAY 1999					
Clifty Cr.	8.9	8.18	7.0	166	18.1
Indian Cr.	8.85	8.27	50.35	185	15.2
JUNE 1999					
Clifty Cr.	5.39	7.78	14	218	22.0
Indian Cr.	6.75	8.15	12.5	265	23.3
Gilmore Cr.	7.31	7.94	11.0	114	24.0
Briary Cr.	5.52	8.04	9.4	250	26.9
APRIL 2000					
Clifty Cr.	-	8.0	-	114	12.4
Indian Cr.	-	8.0	-	133	10.2
Gilmore Cr.	-	7.28	-	81	12.8
Briary Cr.	-	8.29	-	149	15.6

4.0 DISCUSSION

This study suggests that gravel mining can have significant negative effects on stream morphology and biota. While all of the streams in the study have been significantly impacted by other factors in their watersheds such as land clearance and channelization, there were still measurable impacts in the stream which seem to be associated with gravel mining, such as the poor riffle development in Section 3 of Indian Creek and the lower overall macroinvertebrate KIBI scores in all of the mined streams compared to their references. Many of the geomorphic impacts of gravel mining can have important implications for stream biological communities through effects on riffle stability, availability of instream and riparian refuges and other factors.

4.1 Confounding Watershed Properties

It is often difficult in dynamic systems such as streams to separate the "signal" of an impact of interest from the "noise" of the other impacts in a watershed. The Buck Creek watershed and the streams within, while they may look more "natural" in form than the urban streams that have often been used as examples of degraded and managed systems, have been heavily altered by human activities at least since European settlement of this area. One of the most recent and we believe the most significant impacts to Buck Creek and all of the tributaries studied were the channelization and the maintenance of channelized conditions. None of the study reaches in this project was less than 79% channelized over the wide valley sections studied. The continued extraction of gravels and woody debris from these streams to maintain or increase flood flow capacity preserves degraded habitat characteristics in many of these streams and produces impacts identical to extensive "gravel mining". While identifying all of the mechanisms of channelization in these streams was beyond the scope of this project, at least some of the channelization and subsequent incision noted was the result of direct human intervention. For example, comparison of the current position of Indian Creek and the aerial photographs taken in the late 1950s shows that sections of this stream were moved after 1958 from their positions in the center of the valley to new positions at the base of the valley sideslopes. This practice of stream relocation maximized the amount of land available in the valley bottoms for cultivation and, if the new channel was enlarged, provided flood control benefits as the frequency of flooding would be reduced. Even without such direct interventions, other management practices in these watersheds may have contributed to the current conditions. We have no strong evidence for this, but the impact of these other practices may be subtler than those that could be attributed to channelization.

The removal of coarse woody debris from streams was a common practice, often conducted as part of channelization, again primarily to reduce flooding. The major clearing of these basins occurred over 150 yrs ago and would have occurred on a continuous basis before 1958 along with early channelization. None of the abandoned channels observed were lower than the current stream levels in Indian Creek, Briary Creek, Gilmore Creek or Clifty Creek. Also the removal of coarse woody debris would have been accomplished simultaneously with channelization. If there were several episodes of incision, the deepest and widest would form the terrace banks. We only see the terrace banks from activities since about 40-60 years ago since trees on terrace banks are less than 60 years old. Clearance of the steep hillsides and channelization reduced floodplain storage in these watersheds and altered the hydrologic characteristics of the stream basins, but they have had over 150 years to recover from these impacts and to develop new floodplains. There is very little evidence of deep post-settlement alluvium in the form of silts on top of deep gravel alluviums in the banks (see cross sections above). There is less than 0.5 to 0.7 m of silt on top of the gravels in the banks with no clear distinction between pre- and post- settlement. The field evidence that we saw indicates that the current state of the streams today is aggradation driven by channel straightening and enlargement over the last 80 years.

It is important in any system, and especially in the Buck Creek system, that such confounding factors be identified. While gravel mining operations can lead to high, unstable banks and channel incision (see Appendix I and references in the Introduction), all of the geomorphic and biological problems identified in the mined streams could not be attributed solely to gravel removal. For example, bank erosion and channel incision would be present in all streams of the watershed because of channelization and channel evolution after channelization. In this regard, the use of streams that share similar land use histories as opposed to "pristine" streams is a useful approach to isolating gravel-mining impacts.

However, such comparisons of "mined" and "reference" streams should also be used cautiously. While Indian and Clifty Creeks seem well matched as a reference-mined pair, Briary and Gilmore Creeks were quite different from each other in some aspects of the landuse in their watersheds and this may have limited Gilmore's usefulness as a reference. However, in a watershed as highly altered as that of Buck Creek, we did not find a stream of suitable watershed size and geology that could have served as a better reference.

4.2 Theoretical Framework for Biological Responses

One of the concerns that prompted this project was uncertainty about the biological impacts of gravel removal on streams in the Commonwealth. The removal of gravel substrate leads to loss of habitat for riffle dwelling organisms and it would seem that this would be an obvious negative effect on stream riffle communities. However, stream macroinvertebrates live in a disturbance-prone environment and there has been considerable debate about what the long-term and large-scale effects of disturbances in streams are (see Resh et al. 1988; Poff 1992). The "predictability" of the events and the evolutionary responses and histories of the resident populations may influence their responses to gravel removal. Many invertebrates are good colonizers (Mackay 1992), so even populations displaced or killed by disturbances such as gravel removal may be quickly replaced depending on the availability of upstream (and during the flying adult stages, downstream) sources.

One of the common theories of how disturbances can function in ecological communities is the intermediate disturbance hypothesis first proposed by Connell (1978) as a mechanism for explaining the high diversities of tropical rainforest and coral reef ecosystems. Connell proposed that high species diversity in these habitats was the result of tradeoffs between the competitive and colonization abilities of species. This approach has been used to try to explain biodiversity in streams as a function of bed movement (e.g. Townsend et al. 1997) and other factors. We initially planned to use this theoretical approach as well, treating the streams as members along a gradient of gravel mining intensity from low/absent (Gilmore/Clifty) to high (Indian). While this approach has been successful in some streams, we do not now believe it would be appropriate to attempt to use it as a theoretical framework in this case. The population of streams sampled is small (n=4) and while the watershed sizes of the stream pairs are similar, the headwater stream (Indian/Clifty) watershed sizes are considerably smaller than the wadeable streams (Briary/Gilmore). In addition, the surveys of Briary and Indian have revealed a number of channel form and historical differences, such as the major avulsion event in the Briary Creek watershed. The differences in gravel mining technique, extraction in Briary Creek and dredging in Indian Creek, seemed to provide a ready contrast of disturbance with extraction having less of an effect on the stream than dredging. While there may have been fewer direct effects on the steam channel, the indirect effects of the extraction operation (use of berms and the effect of these berms on bed shear stresses) seemed to have side effects that negate some of the benefits that may have been realized by not removing gravels directly from the channel. As a result, we examined the streams as mined/reference pairs, not as a continuum of disturbance impacts.

4.3. General Discussion

One of the most obvious impacts of gravel mining is the loss of riffle habitat as these gravels are removed in the reach of gravel extraction. A reduction in riffle habitat should be anticipated where headcuts generated in the mined reaches propagate upstream and erode gravel stores over bedrock and in upstream. We predicted that macroinvertebrate densities and biomass would be uniformly lower in the mined reaches. In our assessment, we found that densities of macroinvertebrates were generally higher in the reference streams, but this was not always the case. However, it is likely that our methodology underestimated the actual impacts of mining on macroinvertebrates. For instance, in our mining impact site in Indian (equivalent to Section 3-4 of the Engineering Study) riffles comprised 4% or 51 % (3 and 4 respectively) of the channel length, compared to 29% in the similar reach in Clifty; there were 6 riffles over a 1.5 km reach in Indian Creek Sections 3 and 4 while there were 11 riffles over a less than 900 m reach in Clifty Creek. On a reach scale, macroinvertebrate densities and production may be much higher in the Clifty because of the larger amount of suitable habitat in this stream. Riffle spacing to bankfull widths were also much higher in Indian Sections 3 and 4 (20.1 and 19.7) compared to Clifty Creek (10.7). These differences are similar to what Brown et al. (1998) found in their study of mined Arkansas streams, where spacing of riffles in mined systems was always different (larger or smaller, depending on the stream) than that in reference streams and that predicted for alluvial systems. We did not find a similar disparity in riffle % of reaches for Briary and Gilmore, although Gilmore had a larger number of smaller riffles over the study reach than Briary did as reflected in a smaller riffle spacing/bankfull width ratio.

The differences in riffle availability may also affect the fish in the study. The larger number of darters in Clifty vs. Indian Creek and the absence of sucker species in Briary compared to Gilmore are consistent with higher riffle quantity and perhaps quality in reference streams. The higher AFDMs from the stream bed, the higher sediment loads collected in the sediment traps from the mined steams and the higher turbidity of the Indian Creek's water during the May 1999 spate suggest that lithophils may face poorer quality habitat in mined streams than in the reference streams. Brown et al. (1998) reported that fish they classified as "silt sensitive" were less numerous downstream of mining operations in Arkansas streams, and other studies have demonstrated that habitat loss and sedimentation associated with gravel mining can lead to the extirpation of fish species from streams (reviewed in Kanehl and Lyons 1992).

In disturbance-prone environments such as streams, populations of many stream organisms may be maintained by use of refuges during periods of high flow, and in some cases, low flow. High flow refugia may include large bed particles (Townsend 1989), dead zones (Lancaster and Hildrew 1993) and the hyporheic zone (Palmer et al. 1992.) Pool depth, number and placement may be important for stream organisms during the summer months, particularly when rainfall and groundwater inputs into the streams cannot maintain surface flows.

High flows through a reach may result in the death of organisms by mechanical damage or their loss through drift. Flows that do not directly kill or wash out organisms may indirectly affect them by disrupting spawning areas or by exporting stored particulate carbon that could be potential food resources. In the mined sections of Indian Creek, there are few refuges available in space for the resident macroinvertebrates. There is no hyporheic zone over large stretches of this stream and even in areas like Section 4 where there are more riffles, the riffle depth is almost always less than 10 cm, which may limit the usefulness of this refuge at high flows. Also, the high banks along much of Indian Creek preclude any stream organism from seeking refuge in the lower velocity zones of the floodplain. While dead zones were not explicitly modeled as part of this project, the backwater effects of Buck Creek in Section 4 of Indian Creek contribute to the comparatively lower bottom stresses calculated for this reach and may provide a lower stress refuge during high flows. More refuges may be available in Section 1 of Indian Creek because of the deeper hyporheic zone (> 40 cm in many areas), wake zone in channel bends, the LWD present in the channel and the accessibility of the stream's floodplain, which may limit the stresses at many locations of the stream bottom.

We were only able to capture one spate event in Clifty and Indian but the differences in the communities were striking, with densities in Indian being an order of magnitude lower than in Clifty after a bankfull event in both streams. Since modeled bankfull shear stresses are similar in these systems, we suspect it was differences in the available refuges that led to the greatly reduced densities of macroinvertebrates we noted in Indian. It is also possible that some of the macroinvertebrates in Indian Creek were smothered with sediment in the backwater area as a refuge for excessive shear stress may not be refuge for sedimentation. Equally important is the rapid re-colonization of the Indian riffles such that by the following month there was only a small difference in macroinvertebrate densities between Clifty and Indian Creek sites. This highlights a potential weakness in the use of biometrics to assess gravel mining impacts: if there is an active source population for new colonists then impacted reaches which have been under stable flow regimes for long periods may not show a mining "signal" associated with reduced refugia for stream species. Indeed, since KDOW protocols require that no sampling take place within 7 days of a major rain event, mining effects or other impacts that reduce refugia availability may never be detected if there are source populations upstream to replenish the depauperate reach via drift.

It was interesting to note that two sensitive insect taxa, Trichoptera and Ephemeroptera, were found in much higher densities in the hyporheos of Clifty Creek than Indian Creek. This is further, although indirect, evidence that the loss of the hyporheos in Indian Creek may have reduced the resistance of this system to disturbance-induced changes.

Another striking difference between Clifty and Indian Creeks was in the number of pools and their depths. These are likely to be critical habitats for fish and other stream organisms during periods when the streams pool as the study streams often did in the late summer months. For the first two years of the study, Sections 3 and 4 of Indian Creek completely dried, including the few shallow pools that were in those reaches. In contrast, the pools in Clifty Creek never completely dried even when surface flow was completely absent. The presence of sustained pool habitat may explain why Clifty Creek was able to support several taxa of piscivorous fish (*Micropterus* ssp.) and large populations of *Lepomis,* which are pool specialists and indicative of good pool quality (KDOW 2002) while these taxa were absent or much less numerous in Indian Creek. Unlike Indian Creek, Briary Creek's pools were deeper than that of its reference stream Gilmore Creek, and thus there were fewer differences in fish community taxa linked to pools. However, the densities of *Lepomis* were considerably higher in Gilmore Creek, suggesting there may be differences in the suitability of these pools for supporting these species. We noted that there was little riparian vegetation on the banks of Briary Creek, perhaps as a result of its rapid lateral migration rate. Without shading during the summer, temperatures in the pools may have been much warmer in Briary than in Gilmore, leading to stress on the fish. Changes in pool habitat have been commonly noted in previous gravel mining studies but the responses have varied from the lengthening of pool habitats to the eradication of pools in a reach

(Brown et al. 1998; reviewed in Kanehl and Lyons 1992). Gravel dredging may also produce pools when bed material is removed, but these are short lived in many systems where sediment supply is sufficient to fill them. The loss of riffle and pool habitats in the mined streams may have larger scale effects above the reach. Pringle (1997) suggested that degraded reaches in streams and areas downstream of those areas might be population sinks. Adult aquatic insects typically fly upstream to deposit eggs, and extensive areas of bedrock in areas like Section 3 of Indian Creek provide little suitable substrate for ovipositioning. In addition, insects drifting from the better quality habitat in Section 1 may travel for more than 1 km before they encounter suitable habitat for colonization. In cases like this, recruitment to the source population may be compromised if larvae fail to find suitable habitats or disperse so far downstream they cannot make it back upstream to suitable habitat.

One aspect of gravel mining that differs from other impacts such as point or non-point source pollution is the propagation of some of its effects upstream. Headcuts and the resulting upstream incision are commonly identified with gravel mining operations (e.g. Kondolf 1994a) and can have significant effects on some stream species (Hartfield 1993, Pringle 1997). Unfortunately, much ecological research and theory (e.g. the River Continuum Concept) has focused on downstream processing of energy and materials and there has been less attention given to the impacts of processes moving upstream. As a result, there is little information about the biological effects of headcuts or other "legacy effects" (sensu Pringle 1997). Headcuts associated with gravel mining have been linked with effects such as channel incision and bridge piling destabilization (Kondolf 1994a) but seldom directly with biological effects (but see Hartfield 1993). In this study, gravel mine impacts were identified well upstream of any active mining, such as in Section 1 of Indian Creek. While we designed the sampling regimes to encompass areas upstream of gravel mining operations, we did not position our sites far enough upstream to be completely free of influence from the gravel mine impacts propagating upstream. A site in Section 1 of Indian Creek was established and sampled for macroinvertebrates but not for fish for the last two periods of the study. We found that the KIBI scores of the Section 1 riffle of Indian Creek and the % clingers and % sprawlers values were similar to those from the rest of Indian Creek. While it may seem counter-intuitive that an upstream reach with what seems to be superior habitat has an invertebrate community which is little different from downstream communities in degraded reaches, these downstream reaches are the source populations for the adults which will fly upstream into Section 1 to oviposit. This is another indirect but potentially important upstream effect of gravel removal: reductions in density or taxa richness in gravel mining sites may be reflected in upstream communities.

The Functional Feeding Group (FFG) results were unexpected. Karr (1999) has suggested that predators are the only FFG that can be considered reliable when used as an IBI. Other taxa may not always feed in the manner by which they are grouped, taxa may often be misplaced in improper groups and stream size, biogeographic regions, human activities, etc. can all affect the feeding behavior of aquatic insects (Karr, 1999). However, there were no clear trends for predator percent composition between treatments, other than the fact that earlier samples tended to have a higher percentage of predators in the reference streams and the later samples showed the opposite trend. The higher proportion of collector/gatherers in mined creeks and the higher proportion of collector/filterers in non-mined creeks is consistent with data from Brown et al.'s (1998) study of gravel mining in Arkansas. Both of these collector groups are good colonizers but the collector-filterers may be dependent on food resources produced in pools (Brown et al. 1998). Therefore, the lower abundance in the mined streams is consistent with the lower number of pools in Indian and with the fish data that suggests that pool quality may be lower in Briary than in Gilmore. In their review of gravel mining studies, Kanehl and Lyons (1992) reported that shredder groups were also reduced in mined streams because mining can lead to reductions in available CPOM. It is not clear why we did not see shredder effects in this study as leaf material and woody debris was much more abundant in Clifty than in Indian Creek

Perhaps the most interesting macroinvertebrate metrics measured for this study are the percentage of insects with the functional habit of "clingers" (% clingers) or "sprawlers" (% sprawlers) (Merritt and Cummings, 1996). Unstable substrate and silt deposition characteristic of headcuts and other impacts in gravel-mined streams should be much more easily tolerated by sprawlers than by clingers. Thus it follows that the proportion of sprawlers in mined creeks be higher than in non-mined creeks. However, from a morphological perspective, it is possible that most gravel mining takes place in stream reaches with high bank erosion rates and consequential high sediment supply. It is possible that the colonization of the mined streams by sprawlers is a response to the evolution of channelized stream reaches and not by gravel mining, unless we consider channelization as a form of mining.

