

# HISTORICAL SEDIMENTATION AND SEDIMENT TRANSPORT CHARACTERISTICS OF SILVER CREEK, IDAHO, USA

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## Executive Summary

Silver Creek, Idaho, USA, represents a unique, high desert cold stream ecosystem supporting an abundance of fish, birds and wildlife. It is regarded as one of the United States premier fly-fishing locations. The Silver Creek Preserve is managed by the Nature Conservancy. Excess sedimentation within the channel has been identified as problem for the ecology and recreation use of the creek. Extreme sediment deposition has the potential to clog spawning grounds in gravel streams, modify stream temperatures by reducing light transmission, and in high levels, be directly lethal to fish. The aims of this project were therefore to determine the sources of sediment; to examine changes since the arrival of Europeans; determine current sediment transport conditions and assess potential remediation methods.

The initial approach was to calculate a sediment budget, quantifying the inputs, outputs and storage of sediment. Data required for these components was insufficient and the budget could not be quantified. The previous conditions in the catchment and channel were assessed by a review of historical information, including documents, photographs and aerial photographs. The information indicated that there had been intense removal and destruction of native vegetation coinciding with the introduction of agriculture in the 1880s. The increased runoff from removed vegetation and flood irrigation is likely to have caused the increased sediment supply to the channel. Construction of a dam around 100 years ago also has contributed to excess sedimentation by restricting the flow of water and sediment. Increased vegetation density in the channel from nutrient runoff is also significant in promoting deposition. A comparison of aerial photographs from the 1950s and 2000s demonstrated the channel may have attained a stable form by the 1950s.

The sediment transport characteristics and stability of the creek were examined to determine whether excessive sediment deposition is currently occurring in the creek. Transport capacity was assessed using the Rouse Equation, a comparison of sediment transport and settling characteristics. Cross-sections were measured at 14 sites in Silver Creek to calculate shear velocity. Fall velocity was calculated for a range of particle sizes as the sediment size could not be measured. Results from these calculations indicated that smaller particles sizes, particularly silts, are carried in suspension in the water column, and are likely to be transported out of the system. Coarser material is not carried in suspension and is deposited. Additional deposition of sediment within the creek is unlikely if predominantly fine sediment enters the system. Further research is required to determine if this occurs. Channel stability was assessed using a comparison of effective discharge to bankfull discharge. Lack of data availability prevented any results being established.

Dredging and dam removal were considered for remediation of the sediment problem in Silver Creek. Dredging provides an immediate solution although at a considerable financial expense. The feasibility of dredging is based on how long it will take for the dredged area to refill. This can be determined using trap efficiency curves. Dam removal allows the channel to adjust to a natural morphology and is beneficial for the river ecology. For Kilpatrick Pond, the further research is required to determine the effectiveness of dam removal the irrigation diversion has altered the hydrodynamics. Removing the backwater behind the dam would have a negative effect on the recreational use. Further research is required to determine the impacts of these remediation methods.

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## **Chapter 1: Introduction**

### **1.1 Project Aims**

A severe sediment problem has developed in Idaho's Silver Creek since the arrival of Europeans. Excess sediment in the creek has altered the stream ecology by clogging the gravel bed, reducing water depths and modifying temperature distribution in the water column. These modifications threaten the fish population in this world renowned fly fishing stream. Previous research has acknowledged these sediment problems; however, no comprehensive study has been conducted into the source, and contributing factors to sediment deposition. In the context of this previous research, the aims of this project were to investigate the causes of excess sedimentation in Silver Creek; determine the channel stability and transport characteristics; and consider possible remediation techniques. The following steps were undertaken to complete these aims:

- Construct a sediment budget, quantifying sediment input, output and storage
- Document historical changes to the catchment since the arrival of Europeans
- Determine modifications to the channel
- Identify the source of sediment within the catchment
- Assess whether the channel is continuing to deposit sediment
- Develop an understanding of the stability of the channel
- Examine remediation techniques

In order to achieve these objectives, a review of the historical information and field investigations were conducted. The project began with a literature review of erosion, transport and deposition of sediment processes, environmental controls and effects of excessive sediment. In January, a review of the previous studies on Silver Creek and collection of data for the sediment budget commenced. This information was assembled and analyzed to ascertain the historical changes. Further analysis was then conducted using GIS to determine changes to the channel. In May, a field investigation was undertaken to investigate the sediment transport characteristics. This dissertation represents the culmination of the research; documenting changes in the Silver Creek catchment and channel, characterizing the transport characteristics, discussing remediation options and identifying areas for further research.

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## **1.2 Project Location and Background**

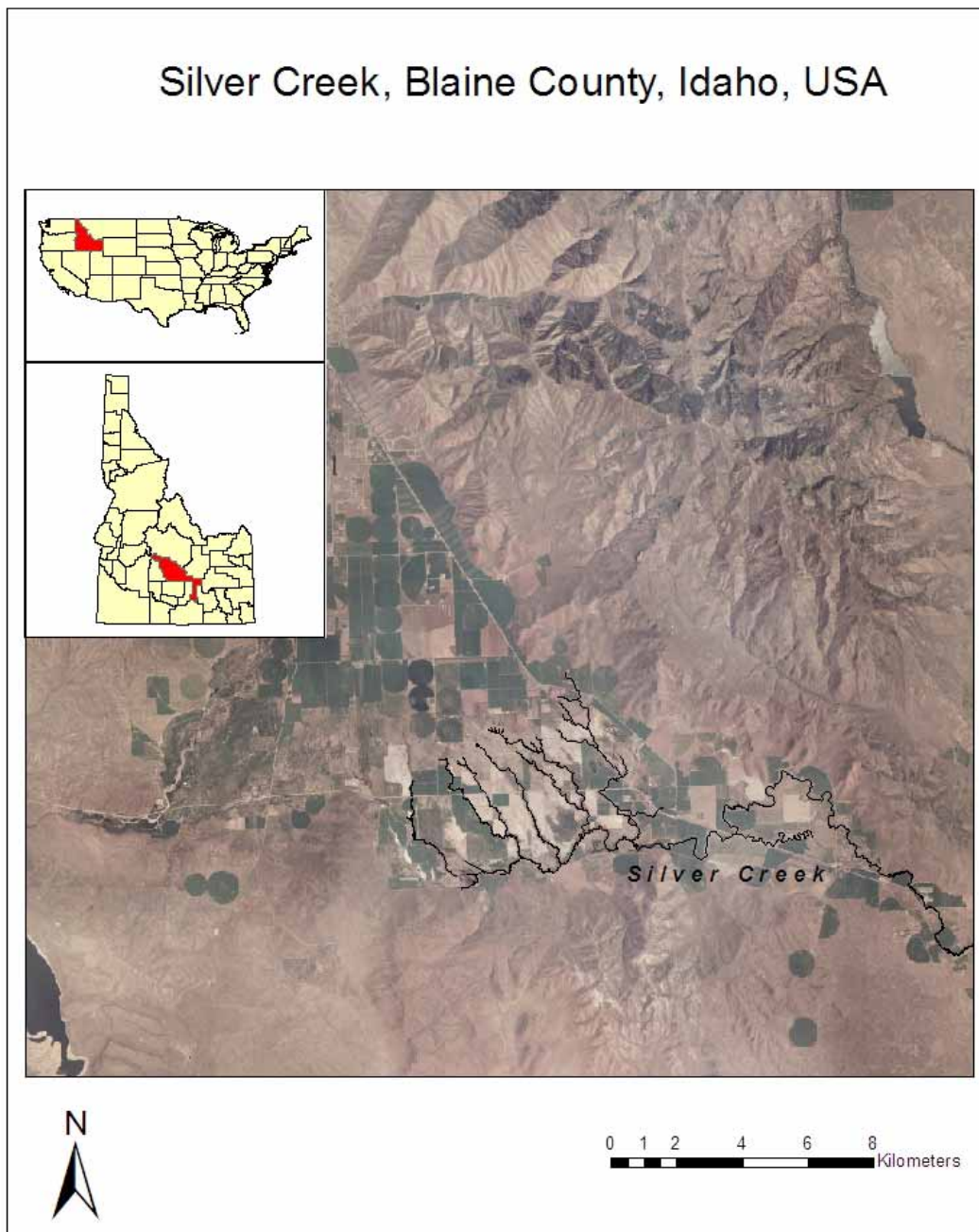
Silver Creek is located in Blaine County in Central Idaho, approximately 30 miles south of Sun Valley, and 4 miles west of Picabo (Figure 1-1). This area is in the lower Wood River Valley, a region surrounded by the Pioneer and Smokey Mountains and the Picabo Hills (Brockway & Kahlow 1994; The Nature Conservancy 2003). Silver Creek represents a unique example of a high desert cold spring ecosystem that supports an abundance of fish, birds and wildlife (Schweibert 1977; Todd 1997; The Nature Conservancy 2005). Owing to its clear waters and wealth of trout, the creek has been regarded as one of the finest fly fishing streams in the United States for the past 90 years (Hauck 1947; The Nature Conservancy 1975). Silver Creek also contributes significantly to the local economy, as around 10 000 visitors each year use the creek for hiking, bird watching and canoeing (Norman 1998; The Nature Conservancy 2005).

In 1976, The Nature Conservancy purchased 479 acres surrounding Silver Creek and established a preserve. Since the initial purchase, a further 403 acres have been added and along with working with local landowners, around 9500 acres are now protected (The Nature Conservancy 2005). The long term aim of this preserve is to maintain and enhance Silver Creek's aquatic and riparian systems by preserving water quality and quantity, restoring and preserving natural habitats and rare species, and increasing the extent of protected land (Todd 1997). Since the preserve was established, The Nature Conservancy has based management decisions on scientific research and they have commissioned many studies to further the understanding of the creek and its ecosystem (The Nature Conservancy 1975). This dissertation will contribute to more effective management of the preserve by investigating the sediment regime within the watershed. As such, funding for this project has been provided by The Nature Conservancy's Idaho Chapter. Further funding and technical support has also been provided by the University of Idaho's Centre for Ecohydraulics Research.

## **1.3 Previous Work**

There have been numerous scientific studies aimed at increasing the understanding of the hydrology of Silver Creek. The first detailed investigation of the water resources of the Big Wood River system was conducted by Rex O. Smith in (1954), and this was followed by an evaluation of the streamflow records by Smith (1960). Castelin and Chapman (1972) constructed a water budget for the Silver Creek area and examined the relationship between the surface and ground water. It was determined at that time, that development within the area was not having a

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**Figure 1-1 Silver Creek Location**

Silver Creek is located in Blaine County in central Idaho (lower inset). Idaho is in the North Western United States (upper inset). Silver Creek drains to the south east of the Wood River Valley.

impact on the water resources. A more detailed investigation by Brockway and Kahlow (1994) modeled the Big Wood River – Silver Creek aquifer and estimated the contribution of discharge in the Big Wood River to the Silver Creek system. More recently, Brown (2001) investigated the creek's sources and attempted to distinguish between natural (precipitation, river seepage) and human activities (irrigation and diversions), although a clear pattern could not be determined.

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Despite several studies into the hydrology of the watershed, there have been few studies into understanding the role of sediment and the impact of land use change within the watershed. The only detailed investigation of sediment in Silver Creek was the work of Manuel et al. (1979). Based on field measurements and monitoring the creek over a 14 month period, the contribution of sediment from Loving, Grove and Stalker creeks was established. However, the major sources of sediment load were not identified and long term trends in the sediment regime could not be determined because of a lack of quantitative data. Since this report, there have been some studies into the sediment load although these have been limited to small reaches of the creek and have focused on evaluating the success of dredging (The Nature Conservancy 2003). In the past 20 years, there has been an increased acknowledgement of sedimentation problems in Silver Creek and despite remediation efforts by The Nature Conservancy, there has not been an overall assessment of sediment load since Manuel et al. (1979).

#### ***1.4 Dissertation Organization***

The initial approach, to facilitate the aims of this project, is to review literature based on the previous descriptions of the problem. This literature is incorporated with a review of historical material, field investigations, GIS analysis and other calculation to describe the historical changes to the catchment and characterize the sediment transport capacity of the creek. The historical changes and transport characteristics are then considered in a review of potential remediation options.

Following the introductory chapter, the theory of sediment transport in rivers, environmental controls of sediment supply and impacts from human modification are outlined in Chapter 2. The review of the key concepts provides a theoretical context for the current investigation. Chapter 3 established the environmental setting for Silver Creek with emphasis on the environmental controls of sediment supply. A review of the data available for constructing a sediment budget and the historical information, detailing changes that have occurred to the catchment and channel, are presented in Chapter 4. The sediment transport characteristics and channel stability are examined in Chapter 5, using results and calculations from field investigations. Using the previous two chapters as a basis, the remediation options; dredging and dam removal, are discussed. Finally, Chapter 8 summaries the findings of this study and areas for further investigation are presented.

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## Chapter 2: Theoretical Context

Water flowing across the Earth's surface is a potent force that has significantly altered the landscape. As water flows it exerts considerable forces that erode the landscape and transport material towards drainage networks. Rivers, therefore, not only play a role in the global water cycle, by connecting oceans with excess precipitation falling on the land, but also by removing sediment from the landscape. On average, rivers worldwide transport around 19 000 million tones of sediment annually (Knighton 1998). The ability to transport sediment depends on the characteristics of the flow, with rivers carrying as much sediment as the energy of the flow permits (Edwards & Glysson 1999). When the system is energy limited, rivers will deposit sediment, and erode sediment when there is excess energy. The processes of transport and deposition of sediment consequently also governs the morphology of the channel (Church 2006). Therefore, by altering the hydrology and sediment regime of a catchment there can be significant impacts on the character and behavior of the river and on the fluvial ecosystem (Knighton 1998). Understanding the movement and controls of sediment is increasingly important for management of watersheds as they are increasingly disturbed by human activity.

### **2.1 Sediment and Rivers**

Sediment is fragmented material that is transported and deposited by water and air and ranges in size and shape (Edwards & Glysson 1999). Particles vary from large boulders to small clay particles, and from rounded to angular shaped (Edwards & Glysson 1999). The processes of sediment transport are interconnected with the stream morphology.

#### **2.1.1 Sediment Transport**

The sediment load within a stream can be divided into three components: dissolved load, wash load and bed load material, and all have distinct transport processes. The dissolved load, material that is carried in solution, is dependent on the surrounding environmental supply conditions rather than flow characteristics, and is estimated to constitute 20% of the sediment carried by rivers worldwide (Knighton 1998). The wash load is material sourced from erosion of cohesive river banks and surface erosion in the catchment and usually less than 0.062mm (Knighton 1998). Sediment in the wash load is transported in suspension by turbulent eddies in the flow and generally moves at the same rate as the flow (Edwards & Glysson 1999). The discharge of suspended sediment is dependent on supply of sediment, flow characteristics and fall velocities of

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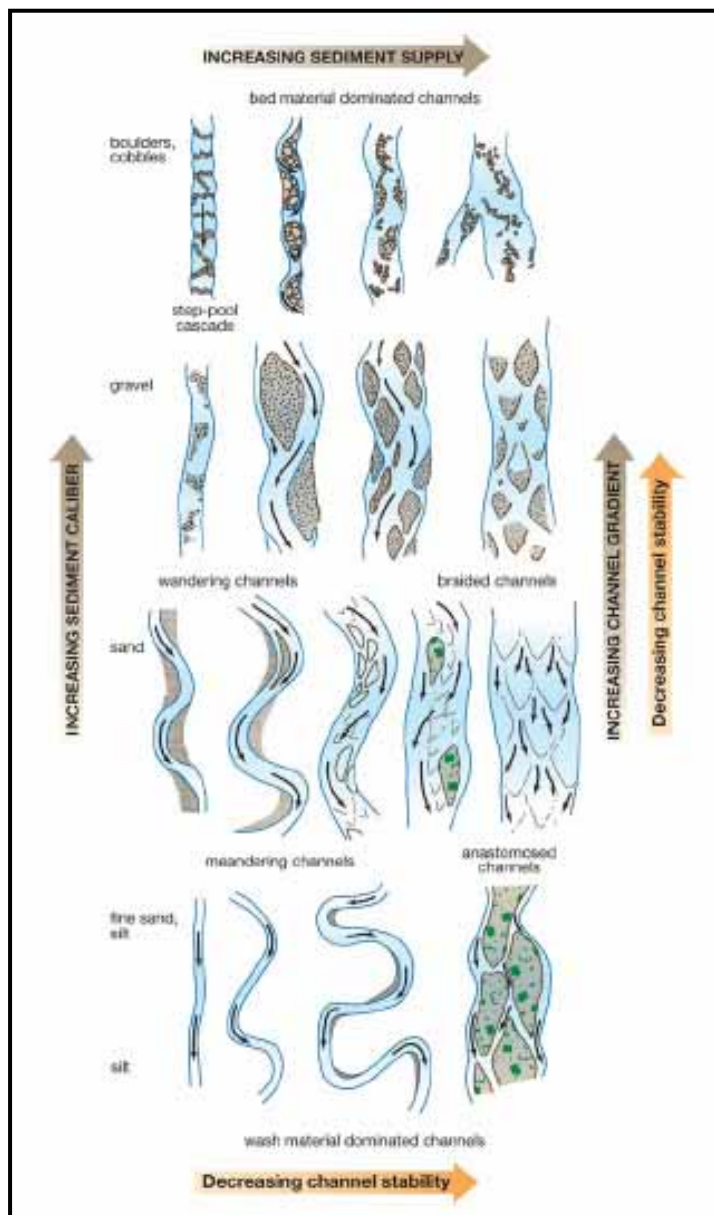
particles (Colby 1963; Knighton 1998). The bed load, which consists of material greater than 0.063mm, is dependent predominantly on the transport capacity of the flow (Knighton 1998). This material is transported when the entrainment shear stress at the bed is exceeded, and sediment is then transported by either rolling, sliding or saltation. There is also a distinction between gravel streams, where particles move individually, and in sand bed streams, where sediment moves in sheets, as migrating bed forms (Knighton 1998).

### **2.1.2 Channel Morphology**

The erosion, transport and deposition of sediment within the channel determines the morphology of an alluvial river (Richter et al. 1997). The variability of channel form and the role of sediment have been demonstrated by several classification schemes. Schumm (1963) developed classified streams based on dominant sediment transport process and identified channel characteristics associated with each. This classification was later expanded to demonstrate the channel pattern that would be expected for a given sediment load, flow velocity and stream power (Schumm 1985). More recently, Church (2006) expanded this work by using the Shield's number as the basis of the transport regime, and this classification is presented in Figure 2-1.

This classification system demonstrates the divergence between channels that transport fine, suspended sediments and those that transport coarser, bed load material. Streams that transport fine sediment exhibit a single, meandering channel, whilst those dominated by bed load, feature step-pool and braided characteristics. The physical processes of sedimentation can explain these channel forms. Firstly, bed load transportation leads to accumulation in the channel, which the stream must flow around, causing wide, shallow morphologies (Church 2006). When the dominant process is suspension of fine sediments, deposition occurs in slack water on bars and the flood plain leading to a narrow and deep morphology (Schumm 1985; Church 2006). These finer sediments also are more cohesive giving strength to stream banks, and encourage vegetation growth (Schumm 1985). Whilst these extreme cases have been observed in the field, there is still uncertainty in the transitional streams where transportation of bed and suspended material occurs in combination, and in these cases, a greater physical foundation is required (Church 2006). It is apparent though that the morphology of a channel reflects the geomorphic processes. This is beneficial as stream morphology can provide information on sediment transport processes which are difficult to observe in the field (Church 2006).

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**Figure 2-1 Alluvial Channel Form and Sediment Supply (Church 2006)**

The classification system demonstrates that with decreasing sediment size, rivers feature a single meandering channel. The quantity of sediment supply and channel slope also influences the morphology.

## **2.2 Environmental Controls**

It is becoming increasingly common to assess rivers from a landscape perspective because of the connection between the channel and the surrounding environment (Allan 2004). The movement of sediment within the drainage basin to rivers is controlled by the environmental characteristics, particularly climate, topography and geology, which govern the geomorphic processes. These controls ultimately determine the morphology of the rivers.

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### **2.2.1 Topography**

The erosion and transport of sediment is influenced by the topography of the catchment, particularly the slope characteristics. Schumm (1967) investigated the statistical relationship between rock creep and environmental factors and determined that rock creep was directly proportional to the sine of the slope angle, or the component of gravitational force acting parallel to the hillslope. Therefore, with steeper relief in a basin, there is greater energy in the system, and more potential for erosion and transportation (Montgomery & Brandon 2002; Chakrapani 2005). In a study of 280 globally distributed catchments, Millman and Syviltski (1992) established that mountainous streams had a greater sediment load than in low relief catchments. This has also been described by Ahnert (1970) who found a linear relationship between the erosion rates and relief in mid-latitude basins. However, Montgomery and Brandon (2002) demonstrated that this relationship does not hold for tectonically active, high relief catchments, where Ahnert's relationship only gives estimates of the lower limits of erosion.

### **2.2.2 Geology**

Geology is a significant control of the sediment regime of a catchment, as the bedrock lithology affects the size and quantity of sediment that can be eroded and transported (Knighton 1998). Over long time scales, various bedrock materials respond differently to chemical and physical weathering, generating different types of sediment, that all respond uniquely to erosional processes. Principally, the geology influences erosion of sediment through the rock strength properties (Safran et al. 2005). Useful examples of the role of geology are the highly dissected landscapes, which feature severe erosion and large sediment yields, known as Badlands. Although favorable environmental conditions are required for these landscapes to develop, it is principally the presence of easily erodible material that controls their formation (Campbell 1989; Salins 1998; Bouma & Imeson 2000). The clay mineralogy of badland materials, particularly smectite and montmorillonite clays, is susceptible to swelling and dispersion, allowing for significant erosion (Imeson et al. 1982; Gallart et al. 2002).

### **2.2.3 Climate**

Climate is central to the movement of sediment in the catchment because it delivers energy through precipitation, influences the vegetation, and over long time scales, affects the sediment characteristics (Knighton 1998). Flow within the river channel must overcome frictional forces, both from the channel boundary and within the turbulent flow before it is able to erode and

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transport material (Knighton 1998). Therefore, higher energy flows, derived from greater precipitation are able to erode and transport more sediment.

The relationship between the precipitation and erosion of sediment is complicated by the presence of vegetation, which can increase infiltration and reduce the amount of runoff. The complication stems from the vegetation characteristics of a catchment also being dependent on the climate. This can be examined by looking at the drainage density, which is a measure of the total length of channels for a catchment:

$$D_d = \frac{\sum L_i}{A}$$

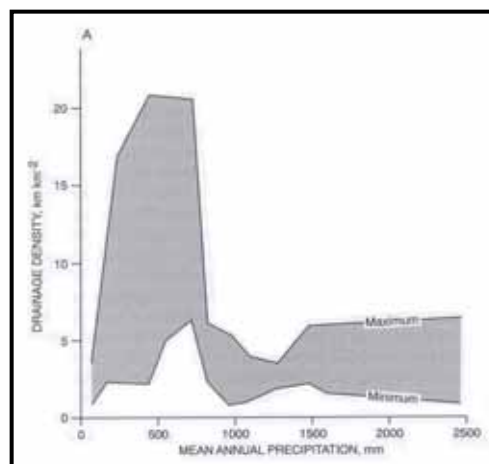
Where,

$D_d$  is drainage density

$L_i$  is the length of a single stream in the basin

$A$  is the area of the basin

The creation and expansion of channels is from erosion processes, which makes the total length of streams, and the drainage density, a useful indicator of the amount of erosion of sediment within a catchment. Gregory and Gardiner (1975) examined the drainage density in 30 basin globally and observed the relationship with climate. The highest drainage density was found in semi-arid areas, with lower densities in arid and humid areas (Figure 2-2). Abrahams (1984) expanded this further, by including super humid areas and found that drainage density increased again in these areas. These results demonstrate that the relationship between precipitation and erosion within a catchment is not linear, and influenced by other factors.



**Figure 2-2 Drainage Density and Mean Annual Precipitation (Gregory & Gardiner 1975)**

The highest drainage densities are found in the semi-arid regions (200-800mm). Lack of rainfall limits drainage density in arid areas (<200mm) and in humid area (>800mm) by vegetation which regulates runoff. Seasonal changes in vegetation cover and intermittent and intense rainfall in semi arid areas accounts for the high drainage density.

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The relationship emphasizes the role of vegetation within the catchment, as it regulates runoff and therefore the erosion of sediment. In humid areas, sufficiently dense vegetation is able to grow, which increases infiltration rate and decreases the runoff and erosion (Daniel 1981). In arid areas there is scarce vegetation, however, precipitation and runoff is extremely limited (Moglen et al. 1998). The sparse vegetation and large storm events that characterize semi-arid areas allow for significant runoff and therefore a high drainage density. Super humid regions feature a high drainage density as the dense vegetation, which is similar to humid areas, is unable to regulate the excess precipitation. Runoff and erosion within a catchment is also influenced by the lithology of a catchment, which along with the vegetation, affects the infiltration rate (Abrahams 1984; Moglen et al. 1998). Tucker and Bras (1998) have also demonstrated that there is a relationship between the topography of a catchment and the drainage density.

## **2.3 Human Impacts**

The character and behavior of river channels represent the surrounding environmental conditions in the catchment. They are the integrated effect of climate, geology and topography controlling the supply of sediment and water within the catchment (Knighton 1998). Increasingly though, human impacts are also influencing the stream conditions. Of particular concern for environmental managers are modified land use in catchments, which affect the environmental controls, and direct impacts on streams from damming (Renwick et al. 2005). These human actions disrupt the flow of sediment and water, frequently leading to degradation of the stream and associated ecology (Ligon et al. 1995; Allan 2004).

### **2.3.1 Land Use Changes**

Changes in land use within catchments, primarily through the introduction of agriculture and removal of natural vegetation, has greatly increased the sediment supply to rivers (Prosser et al. 2001). Of the environmental controls within a catchment, vegetation is the most susceptible to human impacts and over the past few centuries there has been substantial destruction worldwide of natural vegetation for agricultural land, urban areas, mining and forestry (Knighton 1998). Vegetation increases infiltration of precipitation and restricts overland flow, thereby reducing erosion rates within a catchment. Once the natural vegetation is removed, soils are exposed to greater runoff, accelerating erosion and transport of sediment, leading to aggradation of channels (Gregory & Gardiner 1975). This pattern of vegetation removal, increased sediment supply and channel aggradation has been well documented (e.g. Rapp et al. 1972).

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Human impacts within the catchment that alter erosion processes, and increase sedimentation within streams, have detrimental effects on stream ecology, that are either directly lethal or degrade habitat (Ligon et al. 1995; Broekhuizen et al. 2001). With the removal of natural vegetation there is an increase in fine sediment supply to streams, which in high levels is toxic for fish as it clogs gill filaments and opercula cavities (Manuel et al. 1979). In moderate levels, fine sediment can clog gravel spawning grounds, reducing the likelihood of embryos survival (Acornley & Sear 1999). Eggs that are deposited within gravel beds require permeability in the channel bed for exchange of water for oxygen and removal of waste products, however, fine sediments can smother the eggs and prevent these exchanges (Acornley & Sear 1999; Whiting 2002). Furthermore, fine sediment that is deposited on the channel bed can also stifle vegetation and algal growth and reduce the diversity and abundance of invertebrates (Chutter 1968; Broekhuizen et al. 2001). Aggradation of sediments also decreases living space for fish and reduces channel depth which many larger fish species require for cover (Griffith & Grunder 1982).

Within the water column, turbidity can modify stream temperatures by reducing light transmission (Gregory et al. 2000). Heat is ecologically important as it regulates chemical reactions and therefore, cellular activity. Alternations of the sediment regime can potentially drive temperatures outside of the thresholds for cellular activity, reducing the stream biodiversity (Ryan 1991; Clark et al. 1999; Angelier 2003). Reduction of light transmission also restricts plant and algal growth by limiting photosynthesis, which in turn, impacts the herbivores and detritus that rely upon these plants as a food source (Chutter 1968). Ultimately, the effects of sediment are reflected, through the food chain, in the health of the fish population (Ryan 1991).

### **2.3.2 Dams**

In the United States alone, there are millions of small dams and reservoirs, mainly on agricultural land, and ten of thousands of larger structures, built by private land owners and governments for water supply, erosion control and recreation (Renwick et al. 2005). The construction of these impoundments on rivers disrupts fluvial transport processes by trapping sediments, leading to considerable affects both upstream and downstream of the impoundment (Synder et al. 2004). The quantity of sediment that is trapped by a dam depends on the design of the structure, reservoir capacity and inflow (Ligon et al. 1995; Brandt 2000), however, several investigations have found that almost all of the sediment is trapped (Hammond Murray-Rust 1972; Phillips 2003; Lawrence et al. 2004). Channel responses to dam construction vary according to the stream

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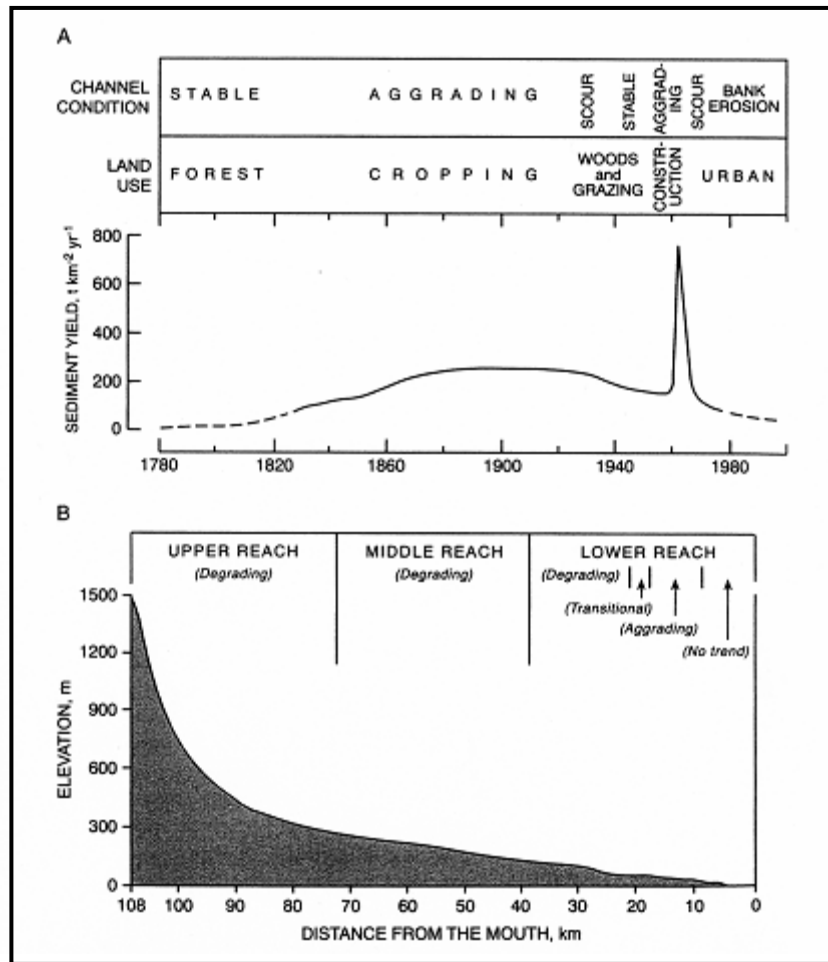
characteristics, and Brandt (2000) provides a classification of these responses to flow regulation. Some generalized impacts include considerable aggradation of sediment upstream, with channels adopting a wider and shallower morphology (Baxter 1977). Downstream, the starvation of sediment leads to bank erosion, channel incision and change in channel patterns which alters the ecosystem's habitat (Ligon et al. 1995).

The construction of impoundments impacts the stream ecology by creating an artificial boundary that prevents the flow of sediment, water, nutrients, energy and biota (Ligon et al. 1995; Graf 1999). Increased sedimentation upstream has many detrimental effects that have been discussed (2.3.1) whilst downstream, erosion of bank and bed material can destroy the riparian vegetation and habitat (Graf 2001). Rivers are important ecological corridor, allowing for the migration of aquatic species, however, dams create artificial barriers that prevent this movement (Ligon et al. 1995; Synder et al. 2004). Impoundments also cause disrupt the flow of nutrients, which are important for ecological processes, and cause abrupt changes in stream temperatures (Graf 2001).

## **2.4 Management**

In order to mitigate the impacts of human modification on the fluvial landscape, management, with a primary basis of understanding the geomorphic processes, is required. A detailed understanding of sediment transport processes and the relation to the environmental conditions of the watershed, allows for prediction of stream responses to future changes (Edwards & Glysson 1999). The difficulty, however, is recognizing that channel responses are likely to be complex, with considerable spatial and temporal lags, as a disturbance in the upper catchment must propagate through the system (Knighton 1998). The variable response is demonstrated by the reaction of Redwood Creek to forest clearance, which featured degradation in the upper and middle reaches, and aggradation in lower reaches (Figure 2-3)(Madej & Ozaki 1996). Owing to the lag in downstream channel responses to disturbances, it also becomes apparent that rivers are influenced by both present and past conditions within the watershed. Successful management of degraded streams must therefore also include an appreciation that the timescales of adjustment for a stream may extend well beyond the initial disturbance.

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**Figure 2-3 Channel Bed Response to Timber Harvesting (Knighton 1998)**

A. Response of sediment yield to land use change. Cropping and construction increased sediment yield from natural conditions. B. Following timber harvesting degradation was reported in the upstream channel and degradation in the lower reaches (Madej & Ozaki 1996).

The timescales of channel response depend primarily on the movement of sediment within the catchment (Church 2006). Estimating sediment transport through a watershed is complicated by storage of sediment, which can constitute a significant portion of the eroded material. The discontinuity between upland erosion and downstream sediment yields has been established by Trimble (1983; 1981), who identified that sediment yield within the stream remained relatively constant despite a significant reduction to the upland erosion. In this case, the sediment yield only accounted for around 6% of the total erosion within the catchment, which emphasizes the importance of storage in understanding geomorphic processes within the catchment. These studies stress the fallibility of only using sediment yields as an indicator of upland erosion. A more comprehensive approach is to develop sediment budgets, which attempts to quantify the processes linking upstream erosion and downstream sediment yields.