High community evenness in other studies (e.g. Townsend et al. 1997) has generally been associated more stable environments where competition is more important than the ability to recover from disturbance or colonize, so it was not surprising that Indian Creek's community evenness was usually considerably lower than that of Clifty or that the overlap in species between Clifty and Indian was consistently around 50%. There are species associations unique to Indian, such as high *Tipula* sp. and *Baetis* sp., densities, which are consistent with its habitat characteristics. The former is a shredder very tolerant of poor water quality, while the latter genus contains good colonizers that can establish and maintain their populations in dynamic environments.

The mined and reference streams also did not differ significantly in the common surface water chemistry parameters (e.g. NO_3, NH_4, SRP) that are often associated with organic point or non-point source pollution. This result was not surprising for Indian and Clifty Creeks given the similarities in their landuses, but the one might expect some differences between Gilmore and Briary Creeks given the differences in land use in their watersheds (particularly the reservoir located on the mainstem of Gilmore Creek). We did not sample water chemistries enough to fully characterize the water quality over the study period, so this data should be interpreted cautiously.

The higher NOx values in the hyporheos of Indian Creek may indicate that the loss of hyporheic zone depth has led to a loss of function. The hyporheos can be an important zone of chemical transformation and storage. Since its volume has been so greatly reduced in Indian Creek, there may not be a significant retention of nutrients or other constituents in this reach. This is potentially an important but heretofore unexamined impact of gravel mining on stream function. The disruption of hyporheic zone processing may have implications for streams that are as serious as altered sediment transport and other better-studied phenomena. This potential impact deserves additional investigation.

5.0 Project Conclusions and Recommendations

Several sets of conclusions were drawn from this study. The first set specifically addresses the geomorphic conditions of the Buck Creek watershed and the study streams. These conclusions may also apply to the streams of the Fishing Creek and Pitman Creek watersheds that have similar land use, geology and climate. The second set pertains to the mining locations and techniques observed in the study streams. The third set follows from the analysis of mining impacts on the study streams of the Buck Creek watershed.

5.1. Morphologic Conditions Specific to the Buck Creek Watershed and Tributaries

Although the streams of the Buck Creek watershed have suffered from many watershed impacts, the most prevalent and significant currently affecting these streams are from channelization measures, including channel enlargement, relocation and straightening. Streams in wide alluvial valley flats in the Buck Creek watershed upstream of KY 461 have been extensively channelized and relocated.

The main channel of Buck Creek has been transformed from a multi-thread, anabranched channel system to a single thread, channel system over much of its length. The main channel has incised and is widening. High rates of lateral migration in the incised channel bends and high rates of streambed aggradation were observed at many locations during the course of this study. Gravel mining of point bar material was found to be prevalent in aggrading reaches.

Channel straightening throughout the watershed has caused streams to incise, resulting in the following characteristics. Currently, a relatively thin layer (less than 1.5 m depth along the stream thalweg) of gravel in the streambeds overlays shale bedrock in aggrading reaches. The shale bedrock is exposed in deep pools of Buck Creek as and in tributaries examined. Shale bedrock in these degrading reaches is exposed over large sections of the streambed where it disintegrates rapidly when not covered by water. The depth of pools is limited by the depth of stored gravel over the bedrock.

Rapid lateral channel migration (estimated at an average rate of 0.5 m/yr) contributes large volumes of gravels in three of the four streams studied. In addition, channel migration has increased channel width to depth ratios that enhance local deposition of channel bed sediments through the building of side and point bars. The growth of bars increases the diversion of flow toward the channel boundary that may in turn exacerbate bank erosion and channel migration. Bank erosion is a response to channelization and part of the gradual evolution of the extensively straightened channel networks. Bank erosion is a significant source of gravel bed material throughout the Buck Creek watershed.

The lateral instability of channels, initiated primarily at channel bends within or upstream of channelized reaches, has caused severe bank erosion in many of the channelized reaches. Bank erosion is widespread on all channels examined. The bank erosion is occurring on the outside of channel bends opposite building point bars and where channel sidebars force the thalweg to be close to streambanks. Gradual channel widening is prevalent where bank erosion occurs opposite of channel sidebars. The streams are laterally unstable and show high rates of channel migration and lateral instability where bends occur in the entrenched and channelized reaches.

Shallow hill slope failures have occurred where streams have been relocated or migrated into valley toes. Colluvium from these shallow, hill slope failures was considered to be a minor source of gravel to streams in the study reaches.

The study streams have degraded vertically through initial channel excavations or in response to channel straightening. Consequently, many of these streams have become entrenched within the pre-channelized floodplain. The result is that floods of higher magnitude than the approximately 2 yr events are contained within the channels. The containment of these floods causes higher boundary stresses than would exist in the channel under the lower, pre-channelization entrenchment conditions. Channel bends are affected heavily by the entrenched channel conditions because of the extreme stress that develops from the non-uniform distribution of flow during floods.

5.2 Specific Mining Locations and Techniques of Buck Creek Watershed

Gravel mining was observed in stream reaches that were aggrading during minor flow events between episodes of gravel mining. The aggrading stream reaches included 1) backwater areas upstream of confluences and 2) areas of high gravel supply from bank erosion and low sediment transport capacity. High sediment supply was associated with rapid channel migration and erosion of terraces with high gravel content. Low sediment transport capacity of the mined reaches was partly attributed to increased channel cross sectional area caused by mining excavation.

Three different techniques of gravel mining were observed in the Buck Creek watershed:

1. **Bar Scalping:** Gravel at locations of active point bars was excavated from the point bars. The limit of the excavation was the low water level.
2. **Bar Pit and Berm Mining**: Gravel pits were excavated at locations of actively building point bars. Berms were constructed within the active channel to prevent direct access of the stream to the pits at near-bankfull flow conditions. The depth of the excavations was typically to the elevation of the underlying bedrock.
3. **Complete Gravel Removal**: Gravel was completely removed from the surface of the shale bedrock across the entire active channel.

The technique of mining practiced correlated to the causes of channel aggradation. Bar scalping was observed where point bars and sidebars formed in Buck Creek. Bar pit and berm mining was observed in aggrading and widening reaches that contained large and rapidly building point bars. Complete gravel removal was observed in one backwater channel of a tributary.

The practice of in-stream gravel excavation to maintain channel flood flow capacity or to prevent bank erosion was widespread. This practice of channel maintenance sustains channelized stream conditions. Although typically not as intensive or extensive as gravel mining operations, the techniques used to extract gravel were similar to combinations of "bar scalping" and "complete gravel removal" described above. A widespread practice used to mitigate bank erosion in channel bends was the excavation of point bar gravel and transfer of the gravel to the face or toe of the eroding bank.

5.3 Specific Impacts of Mining on Study Tributary Streams of the Buck Creek Watershed

Conclusions specific to impacts of gravel mining on the study streams were developed from the detailed examination of two streams subjected to two different techniques of intensive gravel mining. The conclusions were developed on the basis of inferences drawn from field survey data known morphological processes, and the results of comparative analysis of geomorphic and hydraulic parameters of reference and mining-impacted stream reaches.

5.3.1 Complete Gravel Removal in Backwater Conditions: Indian Creek

The technique of "complete gravel removal" was practiced in one study reach of Indian Creek where an environment of sediment aggradation was created from the backwater effect of the confluence with Buck Creek that was located immediately downstream. Gravel mining in excess of gravel supply depleted gravel storage both in the mined reach and in the upstream reach impacted through upstream head cut migration. In all of the channelized streams studied, morphological features such as riffles and pools formed in relatively thin layers of gravel that was stored over bedrock. Depletion of these gravel stores had a large impact on riffle and pool morphology.

The following summarizes specific impacts of gravel mining on riffle and pool morphological parameters:

- The depth of gravel stored over bedrock was greater in the reference reaches than in the mined reach. In the upstream impacted reach, head cuts and occasional channel maintenance completely exposed bedrock creating step/pool reaches.

- The streambed surface material along the stream thalweg was composed of gravel in the reference reaches except in the deepest regions of the pools where bedrock was exposed. Shale bedrock was exposed over most of the streambed in the upstream impacted reach and in sections of the mined reach. Rapidly degrading shale bedrock steps were abundant in the upstream impacted reach and completely absent in reference and mined reaches.

- The number of riffles per stream length, the riffle length, and the percentage of streambed covered by riffles were similar in the mined reach and reference reaches; however, these parameters were extremely low in the upstream impacted reach.

- The average maximum low-flow pool depth was 2 to 3 times deeper in the reference reaches than in the mined and upstream impacted reaches.

- Although all channels were incised because of previous channelization, the depth of channel incision and bank height was greater in the mined and upstream impacted reaches than in reference reaches.

- The processes of bank erosion were associated with debris blockage, channel aggradation and channel avulsion in the reference reaches. Bank erosion was caused by bank toe scour in entrenched channel bends in the mined and upstream impacted reaches.

- Riffle surface sediments in all stream reaches except the mined reach were found to be mobile at the estimated 2 yr flood flow interval. Sediment mobility was based on the one-dimensional modeling of typical sub-reaches of both reference and upstream impacted reaches. The one-dimensional model indicated that the riffle sediments in the backwater-affected mined reach were not mobile at the 2 yr flood conditions.

Under the specific morphological conditions of Indian Creek, the technique of "complete gravel removal" was found to deplete gravel storage over bedrock, to reduce the amount of riffle habitat, and to reduce the maximum depth of pools. In some reaches upstream of the mined reach, gravel riffles were replaced by long reaches of exposed shale bedrock and very shallow pools formed in bedrock.

The upstream impact of gravel mining was limited by the exposure of a siltstone layer in the streambed and the development of boulder-armored rapids. The siltstone bedrock and large siltstone boulder armoring formed a grade control that mitigated the upstream progression of headcuts.

5.3.2. Bar Pit and Berm Mining and Rapidly Aggrading System: Briary Creek

The technique of "bar pit and berm mining" was practiced in the highly dynamic and aggrading study reach of Briary Creek. Rapid rates of channel lateral migration into a terrace with high gravel content provided a high supply of sediment to the study reach. The following conclusions are drawn with the inference that sediment supply to the study reach was in excess both of the amount of gravel mined and also the amount transported to reaches downstream of the mined reach.

- The depth of gravel stored over bedrock was the same or deeper in the mined reach as in the reference reach.
- The streambed surface material along the stream thalweg was composed of large gravel except in deep pools where shale bedrock was exposed. The bed material along the thalweg of reference reaches was similar.
- The number of riffles per stream length, riffle length, and percentage of streambed covered by riffles was similar in both the mined reach and the reference reach.
- The average maximum low-flow pool depth was higher in the mined reach than in the reference reach.
- The depth of channel incision was as low in the mined reach as in the reference reach.

- Bank erosion was extensive in the mined reach and upstream of the mined reach. The processes of bank erosion in the mined reach led to rapid lateral migration into a terrace composed of a high gravel content. Although similar bank erosional processes were occurring on the reference reach stream, the rate of channel erosion and the supply of gravel from eroding banks were much lower.

- Riffle surface sediments in the mined section were found to be much more mobile at the 2 yr flood conditions than in the reference reach. However, they were significantly less mobile at higher magnitude flood levels. Berms created to protect pits from flooding at low flood levels contained flows at low flood levels causing high channel boundary stresses. At higher flow levels the constructed berms are overtopped, causing a significant increase in channel flow area and a reduction in average channel boundary stress. The reduction in boundary stress at high flow levels increases the potential for sediment deposition, building of point bars and migration of the channel into the terraces.

- Although the morphological parameters of the stream profile and channel cross-sectional characteristics for the heavily mined reach of Briary Creek were similar to reference reach conditions, the bank erosion and lateral migration rates were higher despite intensive bar mining.

- The straight reaches downstream of the mined reach of Briary Creek were laterally stable and remained in approximately the same location as that of the channelized stream represented on 1958 topographic maps.

The highly dynamic and high gravel load conditions of Briary Creek were attributed to evolution of the extensively channelized stream network. In particular, several bends in the mostly straightened channelized stream were required because the valley contains several relatively low radius bends. As found at most sites, channel instability and high rates of channel migration were initiated in channel reaches where bends were necessary in the channelized system or where streams were not straightened during the channelization. The reference reach for this study is located in a straight and wide valley where bends in the channelized system are less prevalent, bank erosion rates are lower, and, consequently, the gravel supply is lower than in Briary Creek.

5.4 Future Management

Clear objectives are needed for the future management of the channelized streams in the Buck Creek watershed. Currently, the study stream reaches, which are believed to be representative of the lower section of tributary streams to Buck Creek, are evolving to a more sinuous planform with bank erosion as the main processes driving change. Although many streams are aggrading through bed and bar building, some streams such as Indian Creek continue to incise into the weak shale bedrock because of high gradients associated with channelization and/or reduction in streambed gravel by mining. From an ecological perspective, the development of more sinuous channels with increasing pool/riffle morphology is considered to represent improved habitat, including stable and more frequent riffles, deeper pools, increased floodwater access to floodplains, and increased groundwater levels. In the transformation from the relatively straight channels to more sinuous channels, bank erosion rates are expected to increase in the short term and to gradually diminish as the dimensions of stream planform, slope, and cross sectional geometry stabilize. Gravel mining and channel maintenance disrupt the evolution of these channels. Protection of rapidly migrating bends may reduce migration rates or may shift the migration to another location. From the landowner's perspective, increased frequency of flooding, bank erosion and increased stream sinuosity may not be acceptable where valuable agricultural land or private property is affected.

Effective stream management plans could be developed that would only permit gravel extraction rates which maintain a specific pool riffle habitat. However, a complicating factor in setting such rates is that gravel transport in gravel bed streams is highly episodic, especially in small tributary streams. The concept of mining gravels at a prescribed volumetric rate is unrealistic and has been discredited in other systems (see Kondolf 1994b). Mining at a specified rate will not guarantee an adequate supply of gravels to satisfy gravel extraction and the load required to maintain stream morphology downstream of a site.

An alternative to setting a prescribed mining rate is to establish geometric limits in the stream channel that preserve the channel characteristics. Gravel mining operations should be limited spatially to gravel deposits both above a specified elevation and at particular locations of the channel that minimize morphological impacts. For example, in order to maintain transport capacity of the bankfull channel in a watershed, gravel extraction should not be permitted in the active channel below an elevation equal to about 1 meter above either a) the bedrock or b) the low flow water level, whichever is highest (1 meter is the depth of gravel required to form pools in the gravels stored on the bedrock in reference reaches of this study). The Kentucky Division of Water could then set specific targets, such as the limit for the lowest level of gravel extraction that would occur above the higher of either: a) a prescribed height above the channel bedrock or b) a prescribed height above the low flow water surface elevation. The limit could be determined from reference stream information applicable to the watershed. The geometric limits described here may support an effective strategy for the streams of the Buck Creek watershed; however they may not be effective in other watersheds. Kondolf (1994b), for example, urges that benchmarks limiting depths of extraction be "permanent." Bedrock levels in the streams in the Buck Creek watershed may change and the low flow surface elevation may depend on who is measuring the elevation. It may be difficult to apply blanket regulations that could reasonably apply across a state as diverse as Kentucky, but a serious attempt should be made to ensure that all parties involved understand what is to be measured for permitting and operating a gravel mining concession.

The biological effects of gravel mining should be carefully considered before extraction is allowed in any system. This and other studies (see above) have already established that mining can have negative effects on the biota. Streams which have unique biological resources or listed or threatened species (unionid mussels etc.) should not be mined. In addition, the fact that gravel mining distrubances can propagate both upstream and downstream needs to be considered.

5.2 Recommendations

The following recommendations are for small gravel mining operations on small streams similar to those studied in the Buck Creek watershed.

Mining limited to aggrading streams: Gravel mining should only be permitted in stream reaches that are undergoing detrimental long-term aggradation. Gravel mining in streams that are not actively aggrading will result in streambed degradation after extraction of gravel. Previous channel excavation and channel straightening in many streams has caused significant channel degradation. Current aggradation may represent the recovery of bedforms that are highly beneficial for stream habitat. The aggradation should be clearly identified as detrimental (causing flooding or land loss) before mining is considered for permitting.

An assessment of stream conditions using methods such as those of Rosgen (1994) or Thorne (1998) should be used to determine the sensitivity of the stream to gravel extraction, the potential yield and the potential for stream recovery. At a minimum, the stream should be classified according to either the Rosgen (1994) and/or Thorne (1998) method, areas of bank erosion identified and a determination made as to whether the stream is aggrading or degrading. Mining should be prohibited in "starved reaches" (i.e. reaches below reservoirs) or in streams with important biological resources as recommended by Kondolf (1994b).

Excavation on the downstream side of point bars: In order to minimize the impact of gravel mining on the geometric characteristics of the channel, Rosgen (personnel communication) has recommended that gravel be extracted from the downstream portion (lower 1/3 to 1/2) of point bars. The depth of excavation should not exceed the low water elevation in the channel. Because the water level in many streams in Kentucky drops below the surface of the gravel in long reaches of gravel bed streams during low flow periods, an excavation limit of 0.7 meter above the thalweg is recommended.