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### 2.4.1 Sediment Budgets

Sediment budgets are a conceptual framework for quantifying the mobilization, storage and output of sediment within a catchment (Walling et al. 2002). The basic equation for a sediment budget is (Rovira et al. 2005):

$$I \pm \Delta S = O$$

Where;        I = sediment input  
                   $\Delta S$  = change in sediment storage  
                  O = sediment output

The concept of sediment budgets was first developed in late 1970s with the work of Dietrich and Dunne (1978), who developed and applied the framework upon a coastal basin in Oregon, USA. Since this original study, sediment budgets have been constructed at a variety of scales, in numerous environments, with several different methods (e.g. Trimble 1981; Beach 1994; McLean & Church 1999; Walling et al. 2002; Rovira et al. 2005). Although attractive as a concept, sediment budgets require significant data in order to establish rates of sediment movement, deposition and transportation, which exhibit considerable spatial and temporal variability (Walling et al. 2002).

There has not been a consistent approach to sediment budgets construction, with many different requirements of data and methods being utilized. One of the initial studies was the work of Trimble (1983), who determined for Cook Creek, Wisconsin (2.4). In this study, sedimentation rates were adapted from a reservoir in a nearby catchment, and erosion was calculated from the Universal Soil Loss Equation (USLE). The latter approach has also been employed by Renwick et al. (2005) and Beach (1994), who used several different methods and data sets to calculate erosion rates, which all provided results similar to the USLE. A limitation of this technique, however, is that it estimates rill and sheet erosion, and does not account for gully erosion and channel extensions, which have the potential to contribute significant amounts of sediment to the system. Furthermore, the USLE has also been criticized for only calculating the quantity of soil that is moved on the landscape, which is rarely equal to the amount of sediment delivered to streams (Trimble & Crosson 2000). A more recent approach for calculating sediment erosion rates is the use of  $^{137}\text{Cs}$  tracers, a method capable of addressing the spatial variability within the catchment (Walling et al. 2002). Sediment output from a watershed can be calculated by either long term records of sediment yield (e.g. Walling et al. 2002; Rovira et al. 2005), or sedimentation rates behind dams (e.g. Beach 1994; Synder et al. 2004; Renwick et al. 2005).

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Other approaches to calculating sediment budgets include detailed field monitoring and assessing historical records of streams. Rovira, Batallaa et al. (2005) determined a sediment budget for Tordera River, using a field based approach, that included over 700 sediment samples and 50 cross-sections in a three year period. Whilst this methodology can give detailed results, it requires a significant investment of time and resources for field work for a study that is limited to an 11km reach, over a relatively short timeframe. An alternative approach is that of Kesel, Yodis et al. (1992) who constructed a sediment budget for the Lower Mississippi using historic maps to examine channel form, which was then related to sediment transport processes. This methodology was further explored by Mclean and Church (1999) for the Lower Fraser River, by subdividing the river into reaches and using a sediment continuity equation. Using aerial photos and historical maps is only of value when the channel experiences lateral instability, and widens or narrows in response to changes in the sediment regime (Church 2006). These studies also require estimation of sediment depth in the channel, which can be difficult owing to the size of the stream, or clarity of photos, and therefore, they are not as accurate as field based studies. However, using historical information allows for evaluation sediment fluxes over the timescales that govern sediment movement within the catchment, which short-term field studies may not represent (McLean & Church 1999; Trimble 1999; Walling et al. 2002).

Sediment budgets can provide an effective basis for developing management strategies by identifying sediment sources and sinks that require attention, and a process for assessing potential strategies to mitigate accelerated erosion within the watershed (Walling et al. 2002). Sediment budgets require considerable data to be constructed accurately. In order to constrain the frequency of surveys for establishing a budget, more research is required to identify the timescales that govern sediment movement and therefore river channel responses to catchment disturbances (Church 2006).

## **2.5 Conclusion**

The morphology of rivers is governed by the erosion, transport and deposition of sediment. The sediment supply to streams is controlled by the topography, geology and climate of the catchment. Changes in environmental characteristics of the catchment can alter the sediment regime resulting in modifications to the channel morphology. Rivers are therefore controlled by the catchment environment and evolve with catchment changes. Human modifications through

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land use change can lead to severe changes in the channel. Excess sedimentation is detrimental to river ecology as it clogs gravel beds, modifies stream temperature distribution and reduces the living space. Investigating the sediment problems in Silver Creek requires consideration of the environmental controls, human modifications and historical changes.

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## **Chapter 3: Environmental Setting**

Silver Creek represents a unique environment that is regarded as one of the best examples of a high desert, cold spring ecosystem (Brockway & Kahlow 1994). The distinctive setting of the creek, in particular the climate, geology and vegetation, strongly influences the movement of sediment throughout the watershed. Impacts of humans, including direct influences on the hydrology of the stream, and changes in the surrounding land use, also affect sediment within the system.

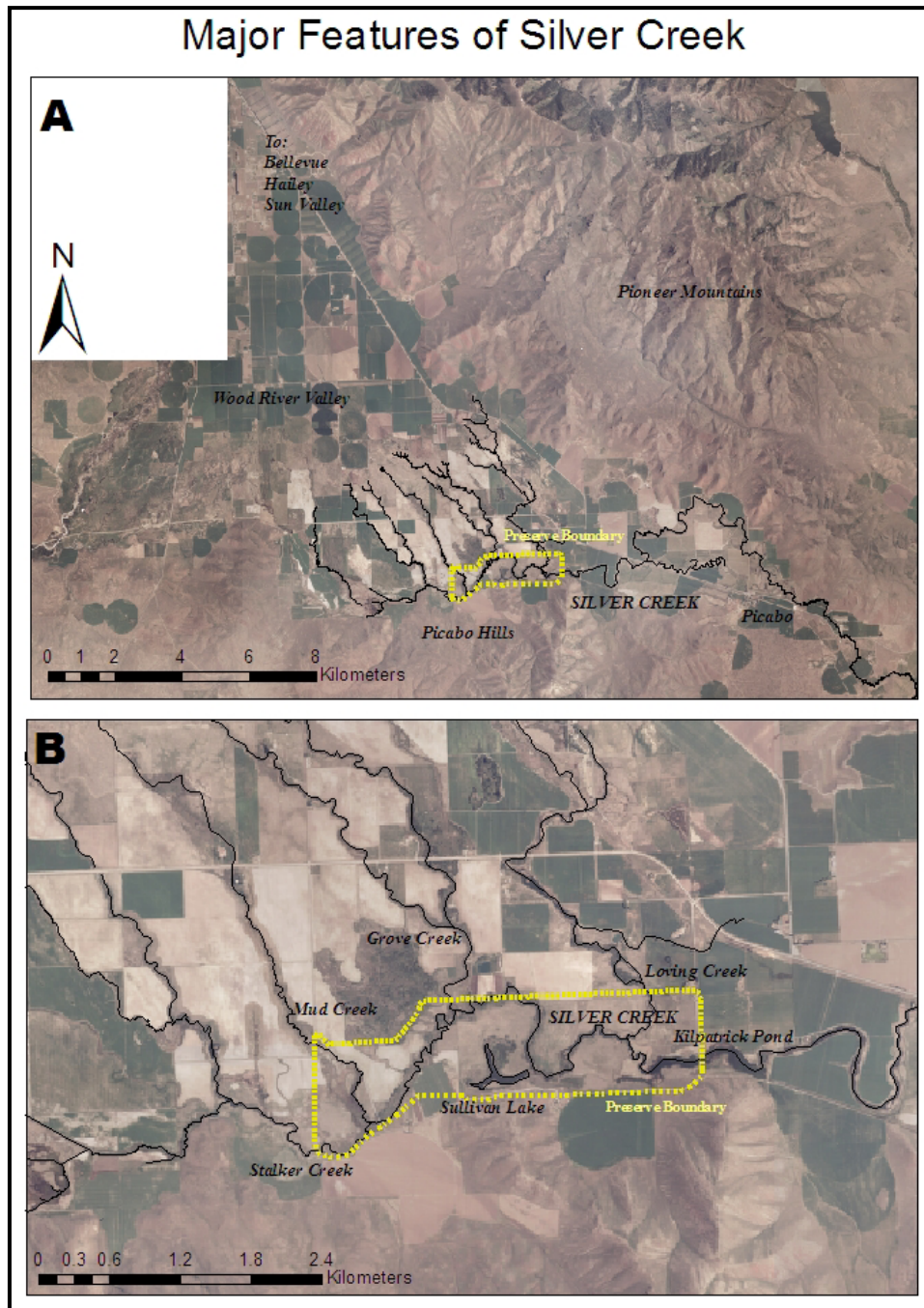
### **3.1 Topography**

Silver Creek is located in the Wood River Valley, an area surrounded by the Pioneer and Smokey Mountains and the Picabo Hills (Figure 3-1). The mountains and hills form a triangle known as the Bellevue Triangle, which is around 1 ¼ miles wide near Hailey and 2 ½ miles south of Bellevue it widens dramatically (Brockway & Kahlow 1994). This area south of Bellevue is predominantly river terraces and is known as Poverty Flats (Castelin & Chapman 1972). Within this triangle, there is a small topographic divide causing Silver Creek to flow towards the South East corner near Picabo, whilst the Big Wood River drains to the South, near Stanton Crossing. Elevations in the region are, 4750ft near Picabo, 4800ft at Stanton Crossing, 5300ft near Hailey and the surrounding mountains reach elevations of 7000ft (Castelin & Chapman 1972).

### **3.2 Geology**

The geology of the valley consists of consolidated sedimentary, volcanic and intrusive rocks underlying a sequence of interbedded clay, sand, silt and gravel (Moreland 1977; Brockway & Kahlow 1994). The underlying rocks, of Tertiary and older age, have a low permeability compared to the valley fill (Moreland 1977). The younger fill material, of Pleistocene and Holocene Age, was formed from glacial deposition and Basalt flows. During the Pliocene, the Big Wood River flowed from the deep, narrow canyon north of Bellevue towards the south east, however, several Basalt flows dammed and changed the course of the river, leading to deposition of sediments across the valley (Moreland 1977). During this time, there were two periods of Glaciation in the upper valley, which provided glacier-melt runoff and deposition of coarse-grained material over the valley (Moreland 1977). The valley is now filled with deposited sediments to a depth of 500ft, with coarser material in the central and northern parts and significant amounts of finer material in the southern valley (Castelin & Chapman 1972).

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**Figure 3-1 Major Features of Silver Creek**

(A) Silver Creek is located in the Wood River Valley surround by the Smokey and Pioneer Mountains and Picabo Hills. The town of Picabo is east of the preserve. (B) The major tributaries of Silver Creek are Stalker, Grove and Loving Creeks. Kilpatrick Pond and Sullivan Lake (or Sullivan Slough) are other significant features.

### 3.3 Hydrology

Silver Creek is a spring fed system, sourced from groundwater that is recharged by irrigation, seepage from the Big Wood River, snow melt, and precipitation. Water is diverted from the Big

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Wood River through a series of canals that provide irrigation for agriculture in the area (Brown 2001). Leakages from these canals and excess irrigation water for crops, contribute to the groundwater recharge (Brockway & Kahlow 1994). In the southern area of the valley, the groundwater table is below the elevation of the Big Wood River's bed and subsequently seepage occurs and the river contributes to ground water recharge (Brockway & Kahlow 1994). Groundwater movement generally moves from areas of higher altitude to lower altitude in the south, where it is largely controlled by the lithology of the valley fill. The fine grained deposits force overriding flows to the surface, creating springs that contribute to the Silver Creek system (Moreland 1977).

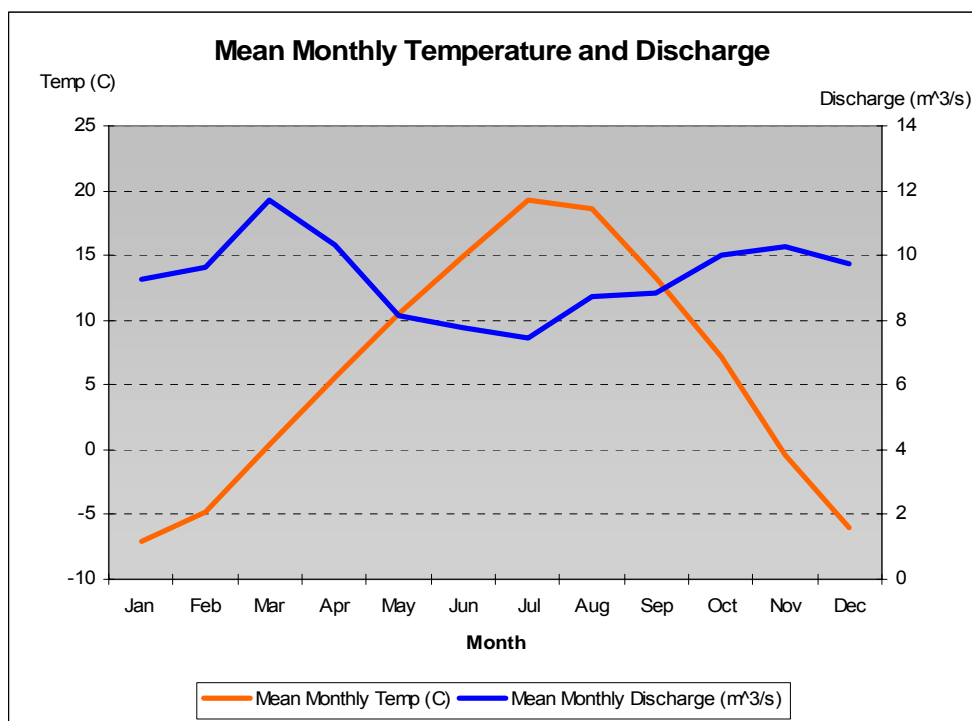
A number of spring-fed tributaries combine to form the headwaters of Silver Creek. The initial tributaries in the system are Stalker, Chaney and Mud Creeks, which are followed by Grove Creek, the largest contributor, and Loving Creek further downstream. Silver Creek itself flows in a southeast direction, eventually joining the Little Wood River. Silver Creek, along with its tributaries, have a small gradient (<1%) and generally steady flows (Wolter et al. 1994; Brockway & Kahlow 1994). The water features a relatively cool and constant temperature (40-60°F) and an alkaline chemistry (Wolter et al. 1994). The other significant feature of this system is Kilpatrick Pond, a stretch that is considerably wider than other parts of the creek. This section is upstream of a dam built on private land around 120 years ago.

Long term trends in stream flow within Silver Creek are difficult to characterize owing to anomalies in data collection. The USGS collected stream flow data in 1936 until 1963, when the program was discontinued (Brockway & Kahlow 1994). In 1975, data collection began again but at a new location, 5 miles to the west of the original (Brown 2001). Although the data is discontinuous, Brown (2001) noted that there were no clear downward trends. Annual variations in stream flow are related to the sources of groundwater recharge and seasonal changes in the area. Snow melt and precipitation cause a peak in flows during spring, in March and early April (Brockway & Kahlow 1994). Lower flows are recorded during the summer, until another peak occurs in October which is caused by spring-time flows in the Big Wood River recharging the aquifer around Silver Creek (Wolter et al. 1994). The flow in Silver Creek has also been observed to rise and fall in proportion to flows in the Big Wood River, which demonstrates the hydrological link between the two streams (Brockway & Kahlow 1994; Brown 2001).

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### 3.4 Climate

Silver Creek experiences a climate characterized by moderately cold, wet winters and warm, dry, summers (Castelin & Chapman 1972). Mean annual precipitation in the area is 260mm however, it can be highly variable, with a maximum value of 510mm recorded in 1983 (Brockway & Kahlow 1994). There is also variability within the Wood River Valley, as the upper valley receives considerably more precipitation than the lower valley. Evaporation rates exceed transpiration rates from May to October, but from October to March, the watershed is covered in snow (Anderson et al. 1996). Around 36% of the annual precipitation falls between April and June. Mean annual temperature for Silver Creek is 43.3°F, with a maximum mean monthly temperature of 67.0°F in July, and a minimum of 18.7°F in January (Figure 3-2)(Brockway & Kahlow 1994).



**Figure 3-2 Temperature and Discharge**

The initial peak in discharge coincides with spring snow melt runoff. The second peak is from groundwater interactions with the Big Wood River. Over the summer months, with a considerable increase in temperature, the discharge values reduce.

### 3.5 Vegetation and Wildlife

The lower Wood River Valley is essentially a desert with sparse vegetation cover owing to the limited amount of precipitation. Prior to the introduction of irrigation, this area was covered in sagebrush, greasewood, and native grasses, however it now features many non-native species

(Todd 1997). Areas that have been disturbed by agriculture are characterized by non-native grasses (Todd 1997). Sagebrush and grasses are still dominant in the surrounding hills, while the lowland areas feature willows and cottonwood (Castelin & Chapman 1972). Vegetation around the creek is comprised of willows, river birch, bulrush, cattail and sedges (Todd 1997). Within the stream, Chara, an alga found in cold alkaline streams, dominates the fast moving tributaries, while Potamogeton is common in the slower moving streams (Wolter et al. 1994). The vegetation within the channels provides cover for the fish species and is beneficial for increasing fish population (Irving 1956).