Grade control upstream of the mining operations: Grade control structures should be placed in the streambed upstream of the gravel mining operation to ensure that the pre-mining upstream channel grade will be maintained. The structures can be placed such that they are not effective unless headcuts from the gravel mining operation expose them. The structures also provide a means for monitoring streambeds because degradation will be obvious at the structures.

Monitor downstream riffles: Permanent cross section monuments should be established in the upper 1/3 along the length of at least two riffles downstream of the proposed mining reach. Annual measurements of the channel cross sections are recommended to determine the impact of sediment deprivation that may occur after mining is initiated. Monitoring could also be improved by including sediment sampling of riffles using a simple pebble counting procedure.

Bank stabilization: Consideration should be given to stream bank stabilization instead of gravel mining to reduce channel aggradation caused by upstream bank erosion.

Record gravel extraction volumes: Developing a set of records of gravel extraction volumes is critical to establishing rates of gravel mining that will not significantly impact stream morphology and habitat. All gravel-mining operations should be required to record the volume of gravel extracted, and all such records should be archived with the Kentucky Division of Water.

Periodic review of gravel extraction rates: Records of gravel extraction rates, cross-sectional data and photographs of the recommended grade control structures should be reviewed and reassessed periodically to determine the impact of gravel mining operations.

Evaluate the Potential for Infrastructure Damage: The potential for damage to highway bridges, pipeline crossings, culverts, bank protection, walls or other infrastructure by upstream migration of headcuts and incision should be evaluated. The flow conditions considered in the design procedure and the type of grade control structure necessary to insure the protection infrastructure should be evaluated carefully.

Floodplain restoration: Many of the studied streams have undergone significant straightening and subsequent channel incision. Currently they are widening through erosion of the pre-straightening floodplains that are now terraces. Excavation of large quantities of the gravels from these terraces at locations of potential erosion could provide large volumes of gravel for private and commercial use without detrimental impacts to the main channel. At the same time, new, low level floodplains could be established adjacent to the current channel. This type of channel and floodplain restoration would provide gravel as well as create beneficial habitat.

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APPENDIX I

Immediate impacts of gravel mining

Location	Response	References
Upstream	1. Impacts negligible	
Mined reach	1. Channel enlarged: increase in width and depth	Yorke (1978) Woodward and Cylde Consultants (1976)
	2. Increase in local slope upstream increases flow velocity at upstream end of dredged reach. NOTE: this is the initiation point for headcuts that propagate upstream	Bull and Scott (1974)
	3. Increased bank height and instability	Benke et al. (1985), Yorke (1978)
	4. Removal of bank vegetation increases instability of the banks	Marzolf (1978), Yorke (1978)
	5. Uniform topographic conditions created through the removal of riffles and pools	Etnier (1972), Yorke (1978)
	6. Enlarged channel causes decreased velocities under low flow conditions through most of the mined reach	Cordone and Kelly (1961), Crunkilton (1982), Woodward and Cylde Consultants (1976), Yorke (1978)
	7. Increased suspended sediment load and turbidity due to mining and washing operations	Woodward and Cylde Consultants (1976), Yorke (1978)
	8. Re-suspension of organic material causing decreased oxygen levels and potentially toxic conditions	Newson and Leeks (1986) Wallerstein (1999)
	9. Removal of large woody debris – effects may be beneficial (flood control) or detrimental (aquatic habitat) depending on the system	
Downstream	1. Increase in suspended sediment load during excavation	Forshage and Carter (1973), Kondolf (1994)
	2. Increase in suspended sediment load from washing operations	Cordone and Kelly (1961), Crunkilton (1982), Woodward and Cylde Consultants (1976), Yorke (1978)

Short-term impacts of gravel mining

Location	Primary Response	References
Upstream	1. Development of headcuts that migrate upstream	Bull and Scott (1974), Crunkilton (1982), Lane (1947), Rivier and Sequier (1985), Scott (1973), Simon and Li (1984).
	2. Vertical degradation of streambed	Bull and Scott (1974), Crunkilton (1982), Rivier and Sequier (1985), Simon and Li (1984).
	3. Increased bank height may induce channel widening through bank erosion	Bull and Scott (1974), Collins and Dunne (1990)
	4. Increased bed material load from bed as source	Collins and Dunne (1990), Sear and Archer (1998)
	5. Possible exposure of underlying bedrock or other substrate, with loss of habitat diversity	Collins and Dunne (1990), Landon and Piégay (1994), see
	6. Reduced frequency and magnitude of overbank flooding	Collin and Dunne (1990)
Mined reach	1. Change from gravel to sand/silt substrate and removal of armor layer	Woodward and Clyde Consultants (1976), Yorke (1978)
	2. Decreased rate of bedload transport	Martin and Hess (1986), Crunkilton (1982)
	3. Increased suspended sediment load	Hamilton (1961)
	4. Reduced frequency and magnitude of overbank flooding	Collins and Dunne (1990)
	5. Removal of riparian vegetation – increased temperature and increase in non-native species	Marzolf (1978)
	6. Overall reduction in biological quality such as loss of spawning gravels, macroinvertebrate habitat, and modification of water physio-chemistry. Gaps created in the vegetation cover reduce the degree of ecological connectivity.	Hupp (1997), Shields et al. (1994),

Secondary responses to gravel mining

Location	Primary Response	References
Upstream	1. Increased channel width as banks fail on both sides	Schumm et al. (1984), Simon (1989), Simon and Hupp (1986)
	2. Increased supply of bed load and wash load materials from stream banks as source	Collins and Dunne (1990), Simon (1989)
	3. Failure of infrastructure (bridge foundations, pipelines, culvert outlets and channel walls) as channels deepen and widen	Collins and Dunne (1990), Cullen and Humes (1975), Kellerhals and Gill (1973), Kondolf (1997), Kondolf and Swanson (1993)
	4. Reduction in groundwater level and associated groundwater storage capacity. Dewatering of floodplain wetlands but increasing of available agricultural land	Collins and Dunne (1990), Eyles (1977), Marsten et al. (1995), Reilly and Johnson (1982)
	5. Undermining of hillslopes (in upland areas) which may trigger landslides and increase sediment loading of stream	Bravard, Kondolf and Piégay (1999)
Mined reach	1. Reduction in height and extent of gravel bars can cause erosion or stabilization	Collins and Dunne (1990)
	2. Decreased velocities in the enlarged channel sections	Etnier (1972), Rinaldi and Simon (1998), Yorke (1978)
	3. Deposition of material released from upstream (although locally may be impacted by secondary knickpoints from downstream)	
Downstream	1. Bed degradation caused by coarse sediment starved condition	Kira (1972), Lane (1947) Einstein (1972), Lane (1955)
	2. Increase in suspended sediment load due to upstream bank erosion	Kondolf and Wolman (1993), Parfitt and Buer (1980)
	3. Eventual fining of streambed with associated losses in spawning habitat	
	4. Reduced channel aggradation rates and migration in channels aggrading prior to mining	

Long-term evolution of channels affected by gravel mining

Location	Primary Response	References
Upstream	1. Aggradation and associated formation of bars within incised channels 2. Channel creates new floodplain within widened channel	Schumm et al. (1984), Simon (1989), Thorne (1997)
	3. Abandonment of pre-mining floodplain (formation of terrace) 4. Decrease in frequency of overbank flooding (of the pre-mined floodplain or the terrace) causes change in vegetation mosaic	Schumm et al. (1984), Simon and Hupp (1986)
	5. New floodplain continues to widen as floods erode banks of the pre-mined floodplain. Increased shear stresses contained within channel mean large flood flows and cause significant erosion	Schumm et al. (1984), Simon and Hupp (1986) Bornette et al. (in press)
Mined reach	1. Aggradation and associated bar formation within incised channel 2. Decreased slope reduces velocities across channel causing sedimentation and formation of bars	Schumm et al. (1984), Simon (1989), Thorne (1997)
	3. Very high velocities for flood flows contained within large channel boundary	Schumm et al. (1984), Simon and Hupp (1986)
	4. Overall the system gradually regains a new quasi-equilibrium state although impact of large flood flows and associated high shear stresses can induce smaller episodes of instability. If the stream was meandering prior to mining then the migrating knickpoints may have created cutoffs that increased the slope. Where this has occurred the stream will have to increase its sinuosity, primarily within the incised channel.	Schumm et al. (1984), Simon and Hupp (1986)
Downstream	1. Increased sediment load caused by upstream channel instability and bank erosion	Einstein (1972), Lane (1955), Sear and Archer (1998)
	2. Change in sediment supply and increase in channel width may lead to planform change, i.e. from meandering to braiding (high sediment supply from destabilized upstream reaches)	Sear and Archer (1998)
	3. Decreased rates of meander migration in channels that meandered prior to mining activities (low sediment supply caused by high rates upstream aggradation)	
	4. If stream flows into lake or sea then aggradation may not be eroded by secondary knickpoints. Wetland areas will develop along with an increased frequency of flooding.	
Catchment	Rejuvenation of tributaries will lead to widespread instability of the drainage system. Tributaries and even downstream trunk rivers may experience similar problems	Schumm et al. (1987)

Appendix II. Geology and soils in the Buck Creek catchment

I. INTRODUCTION

The impacts of gravel extraction on the streams in the study area can be related to the bedrock materials under the streams and floodplains, the residual soils and colluvium on the valley walls, and the alluvial deposits on the floodplains. If gravel extraction causes a lowering of base level in those streams, whether or not those bedrock materials will be eroded is dependant on the properties of the intact rock strata as well as on the rock mass properties such as bed thickness, strata orientation, discontinuities in the mass and weathering of exposed surfaces. The significance of any apparent exposure of bedrock is related to how the bedrock was formed and what processes have operated on the rock since it was formed. Consequently, it is pertinent to examine -

1. The geologic history of the state as it relates to the study area.
2. The bedrock and surficial deposits of Casey, Lincoln and Pulaski Counties.
3. In particular, the characteristics of the Nancy Member and the Halls Gap Member, known outside the study area as the New Providence Shale.
4. Field exposures of the bedrock and surficial materials in channels, on floodplains and on hillsides adjacent to streams in the study area.

II.2 GEOLOGIC HISTORY OF KENTUCKY

Kentucky has been described in terms of physiographic provinces that reflect not only the character of the terrain in those areas but also the types of bedrocks there (McFarlan, 1943). Sedimentary rock strata dominate the geology of Kentucky, but the topography, rock mass structure and rock quality vary tremendously from the oldest hard, massive limestone's of central Kentucky to the sometimes thinly bedded coal, sandstone and shale strata of the eastern and western coal fields (McGrain, 1983). The principal geologic structures in the state include the Mississippi Embayment (basin), the Eastern Interior Basin (containing the Western Coal Field), the Appalachian Basin (containing the Eastern Coal Field) and the central peneplains and plateaus formed around the Cincinnati Arch, which trends northeast southwest from the Ohio River through Lexington to the Tennessee border.

The north central part of the Commonwealth is the Bluegrass Province, and is divided by some into Inner and Outer regions. The Bluegrass is ringed by erosional remnants of later strata, the Knobs, and by the edges of massive layers of Mississippian rock formations (Muldraughs Hill and the Dripping Springs Escarpment). The massive strata of the Ste. Genevieve and St. Louis Limestone's (Newman Formation) are the thickest layers of the Mississippian Plateaus that stretch from the center of the state, northeast in a ring around the Bluegrass, and south to the Tennessee border as far west as Kentucky Lake. The eastern third of the state consists of the Eastern Coal Field, the edge of which is the Pottsville Escarpment. A smaller coal basin, centered on Owensboro, contains strata similar to those in the eastern part of the state, and likewise is bounded by the Pottsville Escarpment. In the far southwestern tip of Kentucky, unconsolidated sediments overlie bedrock throughout the

Mississippi Embayment. The materials that characterize each of these provinces primarily consist of rock layers derived from sediments deposited in marine and fresh-water environments, modified by subsequent folding and faulting, and alternately exposed and covered by cycles of erosion and deposition. Figure I.1 shows the physiographic provinces of Kentucky.

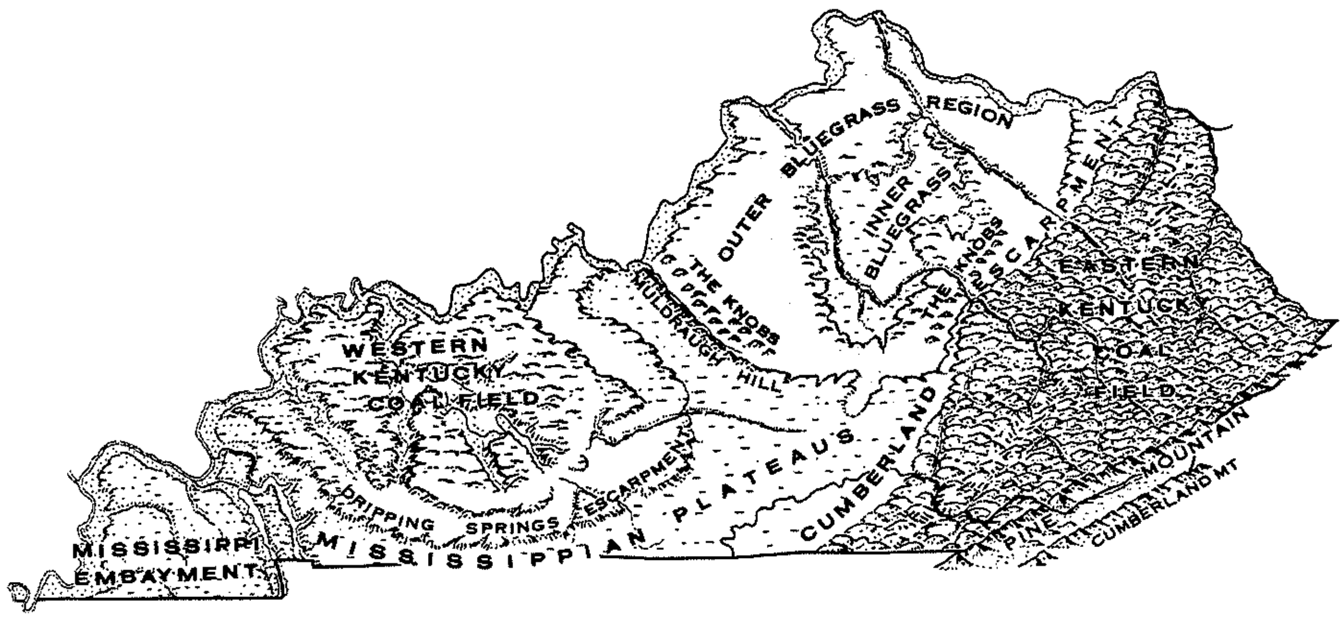


Figure II.2.1 - Physiographic provinces of Kentucky (Rice *et al.*, 1979; Fennmann, 1938).

For all intents and purposes, the geologic history of Kentucky is relevant only in terms of the rock units that are exposed in the Commonwealth. The oldest rocks exposed in Kentucky are Ordovician sedimentary strata of the early-middle Paleozoic Era, and are about 500 million years old. Those rock units deeply cover older Cambrian igneous strata, principally granites, and older metamorphic strata, except for isolated locations where igneous rocks have intruded into near-surface layers. During the Ordovician Period, limestones were deposited in moderately deep seas throughout most of the state; those limestones are exposed along the Kentucky River in the central part of the state. The marine environment changed in Late Ordovician times; the seas became shallow, warm and relatively clear. The sediments deposited during that time, about 450 million years before the present, contained more fine particles than previously deposited sediments, and shales and shaley limestones were formed, often containing rich arrays of marine life (now present as abundant fossils).

In Silurian times, about 430 million years before the present, deposition continued in shallow, warm seas. Coral and brachiopod fossils found abundantly in Silurian limestones and dolomites indicate the type of marine environment in the wide, shallow embayment that extended north from what is now the Gulf of Mexico. During this time also, folding began along the axis of the Cincinnati Arch, with formation of a long anticline (rounded ridge) that divided surrounding areas into basins to the southeast and northwest. The up warping along the Arch continued during the early part of the

Devonian Period when fossiliferous limestones were deposited. Strata were thin in central Kentucky over the ridge of the Arch. Then the nature of the environment changed again in middle to late Devonian times, and highly organic black muds were deposited over the shallow sea floor; those muds have developed into a thick, black shale formation consisting of hard, brittle layers, some only millimeters thick.

Shales continued to be deposited through the beginning of the Mississippian Period about 350 million years ago, but strata formed during the early part of that period also contained delta deposits of muds, silts and sands. Evidence in the rock sequence and quality of the strata suggest that the shoreline of the inland sea stretched from southeast to northwest, shoaling over the Cincinnati Arch, but extending far up into what is now Illinois and Iowa. The shoreline of that sea apparently shifted to the northeast and southwest as much as 600 miles (Swann, 1964). Major streams flowed from northeast to southwest and deposited deltas in the shallow sea; for example, the so-called Michigan River flowed across the middle of what is now the Indiana-Michigan border to branch into at least four major distributaries and generate a delta almost 100 miles wide in west central Indiana and east central Illinois (Thornbury, 1969). The sediments deposited by that stream, most of them clastic sands and silts, were derived from as far northeast as Canada, and the shoreline advanced and retreated at least fifteen times, with as many as 70 local fluctuations; the delta shifted east-west as much as 200 miles. Because of the shifts in the stream and the delta, superimposed channel deposits of sands often are found over more fine-grained floodplain and deltaic layers in central Indiana and Illinois.