Silver Creek features many favorable conditions to support a diverse range of wildlife and fish. The consistent flow and relatively constant temperature prevents much of the average winter kill of fish in other mountainous streams (Schweibert 1977). The creek is a world class fishery, with many species, including Brown Trout, Rainbow Trout, Mountain Whitefish, Speckled Dace, Bridgelip Sucker and the endemic Wood River Sculpin (Todd 1997; The Nature Conservancy 2003). A study of fish population in 2001 estimated an average of 1681 trout/km which is considerably higher than the nearby Big Wood River, and most streams in the United States (The Nature Conservancy 2003). Along with the abundance of fish, the preserve also provides a habitat for over 150 species of birds, including migrating waterfowl, song birds and bald and golden eagles (The Nature Conservancy 1993). The riparian areas also provide a habitat for deer, elk, beaver, muskrat and otter, with mountain lions and coyotes also found on the preserve (The Nature Conservancy 1985; Wolter et al. 1994; The Nature Conservancy 2003).

### **3.6 Land Use**

The landscape within the Wood River Valley has been considerably disturbed by the introduction of agriculture and continued population growth within the valley. The Upper Wood River Valley includes the towns of Hailey and Ketchum and the Sun Valley ski resort and is focused predominantly on recreation and tourism (Brockway & Kahlow 1994). The Lower Wood River Valley, however, has a smaller population and consists primarily of agricultural land. The major crops grown in this area are wheat, barley, alfalfa and oats (Brockway & Kahlow 1994; Wolter et al. 1994). Although the region experiences low amounts of precipitation, these crops are able to be grown as there is extensive irrigation, both from surface diversions from the Big Wood River and groundwater extraction (Brockway & Kahlow 1994). Agriculture has affected the watershed through the removal of natural vegetation, deterioration of riparian vegetation,

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increased field runoff and impacts of grazing (Wolter et al. 1994). Continued population growth and changing demographics in the Wood River Valley also have an impact on the watershed by increasing demand on the water resources in this arid environment (The Nature Conservancy 2003).

The Silver Creek Preserve was established by the Nature Conservancy in 1976 to protect the creek's unique ecosystem, whilst allowing continued public use of the land (The Nature Conservancy 2005). Within the preserve, there has been significant rehabilitation from the impacts of agriculture, focusing on habitat restoration, protection of stream banks and improvements in water quality. The Silver Creek Preserve, an area of 882 acres, and the surrounding conservation easements, a further 9000 acres, are also protected from future development (The Nature Conservancy 2005). Along with the ecological importance, the area has a high recreational value as many locals and visitors use the land for fishing, hiking, canoeing and bird watching. The challenge for The Nature Conservancy is to balance environmental conservation with the recreational and agricultural uses of the landscape (The Nature Conservancy 2003).

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## Chapter 4: Historical Changes

Silver Creek is currently a preserve with significant native vegetation and wildlife, providing a unique example of a high desert ecosystem. These recent conditions are the result of management and remediation of the catchment by the Nature Conservancy. Previous management, however, has not been as ideal, and when determining the current sediment conditions within the creek, past conditions need to be considered. Understanding the previous catchment conditions is important because rivers are historical systems, reflecting the integrated effect of catchment controls (Knighton 1998). Knowledge of historical changes is valuable for forecasting future impacts, which assists remediation work, and is beneficial for developing and constraining numerical models (Phillips 2003). A convenient way of describing changes within the catchment, and organizing the corresponding data, is to use a sediment budget approach, which quantifies sediment inputs, outputs and storage. This quantitative method can be complimented with a qualitative approach combining historical records and photos to construct a conceptual model of changes to the catchment and creek.

### ***4.1 Sediment Budget***

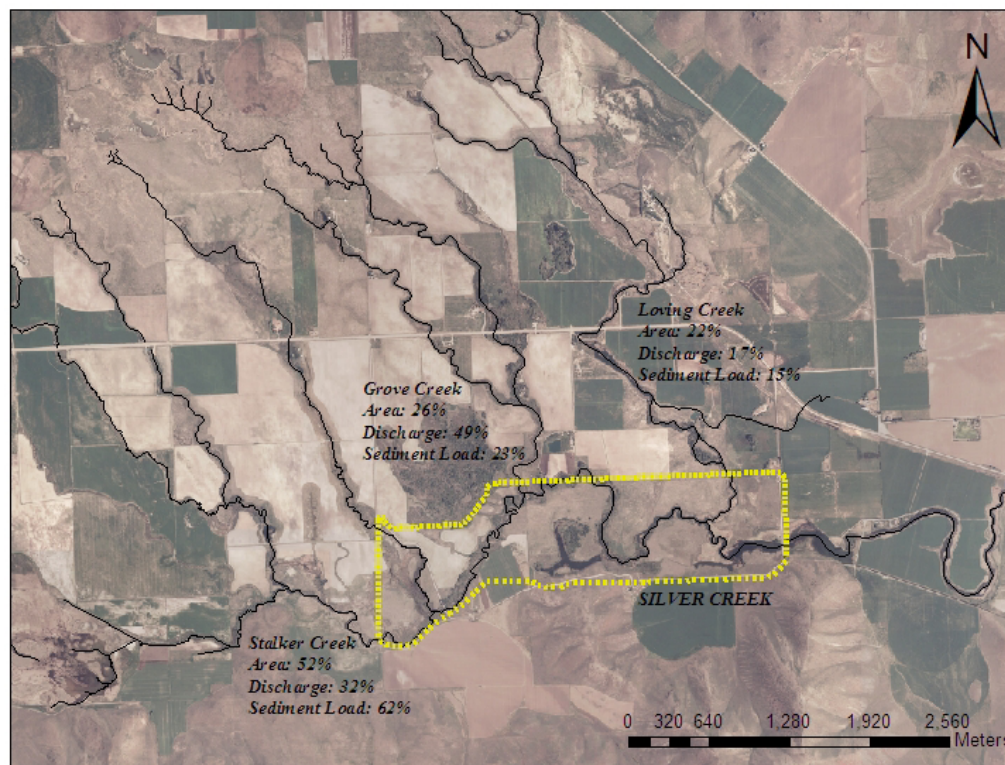
The initial approach considered in this research was to construct a sediment budget for the Silver Creek within the boundaries of the preserve. In order to calculate a budget, as discussed in Section 2.4.1, vast amounts of relevant data is required to quantify the mobilization, storage and output of sediment within the catchment. Owing to the timing of the project, predominantly during winter at Silver Creek, new data could not be collected in the field. The calculation of the sediment budget was therefore reliant on existing data sets, thus a review of the available data was conducted. In the following section a review of the available data which could be utilized in the construction of a sediment budget is analyzed.

#### **4.1.1 Sediment Input**

Sediment input into river channels is originates from erosion within the catchment, either from surface erosion or channel extensions through gully erosion. Efforts to quantify these inputs into Silver Creek have been limited, with the only significant work being that of Manuel et al. (1979) who conducted a 15 month study into the sources and causes of sediment within the creek. From this study, it was determined from field measurements that wind erosion does not make a significant contribution to sediment input to Silver Creek. The sediment input from surrounding

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fields could not be established because of a lack of quantitative data, however, monitoring the major tributaries allowed for calculations of the quantity of suspended sediment input into Silver Creek. Using depth-integrated sampling, it was found that Stalker Creek contributed 62% of the material, while Grove and Loving Creeks supplied 23% and 15% respectively (Figure 4-1). Comparing these values to drainage area, Stalker Creek had a higher percentage of sediment load and discharge to drainage area than the other tributaries owing to the fact that a significant amount of water from Stalker Creek is derived from the aquifer rather than overland flow.



**Figure 4-1 Sediment Input from Tributaries (Manuel et al. 1979)**

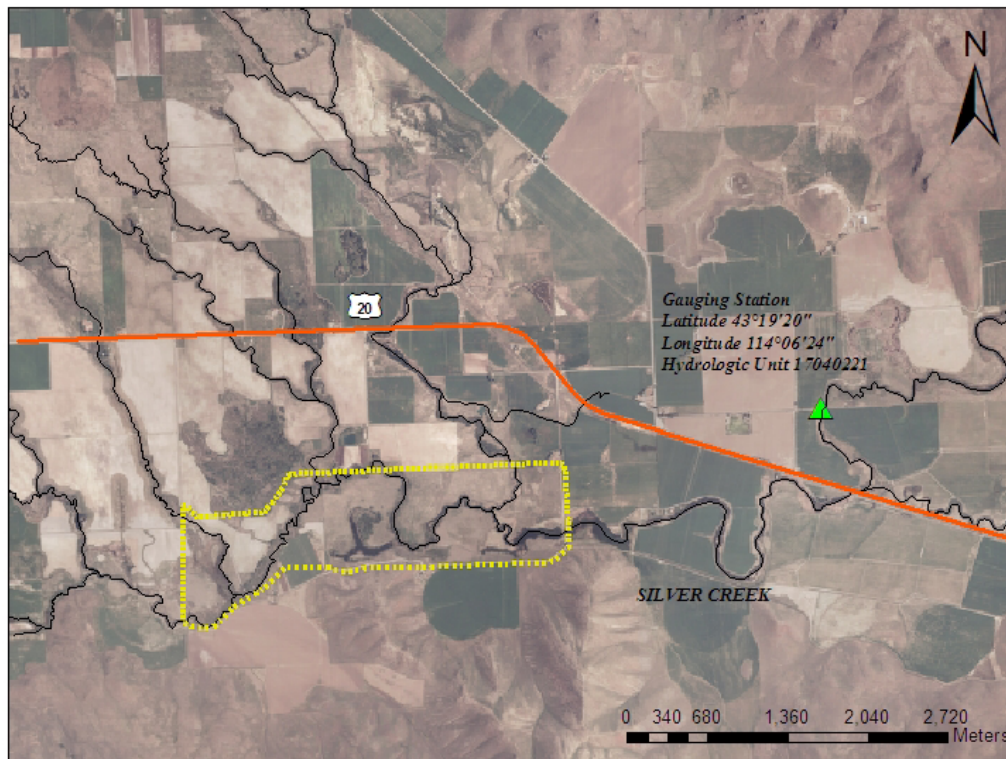
The respective sediment load inputs are shown for Stalker, Grove and Loving Creek.

Whilst this data is useful, incorporating it into a sediment budget is problematic. The data is nearly 30 years old, and would poorly represent current conditions in the catchment, particularly because since then the preserve has been established, and irrigation methods have changed (Brockway & Kahlow 1994). The data do provide a foundation for future studies as by repeating the Manuel et al. (1979) study would a comparison of past and present conditions could be achieved. A further limitation of these data is that it does not provide an insight into the fundamental source of sediment and further study is required to determine the mechanisms by which sediment enters the stream from surrounding fields (Manuel et al. 1979).

Another method considered to establish a sediment budget was to use sediment input data from locations near Silver Creek as an estimate of the quantity of sediment input into the creek itself. There has been considerable work conducted by the University of Idaho in quantifying sediment yield for runoff from irrigated fields around Twin Falls in the Magic Valley, approximately 60 miles south of Silver Creek. Whilst this data is available, it was determined to be unsuitable for comparison because the soils of the Magic Valley are highly erosive and surface irrigation is practiced, whilst in Silver Creek, the soils are less erosive and sprinkle irrigation is common (Allen 2006). No other suitable data sets could be found to estimate sediment input from runoff in the fields.

#### 4.1.2 Sediment Output

Typically sediment output is measured by the sediment yield at the outlet of the catchment. There is a gauging station downstream of the preserve (Figure 4-2), which has continuous daily records of stream discharge from 1974 to present. Water quality data, including turbidity has also been measured infrequently, however, no suspended sediment measurements have been made, so turbidity cannot even be used as a surrogate measure of sediment out. Without this data, sediment output from Silver Creek could not be calculated.

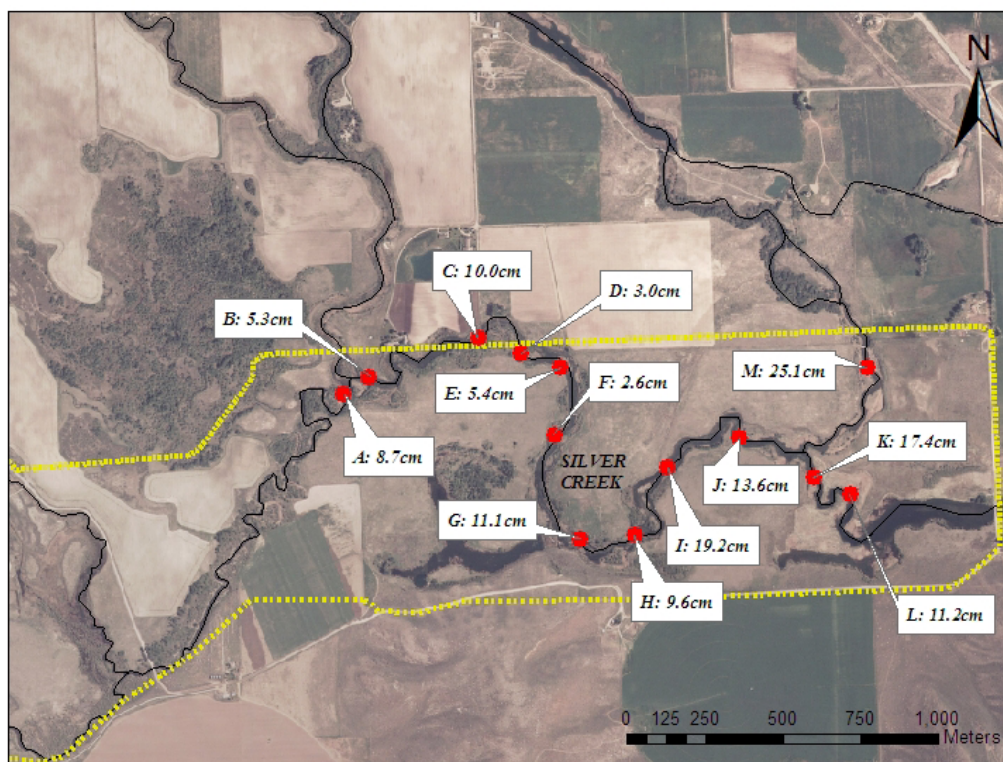


**Figure 4-2 Gauging Station Location**

The gauging station is located downstream of the Silver Creek Preserve as shown with the green triangle.

### 4.1.3 Sediment Storage

Sediment storage in Silver Creek can be calculated based on data from previous studies, changes in channel width in aerial photos and from measurements of sediment depth in channel cross-sections. In a natural state, Silver Creek is a gravel bed stream and therefore, the gravel bed provides a reference for measuring deposition of sediment in the stream (Manuel et al. 1979). The sediment study of Manuel et al. (1979) measured sediment depths at various locations along the creek and the results are shown in Figure 4-3. These values represent mean depth, although it should be noted that there were seasonal differences in sediment depth at some locations (Appendix A). There is a clear trend of increasing depth of sediment downstream towards Kilpatrick Pond where sediment depths have recently been measured up to 1m (Watershed Sciences Inc. 2006) Measuring these sediment depths would provide a useful comparison between past and present conditions.



**Figure 4-3 Sediment Depths in Channel**

Sediment depths measured in the catchment are illustrated. There is a trend of increasing sediment depth downstream. This data was collected in 1978 (Manuel et al. 1979)

Cross-sections are a useful measurement of the change in storage within the creek as they exhibit the sediment depth across the width of the channel, along with information of channel width and

therefore bank erosion. In order to be useful for a sediment budget, cross-sections should be measured over a time series and against a datum so that future measurements can be taken for comparison. The limited cross-sectional information that exists is summarized in Table 4-1. The difficulty with using this data is that it is limited to particular areas of the creek, whether it be Stalker Creek for the '91-'94 data, or Kilpatrick Pond for the 2004 data. Consequently, there is no comprehensive data set for the entire catchment at any time. More problematic, however, is that the cross-sections were not measured against a datum and their exact location is unknown, so they cannot be remeasured for comparison. Regular measurements along the channel would provide valuable information on the quantity of sediment stored within the channel.

**Table 4-1 Summary of Cross-Sections of Silver Creek**

Information about the various cross-sections has been summarized. These cross-sections could not be used for storage analysis as the location is unknown or the survey has not been repeated.

Transect	Location	Co-ordinates	Date	Re-surveys Dates	Notes
1	Stinson Property	No	Jul-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
2	Stinson Property	No	Jul-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
3	Stinson Property	No	Jul-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
4	Cain Creek	No	Aug-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
5	Cain Creek	No	Aug-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
6	Stalker Creek	No	Aug-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
7	Stalker Creek	No	Aug-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
8	Stalker Creek	No	Aug-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
9	Stalker Creek	No	Aug-90	Sept-90, 91, 93, 94	Pre- and post-dredging monitoring
10	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
11	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
12	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
13	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
14	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
15	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
16	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
17	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
18	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
19	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
20	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
21	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
22	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
23	Stalker Creek	No	Jul-03	Jun-04, Jul-04	Monitoring installation of Bio-logs
24	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey
25	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey
26	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey
27	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey
28	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey
29	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey
30	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey
31	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey
32	Kilpatrick Pond	Yes	Aug-04	not repeated	Thermal infrared survey

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A more spatially comprehensive approach is to use aerial photography which provides a view of the entire catchment and captures channel widening and planform migration. The dataset for aerial photographs is more comprehensive than any other for Silver Creek, with regular photographs in the records since the 1940s. In order to identify the channel changes, aerial photographs from 1951 and 2003 have been examined. The results of this comparison are detailed in 4.2.3.