The early Mississippian deposits in south central Kentucky were formed under somewhat less dynamic conditions and included thick layers of shale, siltstone and shaley limestones. In middle to late Mississippian times, the seas became clear again and very thick, relatively pure limestones were deposited in the warm waters. The seas retreated briefly at the end of the Mississippian Period, and much of the sedimentary cover was eroded before deposition of Pennsylvanian sediments began about 320 million years ago. Shallow seas advanced and retreated across Kentucky throughout the Pennsylvanian, and vast forests grew on the edges of the sea and in coastal swamps. Vegetation buried under delta deposits of sand, silt and clay became coal seams under sandstone, siltstone and shale strata. The environment alternated between marine and non-marine conditions. Sediments were deposited during the following Permian Period about 270 million years before the present, but those strata were removed when a series of uplifts throughout Kentucky caused widespread erosion during a long period in which the seas receded. Figures I.2.2 and I.2.3 show the occurrence of Mississippian and Pennsylvanian rock strata in Kentucky and the major geologic structures in the Commonwealth.

Shallow seas extended from the Gulf of Mexico northward over the southwestern part of Kentucky into the Mississippi Embayment and into parts of the Mississippian plateaus, depositing gravels, sands and some fine-grained sediment. Most of those sediments were not lithified and remain unconsolidated where they are found in the Embayment. Deposition continued in the Embayment during a 130 million year period throughout the Cretaceous and Tertiary Periods, but erosion was dominant elsewhere. About one million years ago, glaciers began to advance over the central United States in the Pleistocene Epoch, bringing thick layers of ice-contact drift and till; streams along the front of the ice sheets tended to incise deeply because of the drop in sea level. When the ice sheets

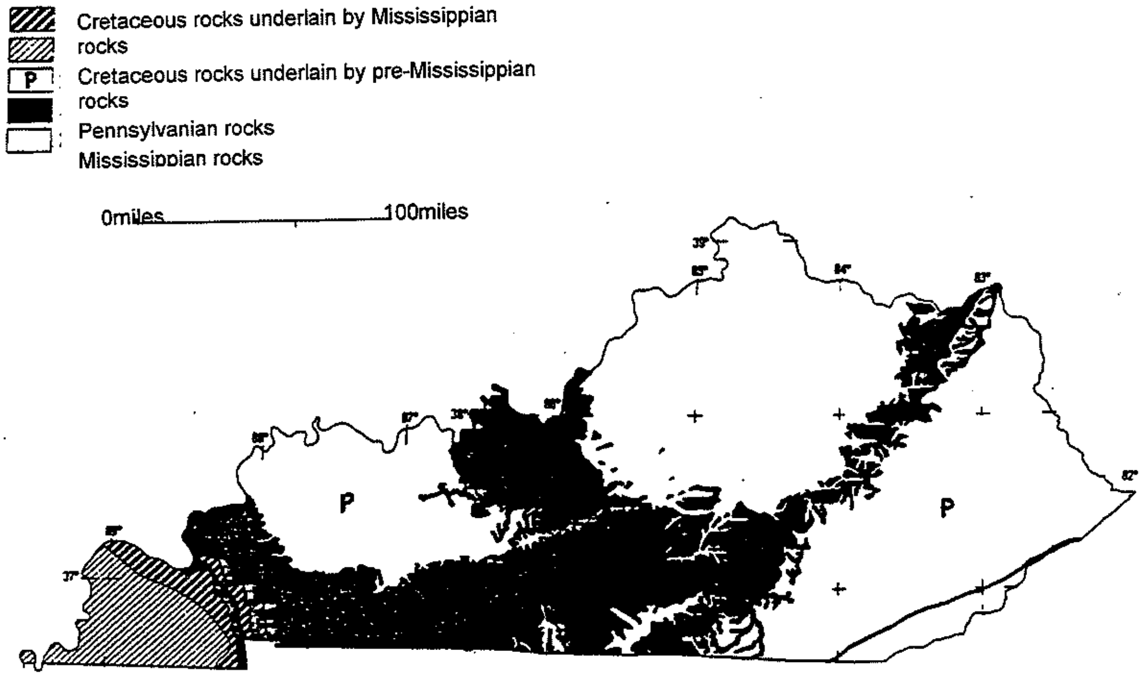


Figure II.2.2 - Mississippian and Pennsylvanian strata of Kentucky.

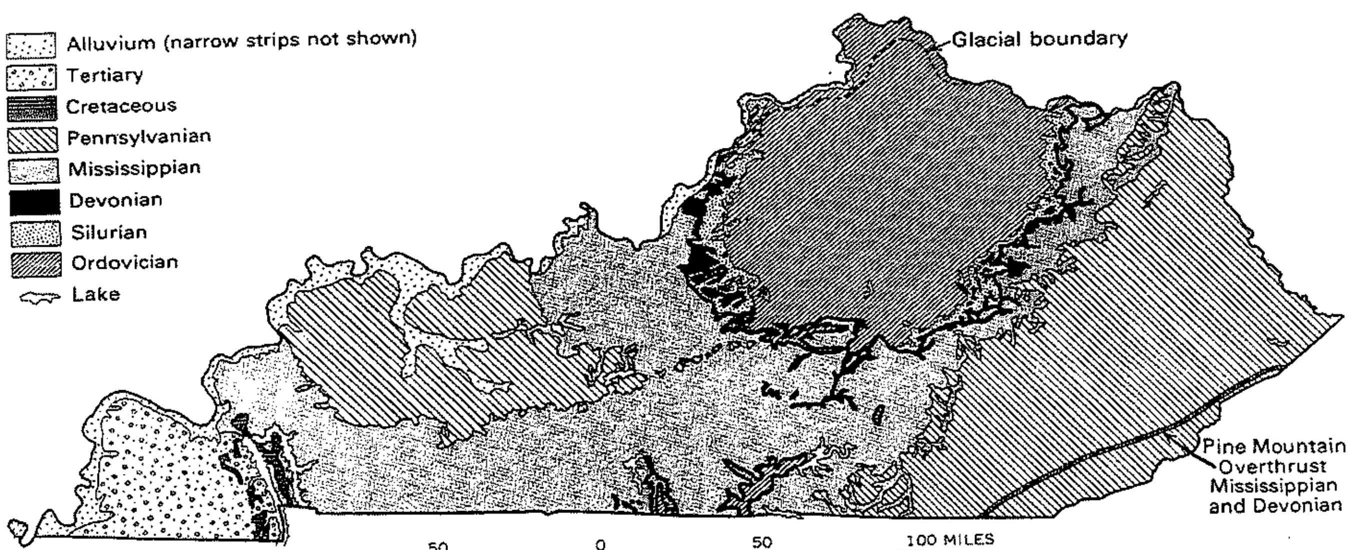


Figure III.2.3 - Major geologic structures in Kentucky finally melted, many of the incised streams were filled with thick layers of alluvium by melt-water flows much larger in volume than present-day discharges; for example, the Ohio River at Louisville flows in a bedrock valley that is about 30 meters deep but is filled with laid down, with black organic sediments deposited in deeper water. Continued compression and local thickening of organic layers occurred during the remainder of the Devonian Period when large amounts of dark clayey silt were deposited; that material was lithified to form the underlying basement shale bedrock for much of the study area..

II.3 GEOLOGY OF CASEY, LINCOLN AND PULASKI COUNTIES

In the study area of Casey, Lincoln and Pulaski Counties, the most significant surficial geologic materials are the deposits of alluvium in the streams and on the floodplains, and the residual soils developed from underlying bedrock. Where the residual soil and portions of the parent rocks have moved downslope on hillsides, the material is called colluvium. Some wind-blown silt (loess) deposits have been found. Silurian and Devonian strata crop out in Pulaski County along the banks and in the bed of Fishing Creek, and underlie much of Lincoln County (Rexroad *et al.*, 1965). The Devonian strata lie unconformably on an erosional surface cut into the Silurian rocks (Figure B3.1). The Devonian formations include the New Albany Shale (40 to 100 feet thick) and the Boyle Limestone (0 to 18 feet thick); Silurian formations include the Crab Orchard Shale (0 to 90 feet thick), and the Brassfield Limestone (0 to 24 feet thick). The Boyle Limestone forms the subsurface layer under eastern Pulaski County, while the Crab Orchard crops out as an outlier in southeast Pulaski County, and the Brassfield Limestone is found only in scattered outcrops. The Boyle Limestone corresponds to the Sellersburg and Jeffersonville Limestones of Jefferson County, and the Duffin/Beechwood/Kiddville formations of east-central Kentucky.

The structure in the Silurian and Devonian strata is dominated by the east flank of the Cincinnati Arch. The rock layers regionally dip gently to the southeast at a slope of 20 to 60 feet per mile. A small anticline (rounded ridge) plunges to the southeast from southeastern Casey County near Fishing Creek across the study area, but the largest local feature is an east-west syncline (basin). Apparently, the Brassfield Limestone and the Crab Orchard Shale were deposited as essentially flat-lying sediments that were folded broadly in the late Silurian. Erosion truncated the folded sediments when a virtual peneplain was formed before the Boyle Limestone was deposited at the beginning of the Devonian Period. Where the Boyle was deposited in low points in the folded sediments, sagging increased. On shoals where water was shallow over high points in the peneplain, carbonates were laid down, with black organic sediments deposited in deeper water. Continued compression and local thickening of organic layers occurred during the remainder of the Devonian Period when large amounts of dark clayey silt were deposited; that material was lithified to form the underlying basement shale bedrock for much of the study area.

The thick black Devonian shale is known variously as the Maury Formation or the New Albany Shale in south-central Kentucky, the Sunbury Shale in northeastern Kentucky, the Ohio Shale in Ohio and West Virginia, and the Chattanooga Shale in Tennessee (Helton, 1968; Stockdale, 1939). The New Albany Shale crops out in western Pulaski County and in Casey County. It typically is dark brown to black, formed primarily from fine-grained silt particles, is fossiliferous and very pyritic, and occurs in hard, brittle layers that vary from several feet to only fractions of an inch in thickness. Little or no erosion appears to have occurred near the end of the Devonian Period, because the overlying Mississippian strata lie conformably over the black New Albany Shale (Rice *et al.*, 1979). The influence of the Cincinnati Arch can be seen in sedimentary strata from the Devonian, but depositional patterns in the shales and siltstones of the Lower Mississippian strata show no evidence of a north-trending arch across central Kentucky in Early Mississippian time (Rice *et al.*, 1979, p. F5). The Appalachian Basin and the Eastern Interior Basin (which contains the Western Coal Field in Kentucky) apparently were connected in Mississippian time across southern Kentucky.

In the immediate vicinity of the streams on which this research is focused, the exposed bedrock consists primarily of lower Mississippian shales, siltstones and thin limestones of the Nancy and Halls Gap Members of the Borden Formation. The streams included in the study effort, Briary Creek, Buck Creek, Indian Creek, and Crab Orchard Creek flow in and on strata of the Nancy Member, which corresponds to the middle and upper parts of the New Providence Shale. The upper reaches of Crab Orchard Creek are underlain by the Halls Gap Member. The Nancy and Halls Gap sandstones, siltstones and shales apparently were deltaic deposits of mixed sediments on shorelines that migrated westerly and southwesterly; the cherty Muldraugh Formation most probably was deposited in shallow water on sea shelf areas. The uplands surrounding the stream valleys are formed on the Muldraugh siltstone, chert and limestone strata (correlative of the Ft. Payne Chert in other parts of Kentucky), and, in Lincoln County, on thick limestone layers of the Middle and Upper Mississippian, including the Salem and Warsaw Formations of rhythmically alternating marine carbonates (shelf limestones) and terrigenous detrital deposits of sandstone and shale on a prograding delta, and the Ste. Genevieve and St. Louis Limestones (shelf limestones).

The Salem and Warsaw Formations, St. Louis Limestone and Ste. Genevieve Limestone, and overlying mixed sedimentary strata (e.g., the Hartselle Formation sandstones) are collectively known as the Newman Limestone. The Muldraugh Formation most likely was deposited seaward of the delta front in basin or tidal area sediments, but the overlying Newman sediments were basin deposits, both tidal-flat/supratidal (St. Louis) and subtidal (Ste. Genevieve). The uppermost Mississippian units, not important in the study area, are the shale, sandstone and marine limestone/dolomite strata of the Pennington Formation, deposited after a period of erosion of Ste. Genevieve materials. The thick limestones form narrow valleys with steep walls; for example where Buck Creek flows south out of the study area.

Upper Mississippian limestone layers form the Muldraugh Hill escarpment, north of the study area, and isolated erosional remnants known as The Knobs north of the escarpment (McGrain, 1983). The hard, resistant ledges in the limestone at the top of the escarpment form a caprock that resists surface erosion and protects underlying softer limestones and shales. Some of the Upper Mississippian limestones are chemically quite pure (McGrain and Dever, 1967) and are subject to solution by acidic precipitation; karst terrains form on the limestone layers south of the Muldraughs Hill escarpment. When erosional remnants initially are isolated from the Mississippian Plateau, they are flat-topped ridges or hills, but weathering of exposed underlying strata leads to toppling of caprocks and the remnants become very rounded in profile. Erosion of the Upper Mississippian

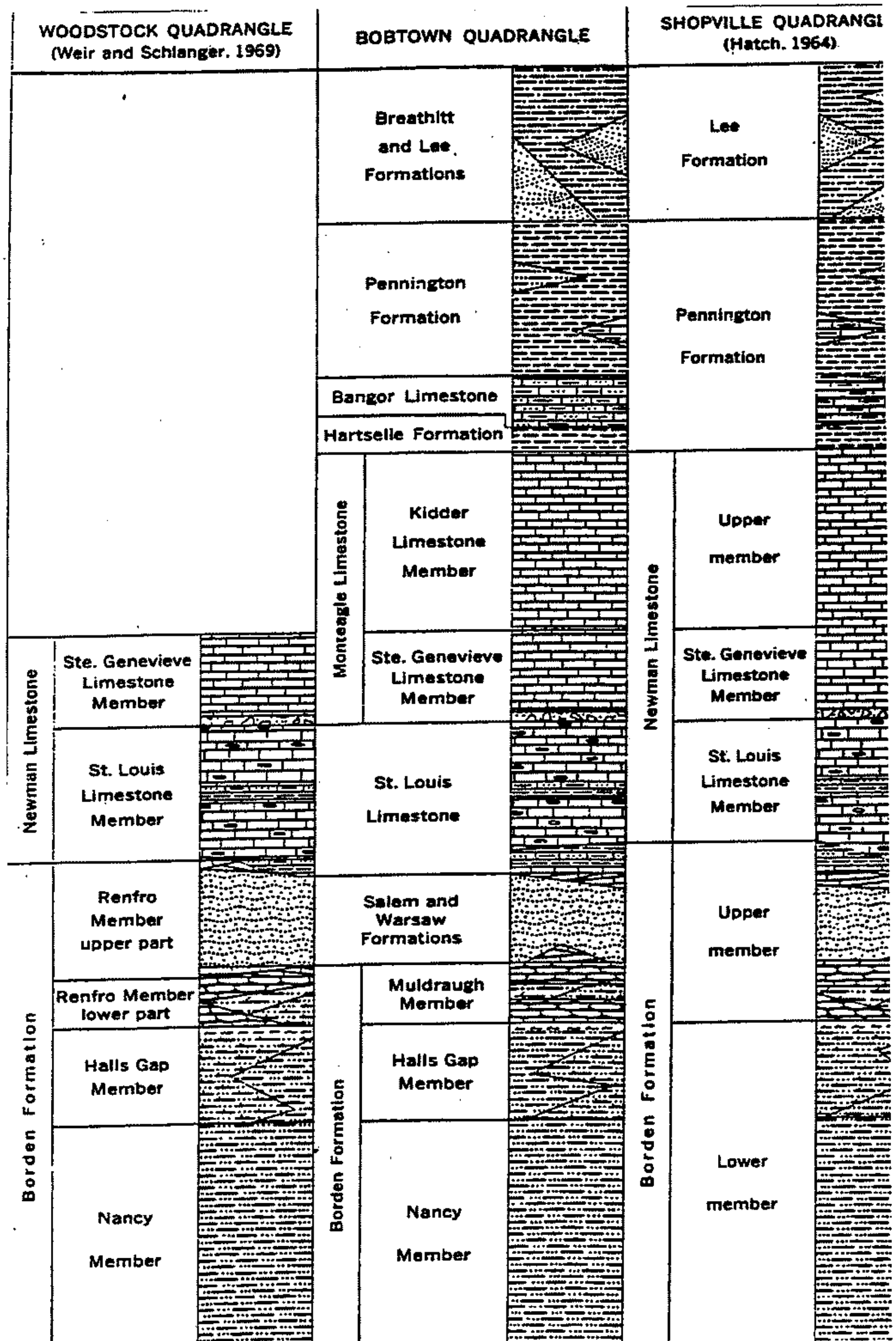


Figure II.3.1 - Stratigraphic column for south-central Kentucky.

strata often leaves significant deposits of geodes in stream valleys into which the resistant geodes are transported. The rock layers of most significance for this research are the lower Mississippian shales of the Borden Formation. During the late Mississippian, most of central and eastern Kentucky was an area of deposition of clastic sediments in shallow marine environments. That type of setting persisted, in the study area, with the addition of large areas of swamps, throughout the Pennsylvanian Period. The deposition during the Pennsylvanian was influenced strongly by subsidence of the Appalachian Basin to the southeast (the axis of the trough is roughly parallel to the fronts of Pine Mountain and Cumberland Mountain). The boundary between Mississippian sediments, primarily of marine origin, and overlying, primarily continental deposits of Pennsylvanian sediments, is an Aintertonguing and intergrading sequence of siltstone, sandstone, and shale (Rice *et al.*, 1979, p. F14). The Upper Mississippian and Pennsylvanian strata are not present near Briary Creek, Indian Creek or Crab Orchard Creek. Consequently, the properties and situation of the Nancy Member and Halls Gap Member strata, particularly the durability of the shale layers, are of great relevance to this study. Considerable study has been devoted to the shales of the Nancy and Halls Gap Members, at times under the classification of the New Providence Shale.

B4 NANCY AND HALLS GAP (NEW PROVIDENCE) SHALES

Physical Characteristics

Comprehensive analytical investigations were undertaken by the Kentucky Geological Survey (KGS) to characterize a representative number of specimens of shales in order to evaluate their commercial potential as source materials for structural products such as brick. The analyses cited herein were completed between 1950 and 1970 by the KGS in conjunction with the Oak Ridge National Laboratory (for chemical /bloating analyses) (Walker, 1951; Walker, 1953; McGrain and Kendall, 1957; McGrain *et al.*, 1960; McGrain and Kendall, 1972). In these tests, samples of shale were obtained and ground to pass the No. 4 standard sieve. The processed material was separated on a No. 20 standard sieve and about fifty pounds of the material that passed the sieve was used for testing. Investigators attempted to ensure that at least 15 to 20 percent of the sample, by weight, would pass the No. 200 standard sieve (equivalent maximum particle diameter of 0.074 mm). The ground shale was mixed with water to form a paste. The water was added gradually to find the minimum amount of water that would make the paste plastic. Paste specimens were molded into bars that were air dried for seven days and then were dried in a convection oven at 104 to 110°C for 24 hours. The dried samples then were weighed.

Three of the parameters that were obtained by the investigators , percentage water of plasticity (WP), percentage shrinkage water (SW) and percentage pore water (PW), are relevant to this research. These parameters were defined as -

$$WP = \frac{\text{weight in plastic state - oven dry weight}}{\text{oven dry weight}} \qquad (I.4.1)$$

$$SW = \frac{\text{volume in plastic state - oven dry volume}}{\text{oven dry weight}} \quad (I.4.2)$$

$$PW = WP - SW \quad (I.4.3)$$

Additional information was obtained by mixing ground shale at plastic consistency with an equal weight of potters flint (sand) before forming cubical samples one inch on edge. After air-drying and oven drying, the finished cubes were submersed in water and supported on a screen with 2.5 openings per inch. The time required for the shale cubes to adsorb water and swell (slake) was measured. The time was recorded when pieces from the cubes, through the mesh. The results were expressed as time to slake (ST) in minutes. Table I.4.1 shows some of the results of this testing. The percentage water of plasticity and percentage shrinkage water tests were analogous but not identical to the geotechnical engineering index tests used to determine the liquid limit, the plastic limit and the shrinkage limit. The slaking test was performed on mixtures of materials and is not a good indicator of slaking behavior of shales *in situ*. However, the data in Table I.4.1 shows that there was little variation in the water absorption properties and shrinkage characteristics among the shales that were tested. This result suggests that there may be little variation among the engineering properties of the shale materials. The behavior of layers within the Nancy and Halls Gap Members would also be affected strongly by the rock mass properties such as bed thickness, discontinuities, degree of weathering and sequence of layers (e.g. hard layers may confine or protect less durable layers). The slaking times in Table I.4.1, while not directly relevant to the slaking of the shales in the beds of the creeks in the study area, are an indicator that slaking characteristics may vary considerably from one layer to another.

Chemical Analyses

Additional insights into the inherent variability of the shales in the study area can be gained by examining results of chemical analyses that were done as part of the same characterization effort that produced the data in Table I.4.1. Chemical analysis data are given in Table I.4.2. Data on samples obtained from Bullitt, Hardin, Adair and Cumberland Counties have been included in the Table I.4.2 for comparison with results obtained on samples from the study area in Casey, Lincoln and Pulaski Counties. The chemical analysis data are ultimate analysis data and do not correspond to mineralogical breakdowns given in terms of amounts of quartz, clay minerals and other mineral species. The data do serve as good indicators of the variation in characteristics that could be expected in the Nancy Member and the Halls Gap Member (New Providence Shale) from one county to another across the state, and from one location to another within the limits of the study area The commercial potential of the Nancy and Halls Gap Members also has been evaluated in terms of the possible use of those shales as source materials for lightweight aggregates in various concrete products (McGrain, 1957). Producing lightweight aggregate involves heating the source material until some constituents release gases that form many small bubbles within the fabric of the heated particles, with a consequent bloating and reduction in bulk density. Portions of sample 148, listed in Tables II.4.1 and II.4.2, were used to evaluate the bloating characteristics of the rock exposed at that location. The partial results are provided in Table II.4.3.

Table II.4.1 - Characteristics of Nancy/Halls Gap(New Providence) shale powders.

Sample	Location	% WP	% SW	% PW	ST (min)
105 basal New Prov.	Bullitt County (KY) for comparison	26.0	10.0	16.0	8.1
118	Lincoln County; on the Southern RR 9.25 mi SW of Stanford	22.0	5.6	16.4	9.5
119 lower New Prov.	Casey County; on KY 35 1.35 mi NE of city limits of Liberty	22.0	6.2	15.8	10.0
244	Casey County; off US 127, 8 mi N of Liberty	21.4	------	------	-----
146	Casey County; 2 mi NE of Clementsville	21.7	5.2	16.5	6.0
147	Casey County; SE side of KY 35, 1.8 mi SW of Liberty	19.9	5.5	14.4	3.5
148	Pulaski County; off KY 1248, 2.3 mi E of Nancy; 5.2 mi W of Somerset	22.8	6.0	16.8	3.9
201 basal New Prov.	Lincoln County; off KY 39, 2 mi S of Crab Orchard	24.8	8.5	16.3	9.0
202	Pulaski County; KY 1248 at Fishing Creek, 4 mi W of Somerset	21.9	6.8	15.1	6.0

Table II.4.2 - Selected results of chemical analyses on Nancy/Halls Gap shale powders (McGrain *et al.*, 1960; McGrain and Kendall, 1972).

No.	County	% loss on ignition	SiO_2 %	Fe_2O_3 %	TiO_2 %	Al_2O_3 %	CaO %	MgO %
105	Bullitt	5.44	62.97	5.98	0.98	17.7	1.02	5.90
118	Lincoln	4.88	59.59	6.18	0.98	17.0	0.42	2.15
119	Casey	4.77	63.58	5.19	0.92	15.2	0.41	1.82
146	Casey	4.44	63.42	6.36	0.63	15.5	0.24	2.15
147	Casey	4.42	65.15	5.46	0.61	13.9	0.38	2.15
148	Pulaski	4.57	67.99	4.70	0.70	16.52	0.36	2.27
157	Adair	4.20	64.90	5.25	0.80	16.2	0.35	2.00
158	Cumberland	6.85	61.77	5.92	0.66	15.5	2.58	2.50
201	Lincoln	4.48	61.81	5.46	0.82	18.9	0.20	1.82
202	Pulaski	4.21	63.34	5.65	0.77	17.34	0.25	1.85
205	Hardin	4.32	61.16	6.33	0.87	18.08	0.21	1.85

Table II.4.3 – Bloating characteristics of the Nancy and Halls Gap Members rocks.

Temperature (°C)	Bulk Density	Remarks
1800	2.17	-
2000	1.62	Beginning of bloating
2100	1.13	Good bloating for aggregate
2300	0.59	Over bloated, very sticky

The good bloating properties of these shales are not relevant to their slaking behavior or to their relative durability in streambeds and banks, but they may be of some relevance to future trends to exploit the mineral resources of the study area, in efforts similar to the gravel extraction that already has been done.

Engineering Properties

Rock Units

In addition to the geological evaluations of the Nancy and Halls Gap Members that have been cited and from which relevant information has been retrieved, geotechnical investigations have been done to evaluate the mechanical properties of these and other shales in Kentucky; these investigations have been done principally in connection with the use of shales as highway sub-grades and as fill materials for compacted embankments (Hopkins and Gilpin, 1981; Hopkins and Deen, 1983). Comprehensive studies have been done of the behavior of compacted shales; those studies have included a systematic investigation in which physical testing of some forty different types of shales was done (Hopkins, 1988). Numerous investigations of slope failures on and in the Nancy Member-Halls Gap Member/New Providence Shale have been completed, including studies of natural slopes and cuts in these shales (Sites, 1985; Sites and Hagerty, 1986). One of the most important processes affecting slope stability in shales is weathering and deterioration associated with absorption of water (Nakano, 1967). Softening by water absorption significantly alters the drilling resistance of some shales (Chenevert, 1969). Slaking and deterioration after contact with moisture has been shown to be important in intact shales in building foundations (Hagerty, unpublished records) and in intact shale pillars and ceilings in underground openings (Hagerty and Ullrich, 1982; Ullrich *et al.*, 1984). Great variability in durability and plasticity characteristics has been found in shales from throughout the United States and from other countries (e.g., Gamble, 1971). In one study, the properties of the Clays Ferry Shale of Kentucky were compared by Cepeda Diaz (1973) with the properties of the Cucaracha Shale of the Panama Canal Zone, the Pierre Shale of South Dakota, and the Claggett Shale of Montana. Some of the results of that study are shown in Table II.4.4.

The SDI values in the Table II.4.4 refer to the Slake Durability Index that is obtained in a standardized laboratory test first developed at the Imperial College of the University of London (Franklin and Chandra, 1972; Franklin, 1981). That test has been modified slightly and adopted by the American Society for Testing and Materials (ASTM). In the slake durability test, ten representative shale fragments, intact and roughly equidimensional and weighing 40 to 60 grams each, are obtained from the field as naturally occurring fragments or as pieces broken out with a hammer. All dust is removed from the specimens and any sharp corners are removed prior to testing. The test specimens are placed in a cylindrical testing chamber with a length of 10 cm and a diameter of 14 cm, made of 2.0 mm (No. 10) square-mesh woven-wire cloth. The test chamber is supported in a trough so that it will rotate about its longitudinal axis. The trough is filled with slaking fluid (usually water) to 20 mm below the chamber axis. The specimens are inserted into the chamber, the specimens and chamber are weighed, and then the chamber and specimens are dried in an oven for 16 hours (or until the mass becomes constant) at a temperature of 110°C. The chamber is then removed, cooled at room temperature for 20 minutes and then weighed to obtain the natural water content of the specimens. Then, the specimens and chamber are placed in the trough and the chamber is rotated for a period of ten minutes at a speed of 20 rpm. Then the chamber and contents are dried again for 16 hours and weighed. A second cycle of rotation, drying and weighing completes the test. The slake durability index is computed as the final weight of specimens divided by the initial weight of specimens, expressed as a percentage. Some shales show large initial decreases in retained specimen weight (low slake durability) while other shales show gradual degradation with each additional cycle of slaking (Duncan, 1986).

Table II.4.4 - Durability comparisons of selected shales.

Material	% clay-size particles	% natural water content	Test No.	SDI After One Cycle	SDI After Two Cycles
Clays Ferry Shale	---	1.2	1	97.06	88.26
Cucaracha Shale	about 23	11.3	1	0.88	0.44
			2	3.69	2.89
Pierre Shale	60 to 70	35.4	1	27.40	0.80
			2	25.40	1.20
Claggett Shale	about 50	9.2	1	57.35	26.81
			2	55.74	24.20

Slaking and moisture absorption in shales has been shown to be important also to stability of highway embankments in which crushed shale is used as fill (Bailey, 1976; Lutton, 1977; Shamburger *et al.*, 1975; Strohm *et al.*, 1981; Karem, 1984). In one investigation, specimens of crushed New Providence Shale were tested to show the influence of compactive effort, molding water and gradation in particle sizes on the strength properties of the compacted shale (Abeyesekera, 1977). Some of the results of that study suggest that the behavior of New Providence Shale may be altered significantly by water absorption long after the shale is removed from its bed, crushed and then moistened and compacted in a fill. Shale particles broke down long after initial crushing and exposure to water. In another study, samples of three shales were crushed, compacted and subjected to cycles of soaking. The three shales tested were the New Albany Shale, the Nancy Member and the Fort Union Shale (from North Dakota and Montana) (Angel-Reyes, 1980). Comparisons were made between the behavior of compacted specimens formed from slaked shales and those formed from unslaked shales. The New Albany shale samples used in these tests were obtained from Estill County about five miles west of West Irvine in a road cut where the base of the formation was exposed. The mineralogy of the New Albany Shale consists of abundant quartz (about 50 percent by weight), illitic and, to a lesser degree, kaolinitic clay minerals and a substantial amount of pyrite and black organic matter (Shamburger *et al.*, 1975).

In regard to the mineralogy of the Nancy Member, the samples used in this study were about 50 percent quartz, with illite (about 30 percent), kaolinite (about 10 percent) and chlorite (about 10 percent) clay minerals. The Fort Union Shale is Tertiary shale formed by compression under sediments and glacial ice, with little or no cementation. The compacted Fort Union samples used in this study were essentially clay that deteriorated rapidly when it was air-dried and then immersed in water. The Fort Union formation contains quartz (about 10 percent) and a mixture of clay minerals, including illite (about 75 percent) and slight amounts of smectite (about 15 percent) (Hickey, 1970). Some of the test results are shown in Table I.4.5.

In this study, as the data in Table II.4.5 show, cycles of exposure to water did not affect the grain size distribution of the crushed New Albany Shale. Cycles of slaking increased the percentage of silt-size particles of crushed Nancy Shale, but did not change the percentage of clay-size particles. Cycles of slaking of the Fort Union Shale produced a progressive doubling of the percentage of clay-size particles. Other research, has confirmed that cycles of slaking have little effect on index properties or strength of New Albany Shale (Barrett, 1983).

Much of the available information on Kentucky shales as components of highway embankments has been summarized by Hopkins and Beckham (1997). Table II.4.6 shows a selection of data on engineering properties of the Nancy Member and Halls Gap Member (New Providence shale) as well as data on other shales from Kentucky for comparison. Field rock samples were crushed in the laboratory. Liquid and plastic limit tests were performed on material that passed the No. 40 (0.84 mm) sieve and grain-size analysis was done on material that passed the No. 10 (2.0 mm) sieve.

Table II.4.5 - Classification and durability test results on three shales.

Material	Preparation method	Specific gravity	% liquid limit	% finer than 2 microns	Slake Durability Index (SDI_{10} %)
New Albany	Crushing only	2.50	21.6	3	98.2
New Albany	Slake, crushed	2.50	22.2	3	-----
Nancy	Crushed only	2.80	27.5	18	71.2
Nancy	Slake, crushed	2.80	26.6	18	-----
Fort Union	Crushed only	2.72	50.5	30.5	59.4
Fort Union	Slake, crushed	2.72	62.0	56	-----

In Table II.4.6, SDI_{10} refers to a Slake Durability Index determined by the ASTM Standard Method in which samples are tested in two ten-minute cycles. The test is performed on ten pieces of oven-dried rock each having a dry mass of 40 to 60 grams. The standard procedure was modified by Hopkins and Gilpin (1981) to use air-dried pieces of shale in one 60-minute test cycle, to obtain a modified SDI_{60}. The rationale for modifying the standard method was that oven-drying appeared to make the shales more resistant to slaking. The Jar Slaking Number was obtained in a test very similar to the procedure described by Shamburger *et al.* (1975) with slight modifications by Hopkins and Gilpin (1981). In the test, a specimen of shale weighing approximately 50 grams was dried for at least six hours in an oven at a temperature of 110°C, and then cooled for thirty minutes. The specimen then was placed in a beaker filled with distilled water and submerged to a depth of at least 13 mm. The specimen was observed at frequent time intervals during the first half hour of submergence and then less frequently during the remainder of a 24 hour monitoring period.

Table II.4.6 - Engineering properties for some Kentucky shales.