#### **4.1.4 Summary**

In summary, the available data for Silver Creek indicates there is insufficient data to calculate a sediment budget for a comparison of historical and current conditions. The most comprehensive data is from Manuel et al. (1979) who characterized sediment conditions in the channel in 1979, with data on sediment inputs and storage, however, there is no contemporary data available for comparison. Future collection of corresponding data would allow for an assessment of current conditions against those of the late 1970s, and therefore, a review of changes to the sedimentation since the preserve has been established could be undertaken. Detailed recommendations for further research are made in 4.3.2. Future collection of data would provide an insight into the channel conditions; however, would not reveal information about the actual sources and mechanics of sediment input into the stream. Following a comprehensive analysis of available data on Silver Creek it becomes obvious that due to a lack of consistent and relevant data, historical changes that have occurred to the catchment and the creek cannot be quantified. However there is a significant amount of qualitative information describing the changes which may be used to create a conceptual model of changes.

## **4.2 Historical Information**

Since the arrival of Europeans there have been significant changes to the landscape surrounding Silver Creek affecting the dynamics within the catchment. These changes could not be quantified using the sediment budget approach therefore as an alternative approach an evaluation of historical information was conducted providing many more relevant details. In reviewing the available historical material, attention has been focused on the environmental controls, which regulate sediment delivery to the stream, and corresponding channel conditions. In additions, a comparison of aerial photographs was conducted to investigate planform changes in the creek. The next section presents an analysis of the historical data.

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### 4.2.1 Environmental Controls

Geomorphic processes in a catchment, which determine movement of sediment and morphology of rivers, are governed by the environmental characteristics; topography, climate, geology and vegetation cover in the catchment (Allan 2004). Changes in the topography and geology generally occur over long timescales and are therefore are an unlikely source of the relatively recent changes in the channel sediment regime focused on in this report. Climate influences sediment movement over long timescales, with climate shifts, and short timescales, with climate fluctuations. Although it appears highly variable, Brown (2001) did not identify any significant changes over the historical climate record for Silver Creek. It is reasonable to suggest therefore that changes in vegetation cover are the primary control and potential cause of increased sediment delivery, within the catchment. A review of the historical information identified three distinct periods of vegetation cover; first the natural conditions, followed by a period of agricultural conditions until the establishment of the preserve.

Prior to the arrival of Europeans and the introduction of agriculture, the catchment had little disturbance from humans and was in a relatively natural state. The few Native Americans inhabitants were primarily hunters of bison, buffalo and other large game, and besides occasional fires, which impacted vegetation density, left the area largely undisturbed (Anderson et al. 1996). The area was covered in sagebrush and grasses on the hills and willows, cottonwoods, marsh and other grasses on the lowland areas (The Nature Conservancy 1975; Castelin & Chapman 1972). These plant species have changed little since the Holocene (Anderson et al. 1996). The density and diversity of plants was much higher than currently exists in the preserve (Todd 1997). Apart from this information, there is little record of conditions prior to the arrival of Europeans in the mid 1800s. The pre European catchment conditions, in particular, the dense vegetation cover, existed for a long period of time, and the river morphology adjusted accordingly. Therefore, the density of vegetation and channel conditions during this period are considered representative of natural conditions and are the baseline conditions for comparison to other periods.

Although the Europeans arrived in the area in the mid 1800s, there was very little settlement as the land was regarded as unsuitable for agriculture, “[These lands] are unfeasible for any kind of cultivation...from the extreme coldness of nights...superadded to the extreme dryness and poverty of the soil” (p. 23 Anderson et al. 1996). It was not until the late 1880s before agriculture was introduced with significant encouragement from both State and Federal Governments. The

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Desert Claim Act of 1877 provided 640 acres to settlers able to irrigate the land, whilst the Carey Act (1894) and the Reclamation Act (1902) were aimed at irrigating the desert landscape (Anderson et al. 1996). Livestock grazing was also established in the area and relied on the natural vegetation for feed (Anderson et al. 1996). During the early periods of agriculture, many irrigation canals were dug and flood irrigation of the fields was used (Brockway & Kahlow 1994).

The introduction of agriculture had a devastating impact on the natural vegetation. Livestock feeding severely reduced the vegetation density, as noted by hunter James Beard in 1903, who described how after many thousands of sheep had been moved through the nearby Little Lost River Valley, there was no feed left to speak of for any other animal, wild or domestic (p. 23 Anderson et al. 1996). Livestock were also able to roam into the creek and in doing so, devastated riparian vegetation and destabilized banks. Furthermore, in the early 1900s, local farmers are known to have burnt trees and shrubs along the stream in order to increase the land available for agriculture (Todd 1997). Principally, removing the native vegetation cover would have resulted in an increase of surface runoff from precipitation and snow melt, and therefore an increase in surface erosion from the fields. This pattern has been discussed in 2.3.1. The destruction of riparian vegetation, and trampling by livestock, would have destabilized the banks, and exposed them to erosion during this period.

During the early 1900s, the Silver Creek area became popular with hunters, including Ernest Hemmingway, who hunted doves and ducks whilst floating downstream on a canoe (The Nature Conservancy 1975). It also began to earn its reputation as one of the premier fly-fishing streams in the United States (Hauck 1947). During the 1970s, public access to the land was threatened, leading to its purchase by the Nature Conservancy, who established the preserve to maintain recreational value and improve on the ecological value of the land (The Nature Conservancy 1993). Since assuming management of the area, there have been many conservation efforts aimed at improving water quality and the riparian habitat. This has included replanting native vegetation, construction of fences to prevent livestock entering the stream and construction of bio-logs to strengthen channel banks (The Nature Conservancy 2003). The result of the Nature Conservancy's work is a denser vegetation cover consisting of native vegetation and strengthened, vegetated river banks.

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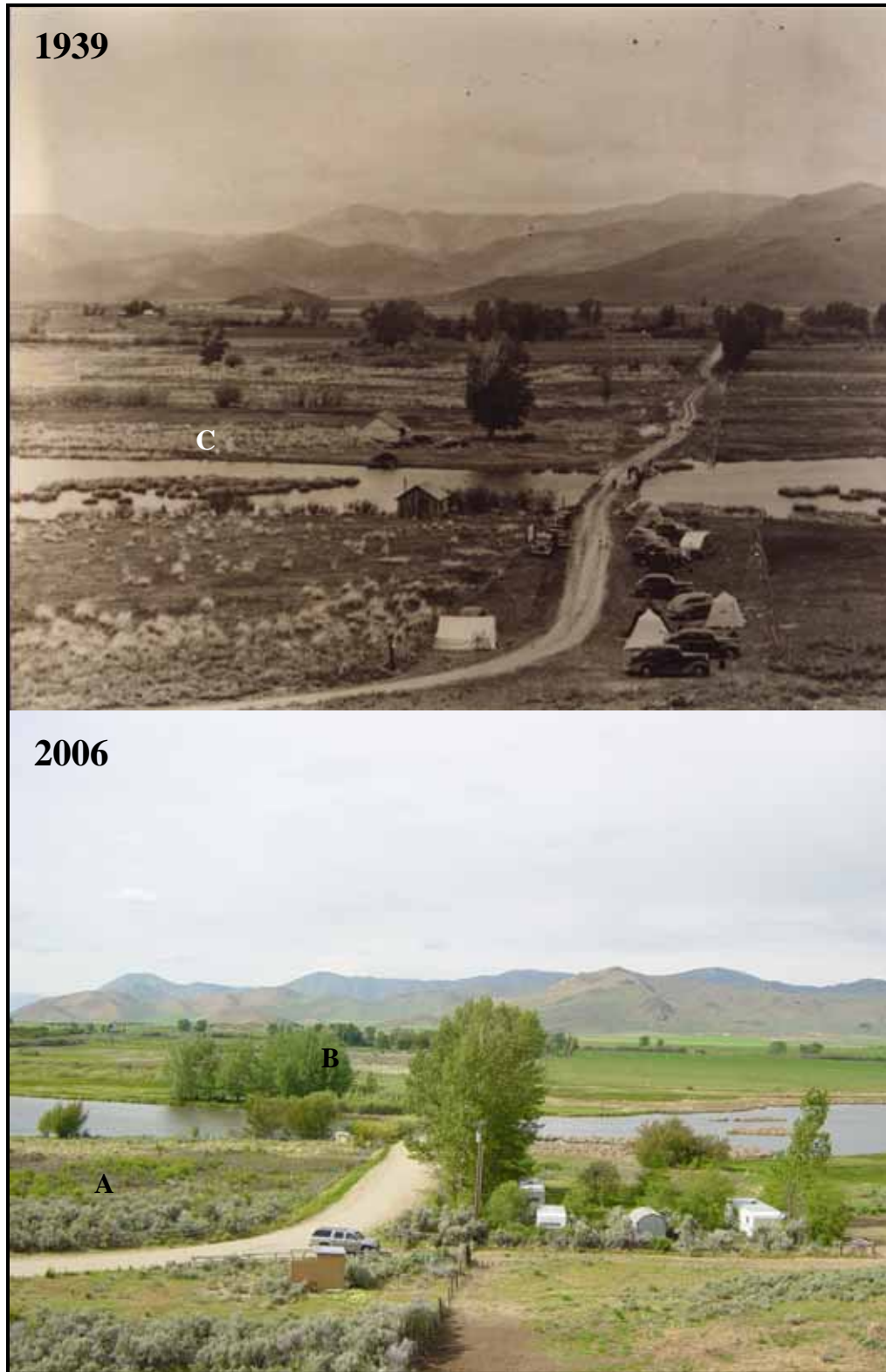
A review of the riparian vegetation cover in 1997 identified that only 33% of Silver Creek and its tributaries have what would be regarded as a native representation of shrub cover, indicating that whilst significant work has been done, the preserve is not representative of pre-agricultural conditions (Todd 1997). In fact, agriculture is still conducted throughout much of the catchment with the preserve only protecting 882 acres. A further 9272 acres is protected through conservation easements and other changes in agricultural practices have further reduced erosion of the landscape (The Nature Conservancy 2003). Surface irrigation has been replaced by sprinkler irrigation, which reduces the sediment yield from the fields (Brockway & Kahlow 1994). The modifications of the landscape between agricultural and preserve conditions can be seen in Figure 4-4, where there denser vegetation is visible. This was the only photograph available for comparison during this study; however, other historical photographs are known to exist, and it would be constructive to compare those to current conditions.

#### **4.2.2 Channel Conditions**

Along with modifications to the vegetation cover within the catchment, there have been considerable changes to the conditions of the creek, primarily the increased presence of sediment. Understanding when the sedimentation occurred is complicated because of conflicting information regarding the channel. It has been suggested that the sediment problem has become prominent only in the past 20 years (The Nature Conservancy 2003), however, older reports have described how parts of the creek have been heavily silted in as far back as the early 1940s (Hauck 1947). The timing of the changes in sedimentation could not be resolved by reviewing the literature; however, the current stream conditions and major modifications could be identified.

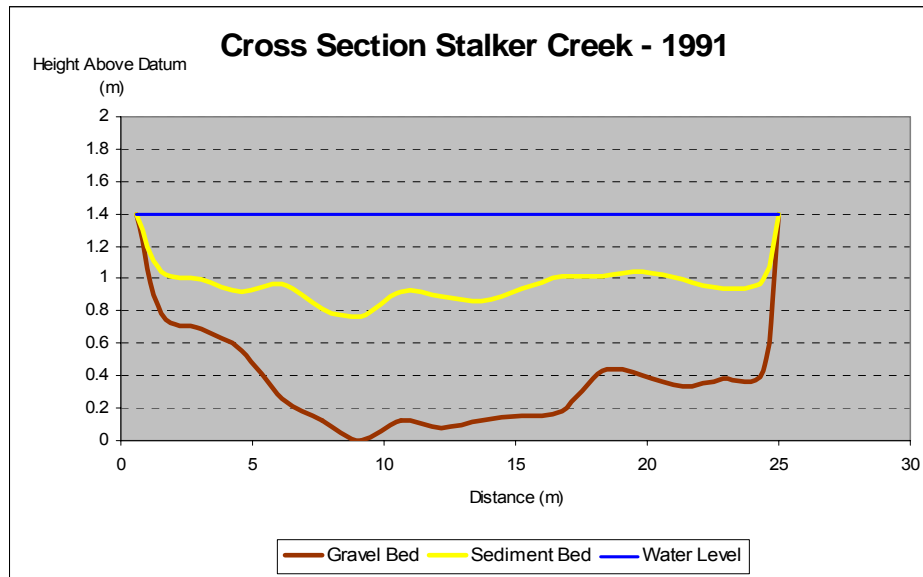
In its natural state, Silver Creek is a gravel bed stream and therefore the existence of fine sediment on the channel bed indicates a disturbance to the system (Manuel et al. 1979). There have been several relatively recent studies that have illustrated the depth of sediment within various parts of the channel. Monitoring work by the Nature Conservancy in 1991 found fine sediment depths of up to 0.8m in Stalker Creek (Figure 4-5), and a more recent study of Kilpatrick Pond identified sediment depths up to 1.5m (Watershed Sciences Inc. 2006). The fine sediment in Stalker Creek and Silver Creek was reviewed during a field visit in May 2006, with the depths of sediment found to be as great as 1m. Although these depths vary along the channel, and no comprehensive dataset exists for the entire stream network, it is clear that there are currently significant quantities of fine sediment in Silver Creek.

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**Figure 4-4 Historical Photographs**

A comparison of a historical photograph with contemporary conditions. There appears to be denser vegetation in the foreground of the contemporary photograph (A) and denser riparian vegetation (B). The earlier photograph also features more vegetation within the channel (C), although that could be due to the flow conditions when the photograph was taken.



**Figure 4-5 Stalker Creek Sediment Depth**

A cross-section of Stalker Creek measured in 1991 demonstrated the depth of the sediment. The gravel bed represents the natural level.

Changes in the sediment characteristics are generally attributed to modifications to environmental controls in the catchment; however, there have also been direct alterations to the channel. The most significant is construction of a dam at the downstream outlet of Kilpatrick Pond. This dam, known as Purdy Dam, is located on private property outside of the boundaries of the preserve (Figure 4-6). The exact age of the dam is unknown, but it is estimated to have been constructed between 80 and 125 years ago (Klahr 2006 pers. comm.). Dams restrict the downstream flow of water and sediment, generating a backwater area featuring slower water and areas of sediment deposition behind the dam (2.3.2). In Kilpatrick Pond, there is considerable sediment deposition in the backwater of the dam. The role of the dam aiding sedimentation was also identified by Manuel et al. (1979) who attributed increasing sediment deposition downstream to sediment settling out when water backs up behind the dam. The problem of sediment in Kilpatrick Pond was the subject of a study in 2004 that demonstrated that the quantity of sediment and resulting reduced water depth cause summer water temperature to increase beyond that suitable for fish habitat (Watershed Sciences Inc. 2006).



**Figure 4-6 Purdy's Dam**

The dam is located on private property east of the preserve at the outlet of Kilpatrick Pond. The lower photograph is a picture of the dam looking upstream.

Along with Purdy's Dam, diversions for irrigation, vegetation in the stream and beaver dams have all altered the channel conditions. In parts of Stalker Creek beaver dams restrict the downstream flow of water and sediment, in a similar manner to human constructed dams, however, little information about the age or impacts of these dams on the creek could be identified. In order to irrigate the agriculture fields, a number of diversion canals have been constructed resulting in reduced discharge through the system. The natural channel in the upper part of Stalker Creek was replaced with a less tortuous course with the construction of Patton Drain in 1952-3 (Manuel et al. 1979). Other changes include the construction of Patterson Drain in 1945, and an irrigation channel from Kilpatrick Pond. It is not well understood how these

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diversions, or increased groundwater use for sprinkler irrigation, affect the streamflow (The Nature Conservancy 2003).

Vegetation within the stream is essential for providing habitat and a food source for insects and reduced vegetation can result in a decline in fish population (The Nature Conservancy 2003; Irving 1956). However, excess vegetation in the creek, associated with increased nutrients from fertilizers use in the catchment, is also detrimental to the creek as it can reduce stream flow velocities and increase sediment deposition (Manuel et al. 1979).