Shale	% *in situ* moisture	% liquid limit	% plastic limit	% finer than 0.002mm	Slake Durability Index		
					SDI_{10}	SDI_{60}	Jar no.
New Albany	1.7	22	NP	3.3	99	99	6
Crab Orchard	4.5	22	14	20.6	72	49	-
Kincaid	5.7	24	19	21.3	44	15	2
Henley	6.7	28	20	33.7	72	33	2
lower Nancy	4.4	30	21	24.2	92	62	3
upper Nancy	4.3	33	21	20.6	94	66	3
Nancy I-64	4.6	20	16	29.8	84	59	3
Kope I-275	8.3	28	25	22.3	63	3	1
Newman	11.6	24	17	35.8	1	2	1
New Prov.	11.0	33	24	30.3	74	34	1
Hardinsburg	6.6	24	18	22.7	8	5	2

After the test, the specimen was classified and placed in one of the following categories –

Jar Slaking Number	Behavior
1	Degrades to pile of flakes or mud
2	Breaks rapidly and/or forms many chips
3	Breaks slowly and/or forms many chips
4	Breaks rapidly and/or develops few fractures
5	Breaks slowly and/or develops few fractures
6	No change

In practice, shales have been classified as mechanically hard and durable for SDI_{10} values of 95% or greater (Jar Slaking Number = 6) and have been used in rock fills. On the other hand, shales with

SDI_{10} values below 50 percent (Jar Slaking Number equal to or less than 2) have been classified as soft and degradable and have been compacted in thin lifts as soil. Intermediate shales are difficult to compact and require heavy equipment.

Examination of the data shown in Table II.4.6 indicates that the durability, moisture absorption properties and mineralogy of shales vary considerably in Kentucky. The plastic limit values in Table II.4.6 are analogous to the percentage water of plasticity values shown in Table II.4.1 and compare favorably. The older, Ordovician Kope shales are notorious as the source of very expensive problems of slope instability and embankment settlement on long reaches of I-71 and I-275 in northern Kentucky. The Silurian Crab Orchard shale also is older than the Nancy/ New Providence shales, and is less durable. The Devonian New Albany shale that underlies the Mississippian shales in the study area is very hard and durable, and contains much less fine-grained particles than the Nancy/New Providence shales. The Henley, Kincaid, Newman and Hardinsburg shales all are of Mississippian age but they all occur over the Nancy/New Providence shales and typically are less durable than the older rocks. The data on the samples from the Nancy and New Providence exposures indicate that the durability of the shales in the study area may vary significantly from one thin layer to another within the sequence of layers in the Nancy and Halls Gap formations, depending on the grain size of the constituent sediments and/or the mineralogy of those particles. The slake durability values of the intact pieces appear to be inversely related to the percentage of fine-grained particles present in the crushed material (the latter values may reflect the texture of the original sediments). On average, shales consist of clay mineral particles, quartz particles, and miscellaneous mineral particles; the miscellaneous minerals may alter behavior significantly, as can variations in the clay minerals that make up the rock. The performance of the Nancy Member and Halls Gap Member as bed and bank materials in the study area will be affected strongly by rock mass properties that can be evaluated only by field research.

Soil Deposits

Degradation and decomposition of bedrock on the ridges and hillsides surrounding the stream valleys in the study area produces residual soil and colluvium. Information on the surficial soils that have developed as residual soils and as alluvium transported and deposited along Pulaski County streams, including Indian Creek and Briary Creek, has been published by the Natural Resources Conservation Service (Ross, 1974). Similar information has not been published for Lincoln County soils, but preliminary descriptions developed by personnel of the Natural Resources Conservation Service can be used to characterize deposits along and above Crab Orchard Creek Adams (1997, in press).

On the floodplains of Indian Creek near Buck Creek, the soil series have been mapped as Nolin silt loam, a well-drained, dark grayish brown silt loam. The upper part (27 cm) typically is classified as ML, a silt of low plasticity, according to the Unified Classification System, and consists of about 80 percent fines (particles that will pass a No. 200 sieve). Below the surficial silt loam are heavy silt loams with higher fines content that are classified ML-CL soils, low plasticity silty clays and clayey silts. The lower soil strata are underlain by coarse alluvium. Upstream from the junction with Buck Creek, the floodplain soils have been classified as Chagrin gravelly silt loam, which is considerably coarser in texture than the Nolin soil. The Chagrin soil series usually show a profile of dark brown loam over dark brown, very friable heavy loam grading downward into gravelly loam. The upper 27 cm or so of the soil classifies as SM (silty sand) or ML (silt of low plasticity), with 75 to 85 percent of the particles finer than the No. 200 sieve. Below the surficial loam layer are layers of gravelly loam (GM, silty gravel or SM, silty sand) over gravelly silt loam (GM to ML). The middle gravelly layers typically have a hydraulic conductivity at least an order of magnitude higher than the silty layers. The Chagrin soils extend upstream along Indian Creek to about the mouth of Dry Branch, where the floodplain soils are less abundant and the dominant soil series is the Garmon-Trimble Complex developed on slopes of 30 to 80 percent. The source material for the Garmon soils is residual soil developed from calcitic shales and shaley limestones on uplands. A typical profile for Garmon soils is a surface layer 0 to 15 cm thick of dark brown silt loam over yellowish brown shaley silt loam to a depth of about 55 cm, where olive brown mottled shaley silty clay loam is encountered. The soil profile typically is underlain by shaley bedrock. The uppermost silt loam classifies as low plasticity silt, ML, with 70 to 85 percent fines content. The shaley silt loam classifies variously as silty gravel, GM, low plasticity silt, ML, or silty clay-clayey silt of low plasticity, ML-CL. The lowermost shaley silty clay loam typically contains less fine-grained material, but the fines may be clayey, and the soil classifies variously as well graded to silty gravel, GW-GM, silty gravel, GM, clayey gravel, GC, silty clay-clayey silt, ML-CL, or low plasticity clay, CL. The Garmon soils make up about 60 percent of the complex, with the Trimble soils developed on colluvium at the bases of slopes and in other areas where colluvium accumulates. The Trimble soils typically are cherty silt loams, classified as silty gravel, GM, or low plasticity silt, ML, over cherty silty clay loam, GM-GC or ML-CL, at a depth of about 1.7 m.

On ridgetops more remote from the immediate valley walls along Indian Creek, residual soils have developed from weathering of limestone, siltstone and sandstone. Lawrence silt loam and Bedford silt loam, derived from residuum produced by weathering of limestones and sandstones, occur on ridgetops and gently sloping areas. These soils have developed low-conductivity precipitation zones, fragipans that inhibit infiltration. Hartsells fine sandy loam has developed from residuum derived from acid sandstones, on hillsides at 6 to 12 percent slopes. The Hartsells soils are higher in sand content than the other ridgetop soils near Indian Creek. Frederick silt loam (6 to 12 percent slopes) and Frankstown cherty silt loam (12 to 20 percent slopes) have developed from residuum on hillsides over mixed limestones and sandstones, and cherty limestones, respectively.

The upland soils vary from cherty gravels (Frankstown, 40 to 55 percent fines, GM-GC), and silty sands (Hartsells, 30 to 45 percent fines), to low plasticity silts and silty clays (Frederick, 55 to 90 percent fines, ML-CL, and Lawrence, 70 to 90 percent fines, ML). The various surficial soil series that have been mapped along Indian, Briary and Crab Orchard Creeks are listed in Table II.4.7.
Along Briary Creek, Chagrin silt loam has been identified near the ford for the Estill Hackney Road, in the study area. The Chagrin silt loam has been described previously. Along most of the reach near the mouth of Briary Creek, near Buck Creek, the soils immediately adjacent to the stream have been classified as Lindside silt loam, a well-drained, dark grayish brown silt loam very similar to the Nolin silt loam mapped around Indian Creek.

Table II.4.7 - Selected surficial soil series along creeks in Pulaski and Lincoln counties.

Indian Creek		Briary Creek		Crab Orchard Creek	
Soil Series	Location	Soil Series	Location	Soil Series	Location
Nolin silt loam (No)	floodplain, at mouth	Lindside silt loam (Ld)	floodplain at mouth	Melvin silt loam (17)	floodplain, lower valley
		Newark grav. silt loam (Ng)	floodplain upstream, near creek	Yosemite gravelly silt loam (14)	floodplain throughout watershed
Chagrin grav. silt loam (Ch)	floodplain, midreach	Chagrin silt loam (Ch)	floodplain, at ford		
Garmon-Trimble Cmpx (GmF)	hillsides and ridgetops	Garmon-Trimble Cmpx (GmF)	hillsides and ridgetops	Garmon silt loam (91F)	hillsides in upper watershed
Frankstow n cherty. silt loam (FcD)	uplands, ridgetops	Frankstow n/ Trimble ch. silt loam (Fc/TrC)	uplands, ridgetops	Frankstow n (79D) 12 - 25 % slopes	hillsides and ridgetops
Frederick silt loam (FdC)	uplands, ridgetops	Frederick silt loam (FdB)	uplands, ridgetops	Ottwell silt loam (26B)	on loess on uplands
Lawrence silt loam (La)	remote uplands	Mountview silt loam (MnC)	upland ridgesides	Christian silt loam (70C)	remote uplands
Bedford silt loam (BeB)	remote uplands	Bedford silt loam (BeB)	remote uplands	Pricetown silt loam (71B)	remote uplands
Hartsells fine sandy loam (HaC)	remote uplands, below SS				

The upper part (75 cm) typically is classified as ML, a silt of low plasticity, according to the Unified Classification System, and consists of about 80 percent fines (pass the No. 200 sieve). Below the surficial silt loam is a stratified silt loam with variable fines content, 30 to 90 percent, classified as SM, silty sand, ML and ML-CL low plasticity silty clays and clayey silts. The lower soil strata are underlain by coarse alluvium.

On the floodplain south of Briary Creek, and lying in a long band parallel to the Lindside soils along the creek, is the Newark silt loam. The Newark soils are not as well drained as the Lindside soils, but are very similar in texture and stratification. A surficial silt loam layer about 25 cm thick has been classified as low plasticity silt, ML, but the top layer is underlain by a thick (1.4 m) layer of silt loam classified as ML-CL low plasticity clayey silt to silty clay, in which as much as 95 percent of the particles would pass the No. 200 sieve. The thick clay-silt layer is underlain by coarse alluvium parent material. Upstream from the ford, near a spot where Briary Creek impinges on the north valley wall, the soils along the creek are coarser in texture than the soils identified near Buck Creek, and have been classified as Newark gravelly silt loam. The gravelly silt loam is as much as 1.5 m thick, is stratified and contains silty gravel, GM, low plasticity silt, ML, and low plasticity silty clay-clayey silt, ML-CL layers, with fines contents from 40 to 65 percent.

The Garmon-Trimble complex has been identified along the slopes south of Briary Creek; those soils have been described previously. In places, above the Garmon-Trimble complex, the soils have been classified as Frankstown cherty silt loam, Frederick silt loam, and Bedford silt loam; those soils also have been described in connection with Indian Creek. In some areas above the Garmon-Trimble Complex, Trimble cherty silt loam has been mapped on slopes of 6 to 12 percent, at the bases of steep slopes. Finally, Mountview silt loam has been identified in association with other upland soils; the Mountview silt loam formed in loamy residuum and is relatively free of coarse fragments. The Mountview silt loam is intermediate in texture between the Frederick silt loam and the Bedford silt loam, and is similar though slightly higher in fines content, to the Lawrence silt loam.

Along Crab Orchard Creek, the soil series and associations have not been described in published data and only preliminary information is available on those soils. However, the principal series identified in the watershed are very similar to the series and associations identified along Indian Creek and Briary Creek. Along the lower reaches of Crab Orchard Creek, the floodplains are very wide relative to the size of the creek. Those floodplains are composed of Melvin silt loam, a very wet bottomland soil that has developed where flooding is quite frequent. Yosemite gravelly silt loam is a floodplain soil that is widespread all along the length of Crab Orchard Creek wherever flooding is fairly frequent. The Melvin soil is similar to the Nolin silt loam along Indian Creek and the Lindside and Neward silt loams along Briary Creek. The Yosemite gravelly silt loam is similar to the Neward gravelly silt loam along Briary Creek and the Chagrin gravelly silt loam along both Indian Creek and Briary Creek. Garmon soils on hillsides and ridgetops are similar along all three creeks, as are the Frankstown cherty silt loams that occur on ridgetops and upper slopes in all three watersheds. The Ottwell silt loam has developed in loess on uplands along Crab Orchard Creek and resembles the Trimble and Frederick silt loams along the other two creeks. Christian silt loam and Pricetown silt loam are upland silt loam soils that occupy positions in the Crab Orchard Creek watershed similar to the situations of the Lawrence, Mountview and Bedford soils along Indian and Briary Creeks.

The information on the series and associations in Pulaski County has been published in the County Soil Report, but the data on Lincoln County soils in the Crab Orchard Creek watershed was only preliminary unpublished data that had been approved for publication but had not been published in a County Soil Report. Most of the surficial soil types of interest in the watersheds of the creeks involved in this study consisted of silt loams and gravelly silt loams. The floodplain soils were variably drained, with those along Indian Creek and Briary Creek somewhat better drained than the frequently flooded soil series on the wide floodplains along Crab Orchard Creek. The colluvial soils on hillsides were very similar in all three watersheds, as expected since the bedrock under those hillsides was very similar in all three watersheds.

B5 SELECTED GEOLOGIC AND GEOTECHNICAL OBSERVATIONS

Briary Creek

A field reconnaissance was made on 17 September 1997. The examination of Briary Creek began at the highway bridge near the junction with Brushy Creek, where the floodplain ground surface elevation is about 925 ft above mean sea level (MSL) (Weir and Schanger, 1969). The rock underlying the creek bed is the upper portions of the Nancy Member, which is overlain by the Halls Gap Member (950 ft MSL and above near the junction of Briary and Brushy Creeks). In the vicinity of Briary Creek and Bruchy Creek, the bedrock strata dip to the east-southeast at a slope of ten to twenty feet per mile. Slight variations in the stratigraphy occur between the areas of Briary and Indian Creeks.

The Nancy Member near Briary Creek contains shale, siltstone and minor amounts of limestone. The bedding of the layers in the formation is not well defined. Some of the layers are thin and fissile. In the top three meters of the unit, greenish-gray clayey siltstone is common, which is less resistant than the siltstones in the overlying Halls Gap Member. Very sparse irregular layers of light gray, clayey fossiliferous, fine- to coarse-grained limestone are present in the lower part of the Member. The limestone lenses are typically only five to eight centimeters thick and only one or two meters in length.

The Halls Gap Member contains siltstone, shale and minor limestone beds. At the base of the Member, the siltstone is clayey and greenish-gray but it changes to light gray and contains very fine sandy grains near the top of the unit. The resistant rock supports very steep slopes immediately above the floodplain elevations along Briary Creek. The top of the Member often is sheltered under an overhang formed by more resistant chert, dolomite and siltstone layers of the Muldraugh Formation (Renfro Member). The Muldraugh Formation is located at the immediate top of valley walls (about elevation 1,020 ft MSL) along Briary Creek. Tributaries to Briary Creek occur in relatively short, very steep valleys developed mostly in the Halls Gap Member and the lower part of the Muldraugh Formation.

The alluvium in the stream was of mixed texture. The larger fragments, up to cobble size, were very angular and platy. Undoubtedly, the large rock fragments in the stream originate in the more resistant siltstones of the Halls Gap and Renfro Members, and in the chert, sandstone and limestone beds of the Renfro Member. The larger fragments consisted of siltstone and chert, mixed with some pieces of siltstone and silty shale and rounded nodules and geodes. A minor amount of fossiliferous limestone was present in pieces as large as cobbles. A significantly finer fraction in the form primarily of sand was mixed with the gravel and cobble size material. In the reaches of Briary Creek that were examined, rapidly degrading shale bedrock was exposed in scattered scour holes between riffles (the very coarse bedload deposit that fills most of the stream cross-section). In some sections of the study reach, trees were absent and/or trees had fallen into the creek as a result of apparently recent undercutting. Exposure of the dark gray shale bedrock in the creek bottom was not widespread or extensive. However, the shale slakes and degrades very rapidly when it is exposed to cycles of drying and rewetting, and large chunks of shale, disintegrated into fine gravel particles and fines, indicated that the exposure of the shale bedrock had been recent (in the winter/spring of 1996-7). Where the shale was exposed in the bed of the creek, it appeared to be covered persistently by water as a result of groundwater discharge from the wide floodplain deposits along the creek, and the persistently wet shale had not disintegrated. Lowering of groundwater level, and consequent lowering of base level in the creek, would tend to expose the shale bedrock to drying and disintegration. At the present time, the banks of the stream in the floodplain soils appeared to be under attack, and some scour of the toes of colluvial hillsides also appears to have occurred recently. Scour holes have formed at scattered locations and degradable shale bedrock has been exposed in those holes, with chunks of shale transported out of the scour holes and deposited on the surfaces of bedload deposits downstream from the scour areas. The state of the transported chunks of shale, partially disintegrated, strongly suggests that the scour holes had formed or had been deepened significantly in the shale bedrock in 1996-7.

Indian Creek

A field examination on 17 September 1997 began at the mouth of Indian Creek where Indian Creek joins Buck Creek. The ground surface elevation on the floodplain adjacent to the mouth of Indian Creek is at about elevation 900 ft MSL, according to geologic and topographic maps of the area (Lewis *et al.*, 1973). The beds of the creeks and the bases of the valley walls have been formed in the upper part of the Nancy Member, which occurs up to about elevation 920 ft MSL near Indian Creek. Most of the steep slopes of the valley walls have been formed in the Halls Gap Member, which occurs up to about elevation 975 ft MSL. The immediate tops of the valley walls are somewhat rounded and the slopes are not as steep as those formed in the Halls Gap Member. The upper slopes have formed in the Muldraugh Formation (lower Renfro Member or Ft. Payne Chert) which is about 16 m (50 ft) thick near Indian Creek. The upper slopes are capped by strata of the Salem and Warsaw Formations (upper part of the Renfro Member), including resistant sandstone layers. The stratigraphy, bed thicknesses and rock quality of the Nancy, Halls Gap and Renfro Members in the area of Indian Creek are virtually identical to those characteristics of the rock units where they occur around Briary Creek.