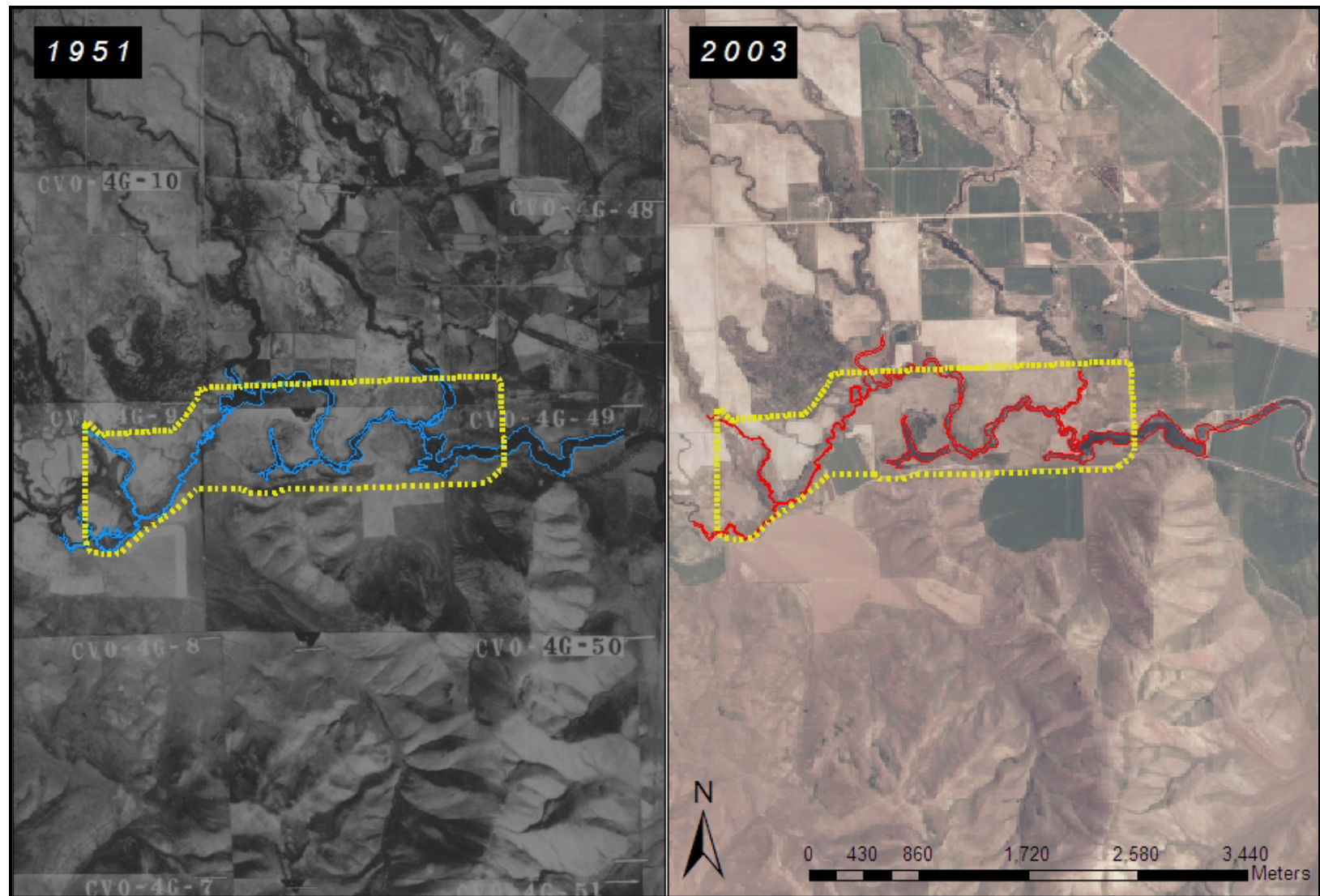
There have been several changes to the Silver Creek channel since the arrival of Europeans in the 1800s. Although it could not be established from the historical literature precisely when the changes occurred, they have resulted in considerable sedimentation in the creek. There have also been direct human modifications of the stream through the construction of dams and irrigation channels, and owing to the use of fertilizers, changes in the vegetation density within the channel.

### **4.2.3 Aerial Photographs**

The most comprehensive record of changes to the catchment and channel are aerial photographs, which have been taken regularly since the 1940s. To assess how the landscape and stream have been transformed since the 1940s, an early set of photographs was compared to the most recent photographs. The oldest set of photographs (1946) was not of sufficient quality for detailed analysis, and therefore the next earliest set (1951) was used for analysis. These photographs were available in a digital form; however, they initially lacked spatial information until they were rectified by Jim Mudd of the Nature Conservancy. These images were compared with the latest set of data, images from 2003. For comparison of planform adjustment and modification, the channel boundaries of the creek were digitized onto the photographs using the GIS program ArcGIS™ Version 9.1. The results of this analysis are presented in Figure 4-7.

The methodology for analyzing these photographs sets has several limitations, many of which are derived from the characteristic of the older photographs. Although the 1951 photographs are in a digital format, they have been scanned in from a series of photographic plates that have been joined together. These different plates create boundaries within the larger photograph and many features do not connect across the boundaries. Figure 4-8, demonstrates a discontinuity of the channel which is clearly an error in joining the photographs. As a result, the 1951 and 2003

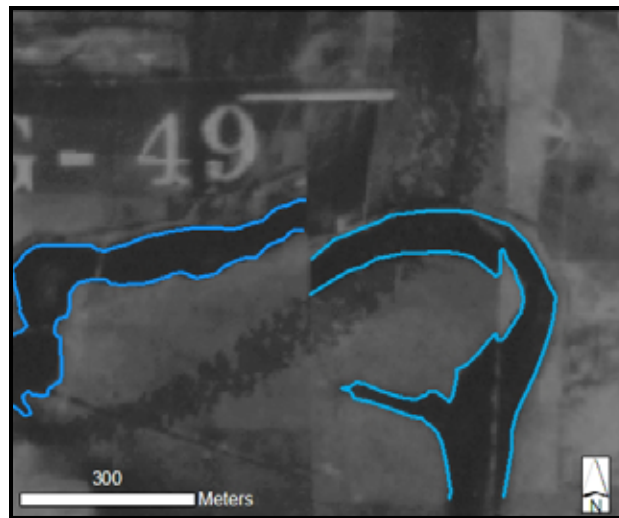
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**Figure 4-7 Aerial Photography Analysis**

Comparison of the photographs was difficult owing to the quality of earlier photograph, particularly because of the low contrast. This prevented the photographs being overlaid. There were no significant changes in the channel with Kilpatrick Pond having a similar morphology.

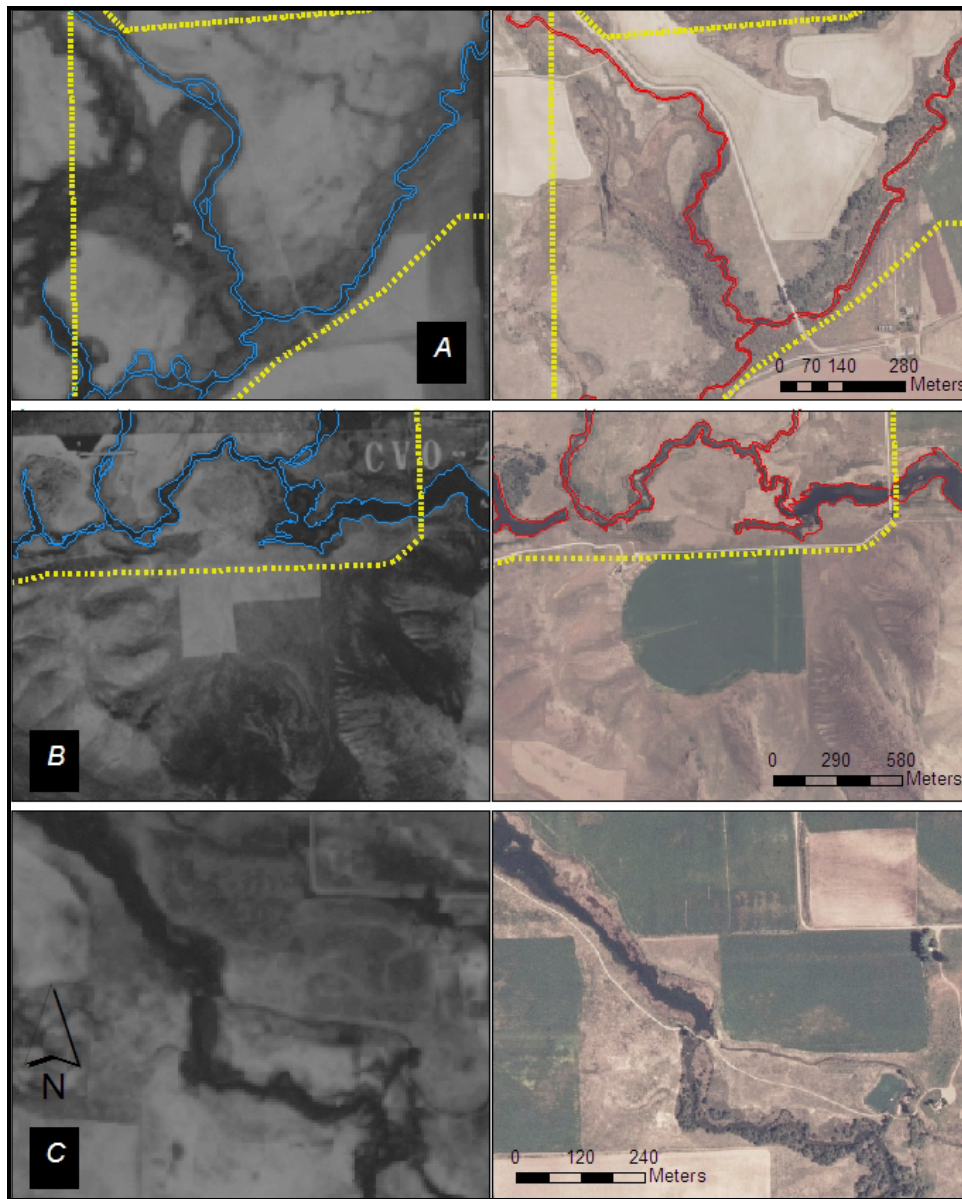
photographs cannot be overlaid, and a direct comparison of the entire channel is difficult. Furthermore, the digitalization procedure used when identifying the channel boundaries has potential errors as reviewed by Leys and Werrity (1999). The particular difficulties in digitizing these photographs were that the channel boundary was difficult to distinguish owing to vegetation cover in the contemporary photographs, and a low contrast in the older photographs, despite improving the image using Adobe Photoshop™ software. Digitizing channel boundaries has also been found to lead to positional errors with a normal distribution and a standard deviation of 2m for 1:10 000 scale maps (Leys & Werritty 1999). These limitations prevented useful quantitative estimations of bank migration rates or changes in the sediment volume and only general observations were possible.



**Figure 4-8 Errors in Aerial Photograph Analysis**

As the 1951 photograph was created from photographic plates joined together by hand, there are errors where the plates do not match. The channel is highlighted in blue and the discontinuity occurs where the plates are joined together.

Comparisons between the 1951 and 2003 photographs demonstrate changes in the vegetation cover in the catchment and a lack of changes in the channel network extent. Most of the agricultural fields are still present in the contemporary photographs. South of the preserve's eastern and western boundaries, it appears that fields have expanded. It is difficult to identify increases in vegetation cover owing to the resolution of the photographs, and the size of the sagebrush vegetation. The more defined boundaries around the agricultural fields are a more useful indication, providing an identifiable shift from exposed ground to ground covered by vegetation (Figure 4-9). There is also, a considerable increase in the riparian vegetation, which can be identified by the presence of larger trees and shrubs which are more visible in the images (Figure 4-9).



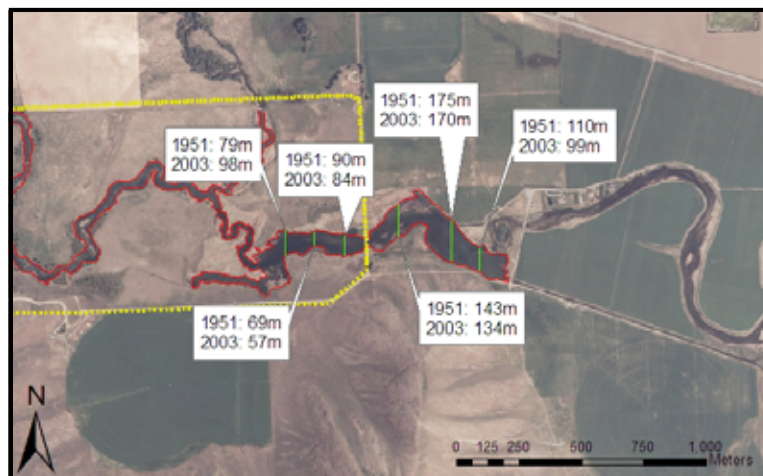
**Figure 4-9 Catchment Analysis**

(A) There are more defined boundaries at the edge of agricultural fields in the contemporary photograph, indicating the vegetation cover outside of the field is different. (B) The agricultural field in the contemporary photograph has increased in size. (C). Less riparian vegetation is present in the earlier photograph.

Gully erosion would not be expected as the catchment has a low gradient and the soils are not highly erosive and these photographs confirm that it does not occur. The aerial photographs illustrate no major extensions to channel network indicating that gully erosion does not occur within the catchment, and therefore the bulk of the erosion is likely to be from sheet erosion from runoff, or erosion of the stream banks.

The comparison of the channel network in the aerial photographs demonstrates human modification to channels, and adjustments of the stream in response to surrounding catchment conditions. The most noticeable channel changes are the direct alternations made for irrigation and drainage of the landscape. The 1951 photographs illustrate the channel prior to the construction of the Patton Drain in 1952-53 which has replaced the meandering natural channel. The irrigation channel from Kilpatrick Pond is also more prominent in later photographs, suggesting it may have increased in size.

Comparing the channels, there are less obvious transformations. With increased sediment deposition on the bed, the channel would be expected to adjust by widening (2.1.2). Therefore analysis of the photographs focused on changes in the channel width. The most noticeable changes include the widening of Sullivan Slough, channel narrowing in Mud Creek and slight adjustments of Kilpatrick Pond. Sullivan Slough (Figure 3-1) demonstrates the most significant widening indicating sediment deposition; however, this system is predominantly recharged by groundwater, and therefore, sediment input by runoff is unlikely. Sediment delivery from the slough to creek does not occur though as the system is connected through groundwater rather than surface flow, so the changes in the Slough will not be considered. The narrowing of Mud creek may indicate erosion of the channel bed in this region of the creek, but the resolution of the older photograph makes it difficult to determine whether the creek width changes. The changes in Kilpatrick Pond are varied and measurements of channel width across the pond showed both widening and narrowing (Figure 4-10), which complicates interpretation of deposition and erosion. Throughout the rest of the Silver Creek channel there are insignificant planform changes.



**Figure 4-10 Kilpatrick Pond Channel Width**

Measurements of channel width were made over the green lines. Results indicated that the pond is narrowing in the downstream area and widening in the upstream section.

The aerial photographs provide an insight into the changes to the channel and catchment between the 1950s and 2003. There has been an increase in the vegetation, particularly riparian vegetation and it appears surface and channel bank erosions are the dominant processes in the catchment. The channel network demonstrates little evidence of changes, suggesting there has not been a significant amount of erosion and deposition within the channel during that period.

### **4.3 Discussion**

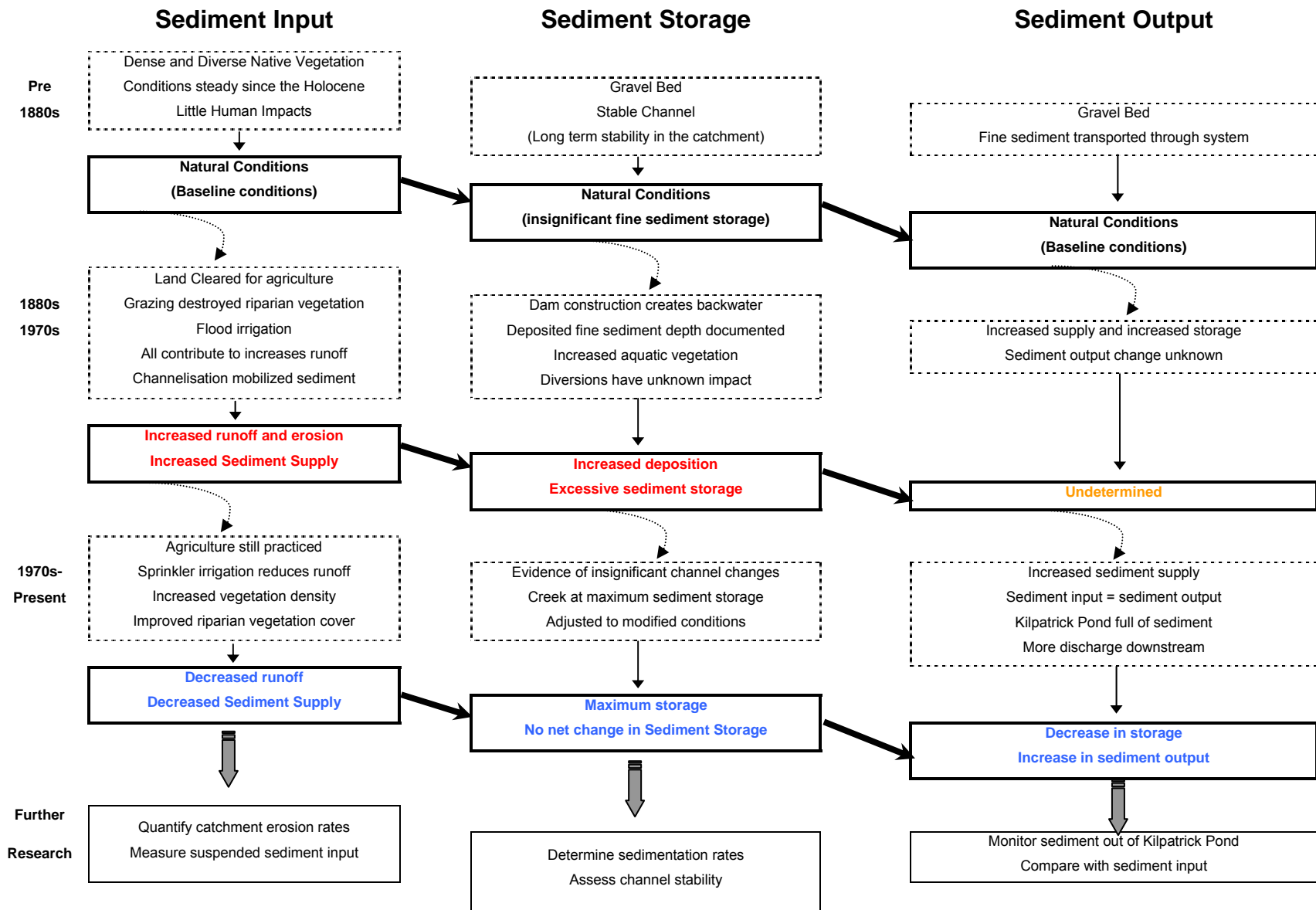
A review of available historical literature, photographs and other data indicates that there have been considerable impacts from human activity on the natural conditions of the catchment and creek since the 1880s. Due to insufficient data required to quantify a sediment budget, a conceptual sediment budget has been developed for Silver Creek based on the current analysis with considerations to the limitations in the methodology. In this section this conceptual sediment budget, its limitations and recommended areas of further research are discussed.

#### **4.3.1 Conceptual Sediment Budget**

The historical literature describing catchment conditions and channel detail sediment inputs, outputs and storage and therefore, can be used to form the basis for a conceptual sediment budget. The budget is calculated for the three significant periods of catchment conditions; before European settlement (pre 1800s), the agricultural period (1880s to 1970s) and the more recent time since the preserve has been established (1970s to present). The conceptual budget is presented in Figure 4-11. Based on the historical information available it appears there is an increase in sediment load within the stream in the past century, which is linked to the introduction of agriculture and the construction of the dam on Kilpatrick Pond.

It appears that the major cause of an increase in sedimentation within the creek is due to the introduction of agriculture into the catchment. From the aerial photographs there is no indication of channel extensions or gully development and in the study by Manuel et al. (1979), wind erosion has been identified as insignificant. These observations suggest that sheet runoff erosion is the dominant erosive process in the catchment. Increases in sheet runoff erosion are associated with the removal of vegetation, which reduces infiltration, increases runoff and exposes the soil to erosion. Erosion from runoff would also have been enhanced by the use of flood irrigation in the fields. Although more information is required to determine the exactly when the sediment problems in the catchment began, the records available suggest it was the early 1900s, which

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**Figure 4-11 Conceptual Sediment Budget**

Natural conditions, the agricultural period and the preserve conditions are described above. The changes to the catchment and channel are in the dashed boxes. Inferred changes in the sediment processes are outlined in the bold boxes. The movement of sediment and movement of impacts through the catchment are shown by the bold arrows. Historical changes in each component of the budget are described in each column. To appreciate the scale of the problem, this budget needs to be quantified.

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corresponds well with the introduction of agriculture. Clearing the riparian vegetation through burning and livestock trampling, would have also exposed the channel banks to erosion and this may have generated a secondary source of sediment within the stream. Aerial photographs indicate limited changes in the bank erosion and associated channel widening and meandering since the 1950s. A final source of sediment may also be channel construction for agriculture, particularly the development of Patton Drain, but this sediment input would be on a much smaller scale than catchment wide erosion from vegetation clearing.

In addition to the increased sediment supply, the construction of Purdy Dam and increased nutrient supply have contributed to the sedimentation in Silver Creek. The Dam has caused flows through Kilpatrick Pond to decrease enhancing settling of sediment transported by the stream. This backwater effect is evident from the increased sediment depth in the channel downstream towards the dam. The problems of sedimentation from dam construction are not unique to Silver Creek as most dams in the United States have experienced similar problems (2.3.2). It is important to distinguish between the role of the dam and agriculture in increasing sedimentation, as the latter is the primary source of the problem, whilst the dam creates conditions that augment the problem by preventing the movement of the increased sediment load downstream. Without the dam, there would still be sediment problems in the stream; however there would be a greater distribution of sediment, particularly downstream of Kilpatrick Pond. In addition to the sediment, nutrient runoff associated with agriculture has also produced conditions favoring deposition in the stream by increasing vegetation growth within the channel. Vegetation restricts the flow, promoting deposition of sediment. As noted by Manuel et al (1979) a cycle can then develop where new vegetation grows on deposited sediment, trapping further sediment and nutrients, which encourages additional vegetation growth. This cycle of vegetation growth prevents entrainment of the deposited sediment.

It is uncertain from the historical information as to when the majority of the sedimentation occurred, and whether the channel has completely adjusted to the environmental conditions that now exist in the catchment. River morphology represents a balance of the geomorphic processes that are controlled by the environmental conditions. Disturbances to the established catchment environment bring about an adjustment in the channel. For Silver Creek, the introduction of agriculture and dam construction has caused channel instability by increasing the sediment input and storage. The most comprehensive and earliest records of catchment change are the aerial

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photographs from 1951. The comparison with the contemporary photographs showed little evidence of progressive changes. This could indicate that the majority of channel changes had occurred by the 1950s and the channel form was, and has remained, stable. Since the agriculture and dam were introduced in the late 1880s, this is not an unreasonable interpretation. If this is the case, sediment storage is at maximum capacity in the channel, and sediment input equals sediment output. This theory was also suggested by Manuel et al (1979). There is however, a requirement for more data to justify this conclusion for the current conditions. The current sediment transport characteristics need to be examined to determine the stability of the channel and predict whether further sedimentation might occur.

### **4.3.2 Further Research**

The historical information provides an insight into the source of sediment and conditions that promote deposition within the creek; however, without quantitative data, the scale and timing of the problem are difficult to comprehend. Owing to this limitation, further research is required to quantify the sediment budget for the three time periods that have been described, and a further examination of historical material is suggested.

Quantifying the components of the sediment budget can be based on field measurements and continued monitoring. A simple comparison should be made between suspended sediment loads and sediment depths measured by Manuel et al. (1979) for 1970s conditions, to identify changes with the sediment input and assess channel stability. The original measurements were made monthly over a 14 month period and similar contemporary measurements would enable the inclusion of seasonal variations that were outside the scope of this project. A more complete monitoring technique would be to regularly measure cross-sections at set locations in the creek against a datum, or by using a differential GPS to assure consistency. Such a monitoring program should begin with a detailed assessment of current sediment volumes in the creek to establish the baseline conditions. Monitoring of suspended sediment load downstream of the dam is also required to quantify sediment output and assess the conclusion that the system is stable. This field work would be useful to assess the current conditions and to describe how they have changed with the introduction of the preserve.

A limitation of the Manuel et al. (1979) approach is that suspended sediment input data does not provide information on the source of erosion within the catchment. Further research is therefore required to determine erosion rates within catchment to determine where remediation efforts

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should be targeted. An alternative approach is the use the Water Erosion Prediction Project (WEPP) model, which uses the Universal Soil Loss Equation (USLE) to estimate soil erosion depending on environmental characteristics such as climate, topography and land use type. This model is suitable for catchments that feature sheet erosion like Silver Creek, and it has been successfully developed to estimate sediment yields for many catchments (Renwick et al. 2005) This model was considered for use in this project; however, it is a data intensive model and producing calculations was not possible given the time and budget of this project. Once the model has been calibrated, it may be possible to use historical information to estimate historic sediment yields and allow the sediment budget to be calculated over the various time periods.

Further research is also required as there is little information regarding the catchment and channel prior to the 1950s. The similarity between the 1951 and 2003 aerial photographs indicates relative stability in the channel; however, the quality of the early photographs limited this analysis. It would be worthwhile to examine later photographs sets, from the 1960s and 1970s to assess whether the channel is in fact stable. Prior to the 1950s, the catchment environment and sedimentation is not well documented. Analyzing all of the historical photographs and collecting verbal accounts from local farmers may provide more insight. A more detailed approach would involve measuring the sedimentation rates within the channel to understand when the erosion occurred. This could be achieved by taking sediment cores throughout the catchment and dating organic material within the fine sediment. Calculating the date of the material, along with the depth of the material within the sediment cores, would provide a rate of deposition which could quantify the rate of sediment storage in the channel.

#### **4.4 Conclusion**

Historical changes in the catchment and channel were analyzed using a sediment budget approach. Insufficient data prompted the construction of a conceptual sediment budget, based on historical literature and aerial photographs. Three periods in recent catchment history were identified; natural conditions prior to the arrival of Europeans, agricultural conditions from the 1880s and the preserve conditions since the 1970s. The majority of the erosion has taken place since the introduction of agriculture, with significant quantities of fine sediment being deposited on the natural gravel bed of the creek. Based on the information available, agriculture is the likely cause of the sediment problems, as vegetation clearing and flood irrigation increased surface runoff and sediment delivery to the creek. The construction of the Dam on Kilpatrick Pond has

contributed to the problem by restricting the downstream flow of water and sediment. Further research including field monitoring, carbon dating and numerical modeling would contribute to the understanding of the historical changes.

The aerial photographs provide the most comprehensive information on changes to the creek since the 1950s. Analysis of these images showed only minor changes suggesting that the creek may currently be in a stable form at maximum sediment capacity. Based on this finding, the sediment transport characteristics of the creek have been investigated and are discussed in the following chapter.

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## Chapter 5: Sediment Transport Characteristics

The review of the historical information for Silver Creek has identified a consistent channel form since the 1950s, indicating that sediment deposition within the creek has potentially ceased. Understanding these sediment dynamics is significant for management, particularly for remediation, as this would allow for prediction of the sediment dynamics in the future. In order to analyze the stability of the system, two approaches have been used. Firstly, the Rouse Equation is used to examine the sediment transport capacity along the creek, comparing the settling and transport characteristics to determine where sediment is carried in the water column. The second approach is to calculate the effective discharge for comparison with the channel morphology, to determine the stability of the channel.

### 5.1 Rouse Equation

The Rouse Equation is a comparison of the downward movement of sediment due to sediment fall velocity and upward movement of sediment due to turbulent fluctuations (Yang 1996). Rouse (1937) developed a ratio of these forces in terms of sediment fall velocity and shear velocity:

$$\text{Where; } Z = \frac{\omega}{kU_*} = \text{sediment fall velocity}$$

$$U_* = \text{shear velocity}$$

$$k = \text{Prandtl-von Kármán universal constant (= 0.4 for clear water).}$$

Using the parameter  $Z$ , it is possible to calculate the sediment concentration distribution in the water column using the Rouse Equation:

$$\frac{C}{C_a} = \left( \frac{h-y}{y} \frac{a}{h-a} \right)^Z$$

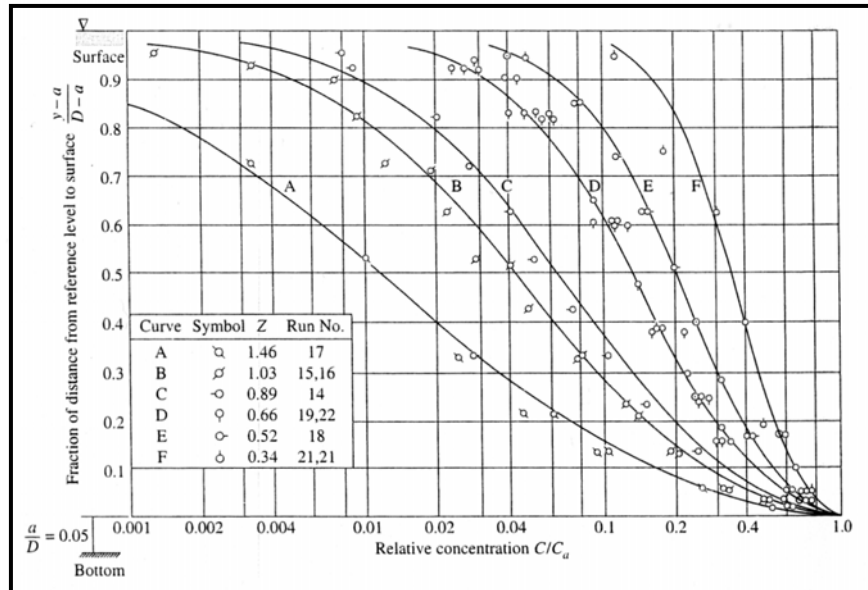
$$\text{Where; } C = \text{sediment concentration at a distance } y \text{ above the bed}$$

$$C_a = \text{sediment concentration at a distance } a \text{ above the bed}$$

$$h = \text{water depth}$$

The concentration  $C_a$  represents an arbitrarily chosen concentration used for comparison. Typically,  $C_a$  is assumed to equal to the bed load concentration, and therefore this point is close to the bed ( $a = 0.05h$ ). Without data to calculate the bed load concentration, the Rouse Equation

can still be used to calculate the vertical suspended sediment distribution, as demonstrated in Figure 5-1. A larger Rouse Parameter ( $Z$ ) value corresponds to higher sediment concentrations towards the channel bed, indicating that sediment deposition is will occur. Conversely, a lower  $Z$  value relates to a higher concentration towards the water surface indicating more sediment is transported in suspension, and deposition is less likely.



**Figure 5-1 Sediment Concentration Profiles (Yang 1996)**

Distribution of suspended sediment in the water column against a dimensionless water height for a range of Rouse Parameter values is shown. Larger values of  $Z$  indicate very little sediment is transported in suspension. Lower values of  $Z$  have a more even distribution of suspended sediment throughout the water column.

### 5.1.1 Methodology

Calculating the Rouse Equation involves determining the sediment fall velocity and the shear velocity at various locations. Sediment fall velocity was calculated using Rubey's Formula, which was developed for gravel, sand and silt particles (Yang 1996):

$$\omega = F \left[ dg \left( \frac{\gamma_s - \gamma}{\gamma} \right) \right]^{\frac{1}{2}}$$

Where

$d$  = particle diameter (m)

$\gamma$  = specific weight of water

$\gamma_s$  = specific weight of sediment (= 2.65 \*  $\gamma$  for quartz material)

$F$  = 0.79 for particles >1mm, in water between 10°C and 25°C

When particle sizes are less than 1mm:

$$F = \left[ \frac{2}{3} + \frac{36\nu^2}{gd^3(\gamma_s/\gamma - 1)} \right]^{\frac{1}{2}} - \left[ \frac{36\nu^2}{gd^3(\gamma_s/\gamma - 1)} \right]^{\frac{1}{2}}$$

For particle sizes greater than 2mm, the fall velocity in 16°C can be calculated by:

$$\omega = 3.32d^{1/2}$$

For Silver Creek, water temperature is generally between 5°C in winter and 15°C in summer, and therefore it was assumed these equations were appropriate for calculating fall velocity (The Nature Conservancy 2003). However, there is no data regarding the particle size of suspended sediment within the creek and therefore exact calculations of fall velocity could not be made. To overcome this lack of data, fall velocity was calculated for a range of particle sizes, from very coarse sediment to very fine silt (Table 5-1).

**Table 5-1 Sediment Particle Size Classification**

The range of sediment particle sizes is presented with their corresponding classification.