Gravel had been extracted along Indian Creek just upstream from the junction with Buck Creek, for a distance of at least 100 m. Bulldozers apparently had been used to excavate the coarse bedload and rearrange the deposit to form a narrow channel in some places along one bank, but to leave much of the stream without any bedload deposit. Active down cutting by Indian Creek was observed at such abrupt changes in elevation, from downstream to upstream in a sequence of head cuts.

With increasing distance upstream from the mouth of Indian Creek, more and more chunks of degradable shale were observed on the bedload deposit in the creek, and shale bedrock was exposed more widely in the bed of the creek. The banks of the creek supported very few large trees, except at elevations significantly above the floodplain, on colluvial slopes. Small trees apparently eight to ten years old were the largest trees growing on the alluvial banks and surface of the floodplain near the creek. The degradation of the persistently wetted shale did not extend into the rock more than a millimeter. The surface of the shale below the water often was covered with fragments of shale and other rocks, but the wet shale surfaces were smooth and essentially intact. Where the shale had been exposed above the water surface and had dried, however, the exposed surface (bed or lower bank) had disintegrated into thin chips about 2 cm in diameter and about 3 mm thick. Each shale surface exposed to the atmosphere had become covered with a layer of chips. Slaking and shrinkage cracking appear to cause severe and rapid disintegration of this shale layer. If the gravel removal caused a relatively permanent lowering of the groundwater in the bedload filling the creek and in the alluvium of the floodplains, the consequent drying of the shale would cause disintegration of the exposed shale to elevations formerly protected by constant wetting.

With increasing distance upstream along Indian Creek, the bed of the creek had been incised deeper below floodplain level. Incision of the creek had occurred to the extent that recent floods had not inundated the floodplain, as indicated by debris and drift accumulation elevations.

Inside a large bend in the creek, a floodplain about 50 m wide had formed adjacent to the right descending bank. The stream in this reach had migrated laterally into contact with the left valley wall and the left descending bank was covered with colluvium. The floodplain had narrowed with distance upstream, and the stream had been incised about two meters below the level of the adjacent floodplain. In that reach, a number of trees had toppled across the creek, and large boulders of siltstone and cemented shale were present on the bed of the stream.

Immediately upstream from the location of the fallen trees, a small tributary (Dry Branch) entered Indian Creek on the right descending bank of the creek. Along the left bank of Dry Branch, a series of shales and thin siltstone strata formed a cliff nearly 6 m high. Whilst Lewis *et al.* (1973) mapped the junction of Dry Branch and Indian Creek at top of the Nancy Member, the reach of Dry Branch along the overhanging cliff appeared to be located in the bottom of the Halls Gap Member. The bed of Dry Branch was about 1 m higher than the bed of Indian Creek where an overhang had formed, and the descent from Dry Branch to Indian Creek involved a rapid plunge in the tributary. The shales in the bed of Dry Branch were degraded and had disintegrated.

Upstream along Indian Creek from the mouth of Dry Branch, a landslide area was noted on the right descending bank. Such landslides provide a major source of residual silty soil and rock fragments to be transported by Dry Branch and Indian Creek. At the slide area, Indian Creek was filled with large fragments of siltstone and cemented shale, as well as some chert fragments, nodules and geodes. The siltstone fragments were as large as 1 meter in dimension, while the chert and shale particles included sand-size pieces. The landslide was shallow and appeared to involve the surficial colluvium in an unstable layer only about 1 m thick. Upstream from the zone of large boulders, the bed of Indian Creek was formed by the relatively more resistance strata at the base of the Halls Gap Member.

In summary, gravel removal in Indian Creek just upstream from the junction with Buck Creek has exposed shale bedrock, which has disintegrated upon exposure to the atmosphere and consequent cycles of drying and wetting. The creek has cut down through the degrading shale, and groundwater levels have been lowered in the bedload in the creek channel and in the immediately adjacent floodplain areas. Headcuts have moved up Indian Creek to and upstream from the mouth of Dry Branch. Bank erosion is widespread in the downstream reaches of Indian Creek, trees have toppled into the creek along those reaches and, in some stretches, trees are missing from the creek banks. Whether trees were removed along those stretches or whether they fell into the creek as a result of creek widening and attendant bank scour, or whether the trees toppled as a result of agricultural activity in the adjacent fields, has not been determined. If agents other than stream action removed those trees, bank erosion may be due in part to destabilizing effects of tree removal. In the upstream reaches of Indian Creek, above the mouth of Dry Branch, the creek banks appear to be much more stable than in the downstream reach near Buck Creek, the creek has not incised its channel recently, and no evidence of recent and widespread stream widening was noted.

Appendix III. - Climate and hydrology of the Buck Creek catchment

III.1 INTRODUCTION

This short report summarizes the hydrologic study performed on the Buck Creek and Indian Creek watersheds in order to assess the water budget and develop stream flow discharge estimates for the streams in the region where gravel extraction activities occurred or continued. The discharge rates provide information for understanding the generation and transport of streambed materials. Additionally, the flow estimates can provide an indication of the flood flow frequency or return period for a range of flow magnitudes. This information provides a means of developing insights into the expected occurrence frequency of a given flow rate or discharge and is useful for understanding the natural potential for gravel sources to contribute to the streambed material.

This short report is organized into 2 main components. This first component presents a summary of the historical data records and hydrologic setting of the region. The second component focuses on the application of the data archive in a modeling setting and explains the development of the flow magnitudes and flood flow frequency curve for the Indian Creek watershed.

In summary, this short study used 12 years of observed discharge and concomitant precipitation data to develop estimates of the maximum discharge versus return period for Indian Creek. This information was estimated using a geomorphic-based area ratio method applied to the observed flow records from Buck Creek. The results indicate the maximum flow in Indian creek ranges from 5 m^3/s (175 cfs) to 15 m^3/s (530 cfs), for return periods of 0.5 to 15 years. The bank-full discharge is typically considered to be the 1.5 to 2 year return period flow and at Indian Creek this flow was found to be approximately 8 m^3/s (285 cfs) under the methods of this study.

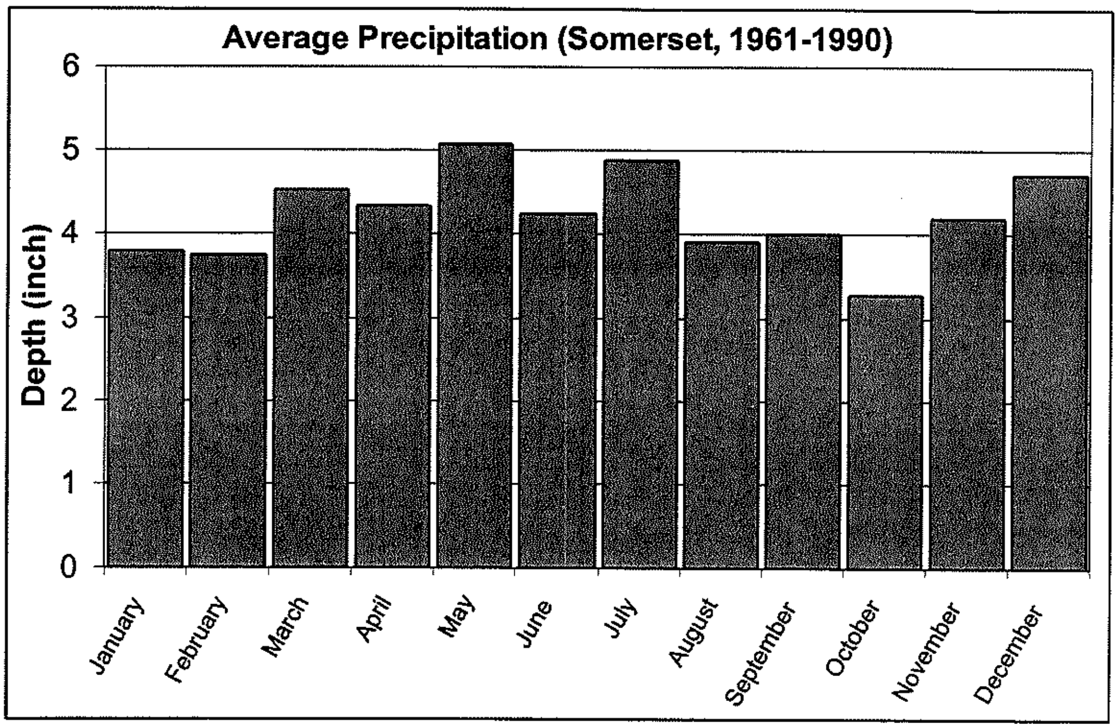
III.2 HYDROLOGIC AND GEOMORPHIC CHARACTERISTICS

The Indian Creek basin has an area of 5.641 mi^2 (14.44 km^2) and constitutes one tributary of the Buck Creek watershed (Buck Creek basin area=165 mi^2, 422.4 km^2). Indian creek is approximately 3.4% (5.642/165) of the total area of the Buck Creek watershed. The land-use and vegetation in the basin is primarily agriculture, meadow, and forest resting on an alluvial soil. The basin elevations range from 271m to 326m with a mean slope of about 10% (10m/100m).

III.3 PRECIPITATION AND CLIMATE

The precipitation in the region is characterized by frontal systems in winter season and summer precipitation generally results from convective storm activity. The regional climatic precipitation records indicate a bimodal form with the two peaks occurring respectively in May and December. For example, the climatic precipitation records from the Somerset, Kentucky observation station is shown in Figure 1 (MCC 1999). The annual average rainfall for the climate period 1961-1990 was 50.73 inches.

Figure III.3.1 - Average Monthly Precipitation at Somerset, Kentucky for 1961-1990.



Discharge and Precipitation Records

A relatively long record of rainfall and flow measurements exists for Buck creek, on the other hand, Indian creek is an ungaged basin and no flow records exist for this smaller watershed. The data used in this study includes 42 years of flow observation for Buck Creek (1953-1995), and 12 years of concomitant rainfall observations for 3 stations - Somerset, Waynes and Crab Orchard.

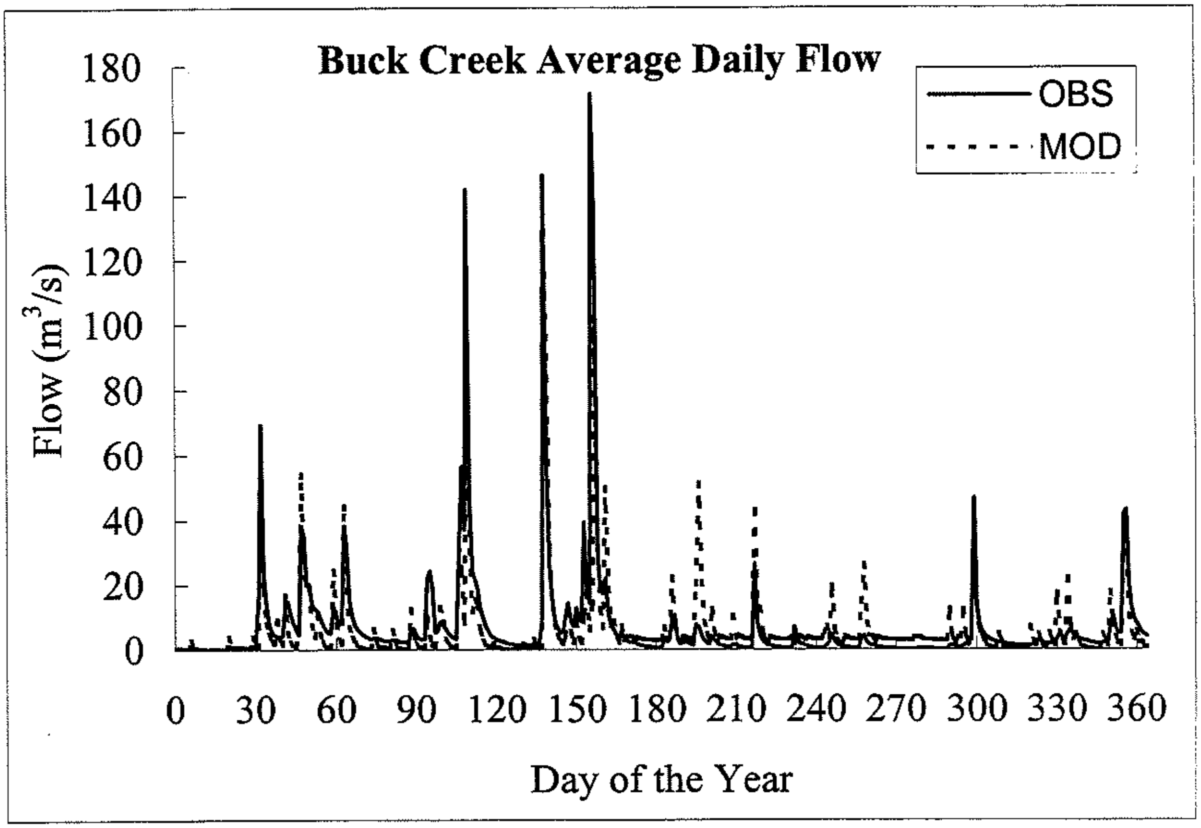
Discharge Estimation Modeling

For this study, it is desirable to have an estimate of the historical hydrologic flow regime in Indian Creek. Since there are no flow records for the Indian creek basin, and considering the similar hydro-geomorphic climate and physiographic characteristics of the Buck Creek and Indian Creek basins, the flow in Indian creek was estimated using two approaches. First, an area ratio method was used to scale the observed discharge record from Buck Creek to Indian Creek; second, a form of a hydrologic model (the Sacramento model) was implemented. The areal extent ratio approach accounts primarily for differences in basin size; the hydrologic model incorporates some level of watershed hydrologic dynamics as well as accounting for basin areal extent. In each case, the rainfall observation record from Somerset (the nearest rain gage) over a period of 16 years was used.

Initially, the hydrologic model is calibrated to the flow records of Buck creek discharge using the 12 years of observed discharge and concomitant precipitation data. Figure III.3.2 shows an example, for a selected year of the record, of the flow estimate from the calibrated model (labeled MOD, dashed line) compared with the observed flow (labeled OBS, solid line) for Buck creek. In general, the model reproduces the basin behavior well.

Considering the two approaches for flow estimation, Figure 3 compares the maximum annual flow estimated using the area ratio (dashed line) with the flow estimated from the hydrologic model (solid line). The maximum annual flow estimate is larger at low and high magnitudes based on the hydrologic model. In the mid-range of flow magnitude, the area ratio approach indicates higher flow magnitudes. In either case, both estimates indicate discharge of the same order of magnitude and are useful indicators of the hydrologic climate of the stream. In summary, for the Indian Creek basin, the area ratio provides an adequate estimate of the flow for indicator of the maximum flow. As a complementary approach, the hydrologic model provides an improved representation of the basin response to a particular rainfall event, and for long-term discharge variability.

Figure III.3.2 - Buck Creek average daily flow: model estimate and observed flow.

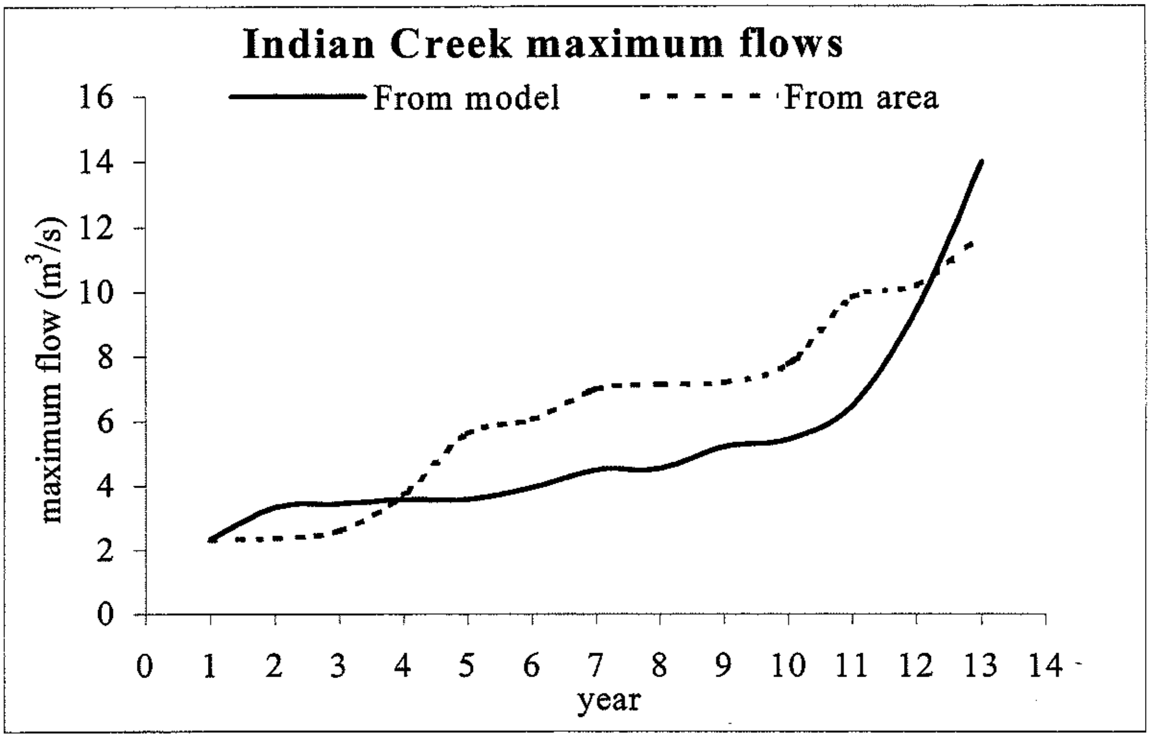


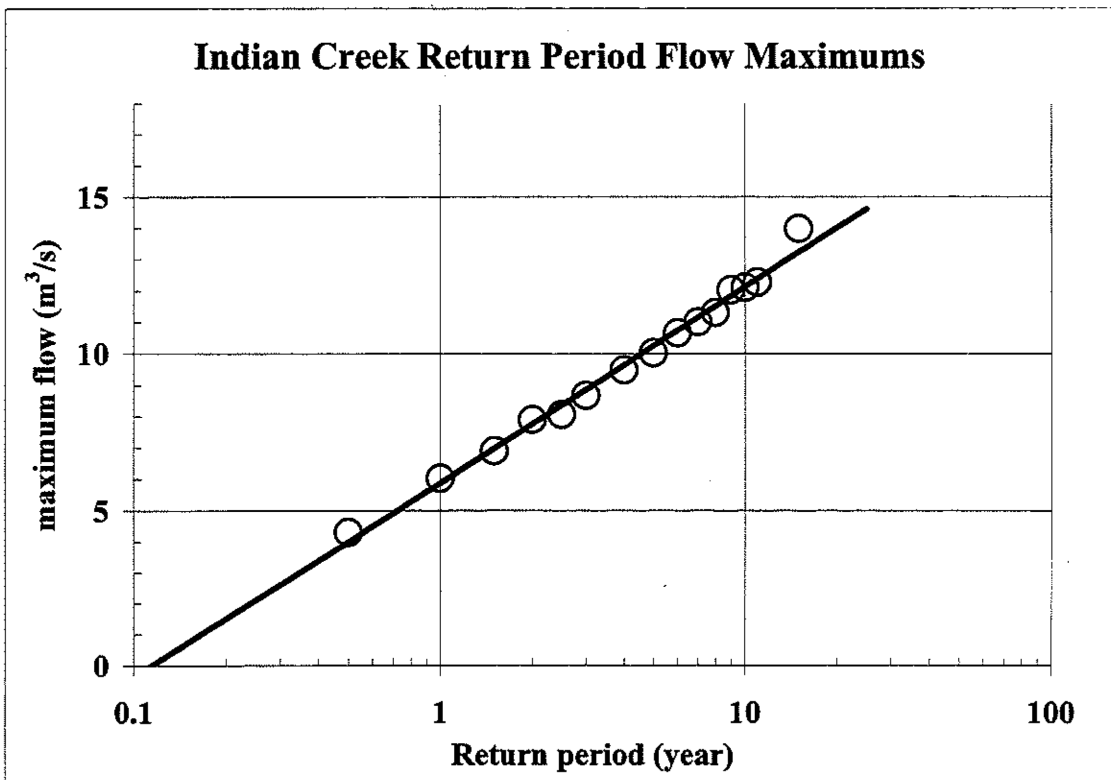
Finally, Figure 4 shows the maximum discharge versus return period for Indian Creek. This information was estimated using an areal extent ratio applied to the observed flow records from Buck Creek. The results indicate the maximum flow in Indian creek ranges from 5 m^3/s (175 cfs) to 15 m^3/s (530 cfs), for return periods of 0.5 to 15 years respectively. The bank-full flow, typically associated with the 1.5 to 2 year return period event, has a magnitude of approximately 8 m^3/s (285 cfs) under the methods of this study.

III.4 FUTURE STUDIES

Results presented here provide a foundation and framework for summarizing and defining the hydrologic climate of the Buck Creek and Indian Creek basins. These results are a preliminary analysis and additional study is required asses the uncertainty associated with the flow estimates. Later efforts could be directed to estimate components of the hydrologic system response during low flow in Indian Creek, and investigation of the hydrologic flow regime in the Brushy creek and Clifty creek watersheds.

Figure III.3.3 - Indian Creek maximum flow estimation from model and area ratio.





Indian Creek Return Period Flow Maximums
maximum flow (m3/s)
15
10
5
0
0.1
1
10
100
Return period (year)

Appendix IV. Detailed topographic maps

The following plates include topographic maps with 0.5 foot contours:

Sheet II.1.1	INDIAN CREEK	Southern reaches, Sections 1 – 3.
Sheet II.1.2	INDIAN CREEK	Section 3; intersection of small tributary
Sheet II.1.3	INDIAN CREEK	Sections 3-4
Sheet II.1.4	INDIAN CREEK	Section 4
Sheet II.2.1	CLIFTY CREEK	Large sidebar and Low radius bend
Sheet II.2.2	CLIFTY CREEK	Flow under Hazeldell Elrod Road
Sheet II.2.3	CLIFTY CREEK	Southernmost reach
Sheet II.3.1	BRIARY CREEK	Southernmost reach and 1976 channel
Sheet II.3.1	BRIARY CREEK	Northernmost reach and 1952 channel
Sheet II.4	GILMORE CREEK	

Appendix IV

Gravel Mine Comprehensive Species List: May 1998				
Organisms found only in composite samples are denoted with an x.				
	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Species				
Insecta				
Ephemeroptera				
Baetidae				
Baetis sp.	7	57	22	14
Acentrella sp.	x	35	3	151
Heptageniidae				
Stenonema femoratum	2	21	7	8
Leucrocuta sp.	1	1	2	41
Stenacron sp.				1
Rhitrogena uhari		1		3
Heptagenia sp.	1			
Isonychidae				
Isonychia sp.		13	3	4
Leptophlebiidae				
Haprophlebiodes sp.		1	x	3
Ephemerellidae				
Attenella attenuata		x		5
Ephemerella sp.				2
Caenidae				
Caenis sp.	x	x	10	
Ephemeridae				
Ephemera sp.	1			
Plecoptera				
Perlidae				
Perlesta sp.	2	72	16	112
Acroneuria sp.#1				1
Acroneuria sp.#2	2	26		139
Nemouridae				
Amphinemura delosa	2	2	1	26
Perlodidae				
Isoperla sp.		9	1	5
Leuctridae				

	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Leuctra sp.		x		66
Chloroperlidae				
Allopera sp.				14
Trichoptera				
Philopotamidae				
Wormaldia sp.	2	61	1	24
Dolophilodes sp.	3	1		
Chimarra sp.				4
Hydropsychidae				
Cheumatopsyche sp.	2	2	1	10
Glossosotomatidae				
Agapetus sp.				3
Limnephilidae				
Pycnopsyche sp.		x		
Polycentropodidae				
Polycentropus sp.			3	3
Hydroptilidae				
Ochrotrichia sp.				1
Diptera				
Chironomidae				
Orthocladiinae	7	6	12	28
Chironomini	22	52	28	24
Tanypodinae	27	7	46	35
Tanytarsini				1
Tipulidae				
Tipula sp.	x	1	2	1
Pilaria sp.	x	x		
Hexatoma sp.				1
Simulidae				
Simulium sp.	1	1	3	2
Empididae				
Hemerodromia sp.	3			
Stratiomyidae				
Stratiomys sp.		1		
Muscidae			1	
Coleoptera				
Elmidae				
Stenelmis crenata	5	5	2	19
Dubiraphia sp.				3
Psephinidae				
Psephenus herriki	1	6	3	10

	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Lioporous sp.	x			
Dryopidae				
Helichus sp.	x			
Staphylinidae				
Micralymma sp.			x	
Hydrophilidae			1	
Megaloptera				
Corydalidae				
Corydalus comutus		1	1	1
Nigronia serricornis	x	x		2
Odonata				
Coenagrionidae				
Argia sp.		1		
Gomphidae				
Stylogomphus sp.		1		9
Calopterygidae				
Calopteryx sp.	x		1	
Aeshidae				
Boyeria vinosa			x	
Hemiptera				
Veliidae				
Microvelia sp.		x		
Lepidoptera				
Pyralidae		1		
Crustaceans				
Isopoda				
Asellidae				
Lirceus sp.	5	2	5	
Amphipoda				
Gammaridae				
Gammarus sp.		1		
Gastropoda	x	x		7
Oligochaete	1	1	1	14

Gravel Mine Comprehensive Species List: May 1999				
Organisms found only in composite samples are denoted with an x.				
	Indian Creek	Clifty Creek		
Species				
Insecta				
Ephemeroptera				
Baetidae				
Baetis sp.	3	29		
Acentrella sp.		28		
Heptageniidae				
Stenonema femoratum	2	15		
Leucrocuta sp.	11	103		
Stenacron sp.		5		
Isonychidae				
Isonychia sp.	1	3		
Leptophlebiidae				
Haprophlebiodes sp.	5	4		
Ephemerellidae				
Attenella attenuata		6		
Caenidae				
Caenis sp.	3	4		
Ephemeridae				
Ephemera sp.	1			
Plecoptera				
Perlidae				
Perlesta sp.	1	359		
Acroneuria sp.#1	3	149		
Acroneuria sp.#2		4		
Nemouridae				
Amphinemura delosa	12	111		
Perlodidae				
Isoperla sp.	5	6		
Leuctridae				
Leuctra sp.	2			
Chloroperlidae				
Allopera sp.		3		

	Indian Creek	Clifty Creek		
Trichoptera				
Philopotamidae				
Wormaldia sp.		520		
Hydropsychidae				
Cheumatopsyche sp.	2	2		
Limnephilidae				
Pycnopsyche sp.	1			
Polycentropodidae				
Polycentropus sp.	1	3		
Diptera				
Chironomidae				
Orthocladiinae		51		
Chironomini	25	57		
Tanypodinae	8	11		
Tipulidae				
Tipula sp.	1			
Pilaria sp.	1	1		
Hexatoma sp.				
Simulidae				
Simulium sp.	1	2		
Stratiomyidae				
Stratiomys sp.	1			
Muscidae		1		
Coleoptera				
Elmidae				
Stenelmis crenata		28		
Dubiraphia sp.	1			
Psephinidae				
Psephenus herriki	5	15		
Dytiscidae				
Hydroporinae	1			
Dryopidae				
Helichus sp.		x		
Staphylinidae				
Micralymma sp.	2	x		
Bledius sp.	x			
Stenus sp.		x		
Hydrophilidae				
Cymbiodyta sp.	1	x		
Scirtidae		x		

	Indian Creek	Clifty Creek		
Megaloptera				
Corydalidae				
Corydalus cornutus		3		
Nigronia serricornis	1	3		
Odonata				
Coenagrionidae				
Argia sp.	1			
Aeshidae				
Boyeria vinosa		x		
Hemiptera				
Veliidae				
Microvelia sp.		1		
Hebridae	1			
Crustaceans				
Isopoda				
Ceacadotia				
Lirceus sp.		2		
Amphipoda				
Gammaridae				
Gammarus sp.		1		
Gastropoda	2	3		
Oligochaete	4	1		

Gravel Mine Comprehensive Species List: June 1999				
Organisms found only in composite samples are denoted with an x.				
	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Species				
Insecta				
Ephemeroptera				
Baetidae				
Baetis sp.	320	102	98	3
Acentrella sp.	4	1	x	
Ameletidae				
Ameletus sp.	1	8		
Heptageniidae				
Stenonema femoratum	30	112	31	610
Stenonema vicarium		2		
Leucrocuta sp.	x	65	6	11
Stenacron sp.	x			1
Isonychidae				
Isonychia sp.	17	60	8	1104
Leptophlebiidae				
Haprophlebiodes sp.		1	5	8
Choroterpes sp.			10	1
Ephemerellidae				
Ephemerella sp.				1
Caenidae				
Caenis sp.	5	20	12	100
Ephemeridae				
Ephemera sp.	1	x		
Plecoptera				
Perlidae				
Perlesta sp.	6	109		335
Acroneuria sp.*1*	2	45		
Neoperla sp.		114	3	179
Eccoptura sp.				70
Agnetina capitata				2
Nemouridae				
Amphinemura delosa		1		2

	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Leuctridae				
Leuctra sp.		3	4	84
Chloroperlidae				
Allopera sp.		2		2
Trichoptera				
Philopotamidae				
Chimarra sp.	9	24	1	23
Hydropsychidae				
Cheumatopsyche sp.	55	77	26	109
Ceratopsyche sp.	6	4		
Polycentropodidae				
Polycentropus sp.				5
Diptera				
Chironomidae				
Orthocladiinae				28
Chironomini	67	65	49	41
Tanypodinae	387	352	211	358
Tipulidae				
Tipula sp.		x		4
Pilaria sp.				4
Hexatoma sp.	x		1	1
Simulidae				
Simulium sp.	87	5	17	
Empididae				
Hemerodromia sp.	10	24	3	
Muscidae				
Limnophera sp.	1			
Anthericidae				
Antherix sp.		3		
Dolichopodidae	x			
Culicidae				
Anopheles sp.	x		x	
Ceratopogonidae				
Bezzia Palpomyia spp. group		5	1	1
Dixidae				
Dixa sp.		x		
Tabanidae				
Tabanus sp.				1
Optioservus trivitattus			3	7

	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Coleoptera				
Elmidae				
Stenelmis crenata		101	13	66
Macronychus glabrattus	2			9
Psephinidae				
Psephenus herriki	9	48	2	13
Dytiscidae				
Lioporous sp.		x		
Dryopidae				
Helichus sp.		2		4
Staphylinidae				
Micralymma sp.		1		
Hydrophilidae				
Paracymus sp.		x		
Tropisternus sp.			1	1
Enochrus sp.	1		2	
Curculionidae		1		
Gyrinidae				
Dineutus sp.	21	1		
Megaloptera				
Corydalidae				
Corydalus cornutus	1	2		1
Nigronia serricomis	1	1	1	13
Sialidae				
Sialis sp.		12		7
Odonata				
Coenagrionidae				
Argia sp.		x	1	1
Gomphidae				
Stylogomphus albistylus		11	1	
Gomphus sp.			3	16
Aeshidae				
Boyeria vinosa				x
Hemiptera				
Veliidae				
Microvelia sp.	2	29		1
Gerridae	x			
Corixidae	x	1		
Ochteridae				
Ochterus sp.				x
Asellidae				
Lirceus sp.	1	3	2	

	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Crustaceans				
Isopoda				
Amphipoda				
Gammaridae				
Gammarus sp.				4
Gastropoda	x	1		20
Oligochaete	1	2		

Gravel Mine Comprehensive Species List: April 2000				
Organisms found only in composite samples are denoted with an x.				
	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Species				
Insecta				
Ephemeroptera				
Baetidae				
Baetis sp.	16	2	22	2
Acentrella sp.	69	204	95	141
Plauditus sp.	14	152	158	13
Ameletidae				
Ameletus sp.	13	1	19	x
Heptageniidae				
Stenonema femoratum	79	114	171	202
Rhitrogena uhari		40		54
Leptophlebiidae				
Paraleptophlebia sp.	1	7		25
Leptophlebia sp.			x	
Ephemerellidae				
Eurylophella sp.	1		3	46
Ephemerella sp.*#1*	3	29	9	15
Ephemerella sp.*#2*			1	
Caenidae				
Caenis sp.	62	15	10	
Ephemeridae				
Ephemera sp.	1			
Plecoptera				
Perlidae				
Perlesta sp.	23	143	93	2
Acroneuria frisoni		1		
Perlinella sp.			1	
Neoperla sp.	1			
Nemouridae				
Amphinemura delosa	158	739	563	504
Prostoia sp.				2

	Indian Creek	Clifty Creek	Briary Creek	Gilmore Creek
Perlodidae				
Isoperla nana (nr)	26	255	506	371
Isoperla namata			1	28
Isoperla burksi				1
Clioperla clio			6	8
Leuctridae				
Leuctra sp.			1	7
Chloroperlidae				
Sweltsa sp.	2			
Trichoptera				
Philopotamidae				
Wormaldia sp.	10	1165	274	1960
Hydropsychidae				
Cheumatopsyche sp.	1		1	
Glossosotomatidae				
Agapetus sp.		2		362
Limnephilidae				
Ironoquia sp.	x	x	x	x
Rhyacophilidae				
Rhyacophila lobifer	13	18	14	134
Diptera				
Chironomidae				
Orthocladiinae	118	17	18	25
Chironomini	381	188	103	82
Tanypodinae	94	9	12	2
Tanytarsini	64	9	4	3
Tipulidae				
Tipula sp.	19	2	2	1
Pilaria sp.	3			
Tabanidae				
Tabanus sp.			1	
Simulidae				
Simulium vittatum	317	11	96	23
Prosimulium sp.				x
Empididae				
Hemerodromia sp.	48	51		
Ephydridae		1		
Tanyderidae				
Protoplasa fitchii			2	