Sediment Type	Grain Size (mm)
Extremely Coarse Sand	2.0000
Very Coarse Sand	1.0000
Coarse Sand	0.5000
Medium Sand	0.2500
Fine Sand	0.1250
Very Fine Sand	0.0625
Coarse Silt	0.0313
Medium Silt	0.0156
Very Fine Silt	0.0078
Extremely Fine Silt	0.0039

Shear velocity was calculated based on measurements taken from a field visit in May 2006. Shear velocity is a function of channel characteristics:

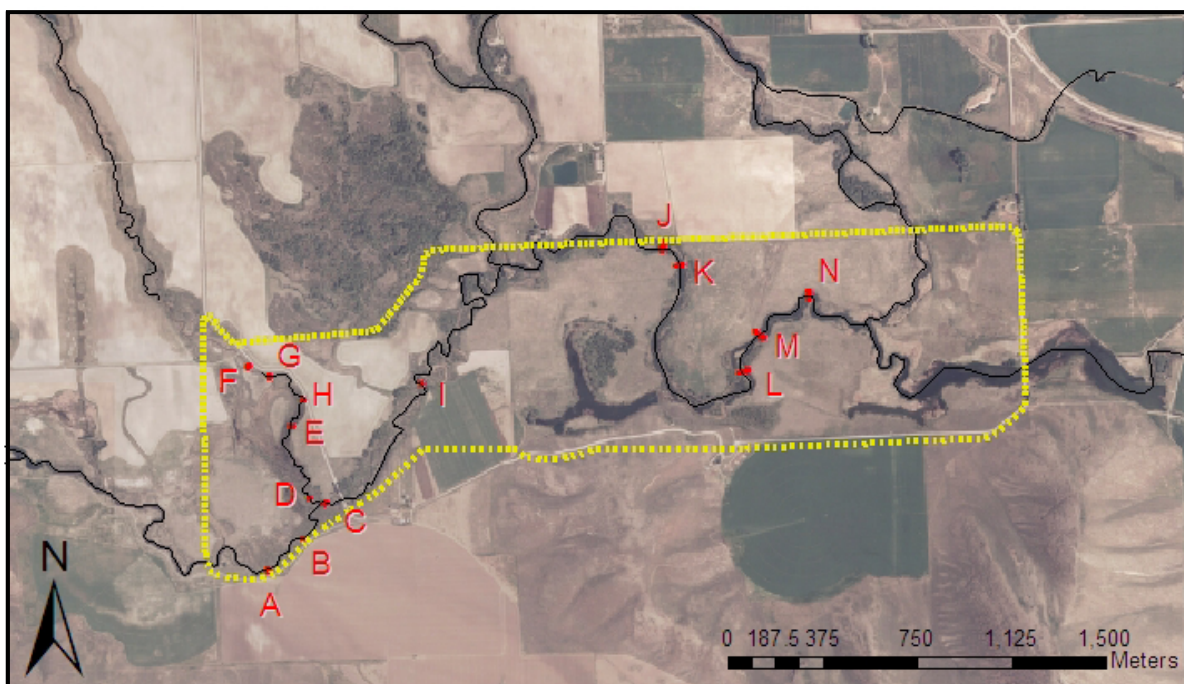
$$U_* = \sqrt{gRS}$$

Where

S = slope

R = hydraulic radius (=cross-sectional area divided by wetted perimeter)

The hydraulic radius was calculated from cross-sections of the creek. These were measured using a Leica GPS System 500 which is a differential GPS system with a vertical accuracy of 2cm. The coordinates system used was Idaho West NAD 83 and the data is presented in Appendix B. The sampling strategy was to measure cross-sections along the entire creek from Stalker and Mud Creeks downstream to Kilpatrick Pond. Owing to the dense riparian vegetation, sediment depth in the creek and time constraints, cross-sections were measured in the locations shown in Figure 5-2. These locations give a fairly comprehensive coverage of the creek within the preserve. Slope was measured using elevations from the cross-section data, and measurements of stream length using ArcGIS 9.1.



**Figure 5-2 Cross-Section Locations**

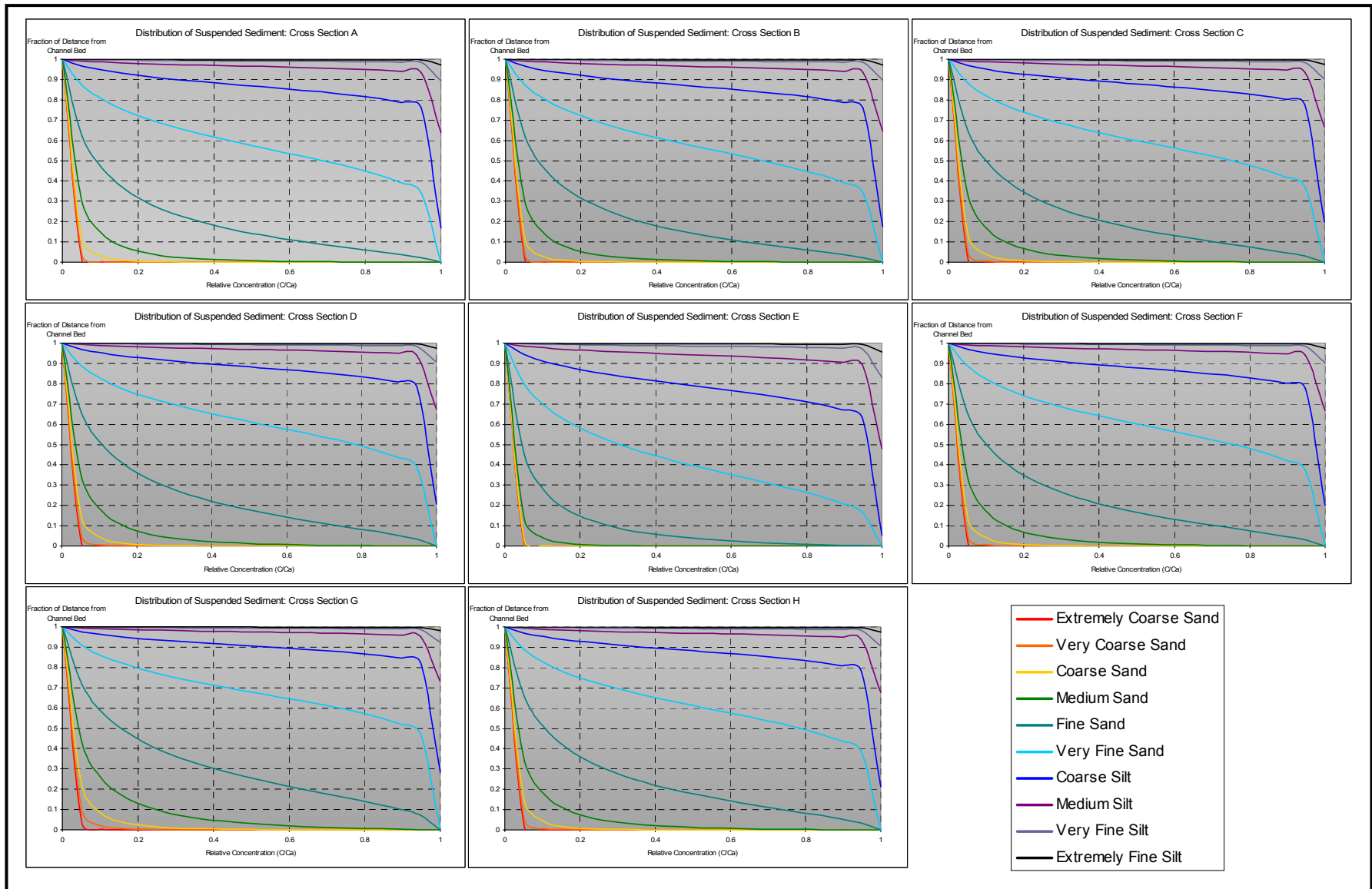
Cross-sections were measured in 14 locations to represent the conditions throughout the preserve. Dense riparian vegetation and deep sediment within the channel prevented some locations being measured.

Shear velocity and fall velocity were then used to construct sediment profiles with the Rouse Equation. Steady flow conditions, and a Prandtl-von Kármán constant of 0.4 (for clear water) were assumed. Sediment concentrations profiles at each cross-section were calculated for the fall velocities of each particle size.

### 5.1.2 Results

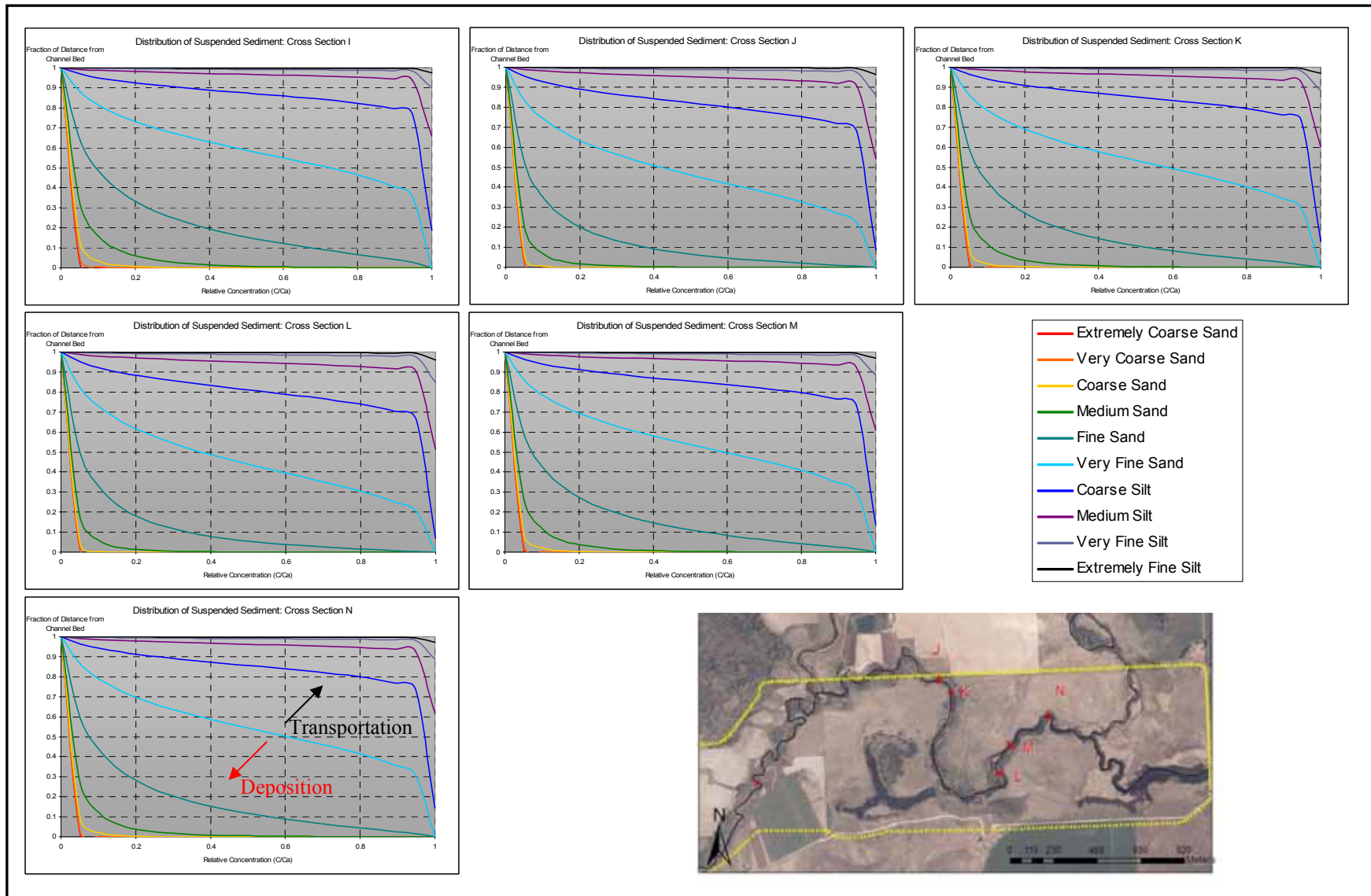
The results for the 14 cross-sections are presented in Figure 5-3 and Figure 5-4 and the calculations are presented in Appendix C. Comparing the graphs, there are no obvious variations downstream along the channel, or between Stalker Creek, Mud Creek and the main Silver Creek channel. All of the plots demonstrate a uniform distribution of fine sediment in the water column, whilst the coarser material is carried in higher concentrations towards the channel bed. Consequently, it appears that fine material is carried in suspension and coarser material is deposited. A transition between the two transport characteristics occurs with very fine sand which has a uniform distribution in the lower quarter of the water column and then reduces in the upper section. This transition is important, as material finer than very fine sand (i.e. silts) are transported, whilst coarser materials (i.e. sand) are deposited. Further research is required to determine the type of sediment entering the system.

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**Figure 5-3 Sediment Concentration Profiles (A-H)**

The sediment concentration profiles indicated no downstream trends. The graphs demonstrate that there the transport capacity in Stalker and Mud Creeks are dependent on the particle size of the sediment input. Fine material is transported in suspension while coarse material is transported as bedload.



**Figure 5-4 Sediment Concentration Profiles (I-N)**

Sediment transport capacity results for Silver Creek are similar to those of Stalker and Mud Creeks. There is a clear transition between the finer silt material and coarse sand material. The boundary for deposition and transportation is therefore very fine sand material as shown in cross-section N. Fine material than this is transported and coarse material settles out.

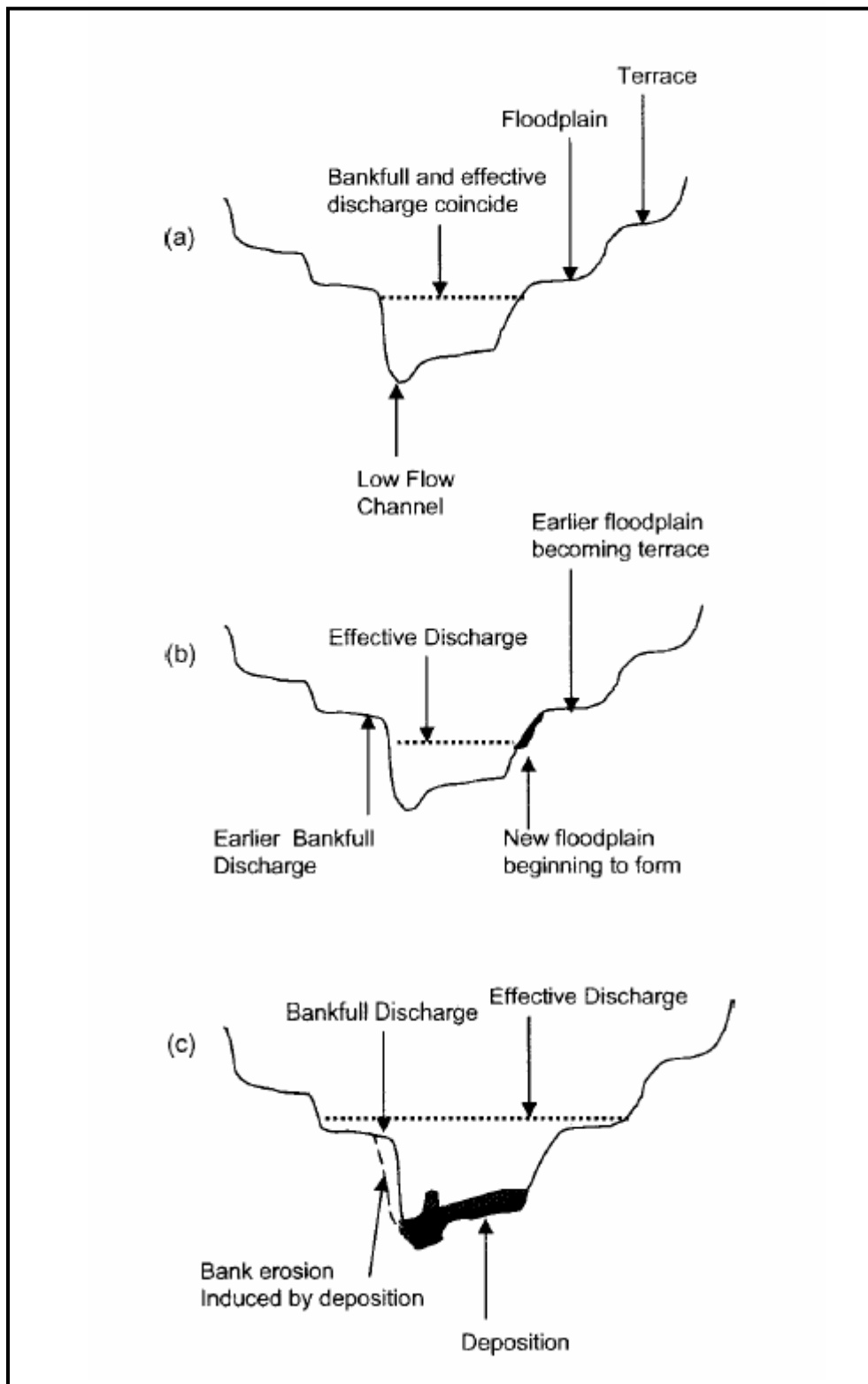
## ***Effective Discharge***

Effective discharge is a technique for evaluating hydrological conditions in the field (Goodwin 2004). As discussed in 2.1.2, sediment discharge controls the cross-sectional and planform morphology of a river. Therefore, the discharge that transports the most sediment over a specific timeframe, known as the effective discharge, is crucial for determining the channel morphology. Consequently, the effective discharge represents the discharge to which a channel will adjust its morphology. Alternatively, the discharge that the cross-section has adjusted to, by containing within the banks, is known as the bankfull discharge (Knighton 1998). A comparison of the bankfull and effective discharges; the discharges to which the channel currently represents and which is adjusting to, provides an insight into the stability of the channel. If the effective discharge is contained within the banks, it indicates the channel may be incising, whilst, if the effective discharge cannot be contained, the channel may be experiencing deposition (Goodwin 2004). If the effective discharge and bankfull discharge are equivalent, then the channel is in a stable form, without considerable deposition and incision (Goodwin 2004). This concept is presented in Figure 5-5.

### **5.1.3 Methodology**

As effective discharge analysis relies on comprehensive discharge data, Silver Creek channel stability was assessed at the gauging station, downstream of the preserve and Purdy Dam (Figure 4-2). Bankfull discharge is calculated from a measurement of the channel cross-section to determine the area of the flow, which is then multiplied by the flow velocity. In order to determine the flow velocity, measured water level and discharge values are required. The water level can be used to establish the cross-sectional area for a specific discharge, and dividing the discharge by the area gives the flow velocity. Assuming flow velocity does not change significantly with discharge, a relationship between discharge and cross-sectional area can be established. A comparison with effective discharge is then possible as the cross-sectional area from the effective discharge can be calculated, or the bankfull discharge can be evaluated from the field measurements.

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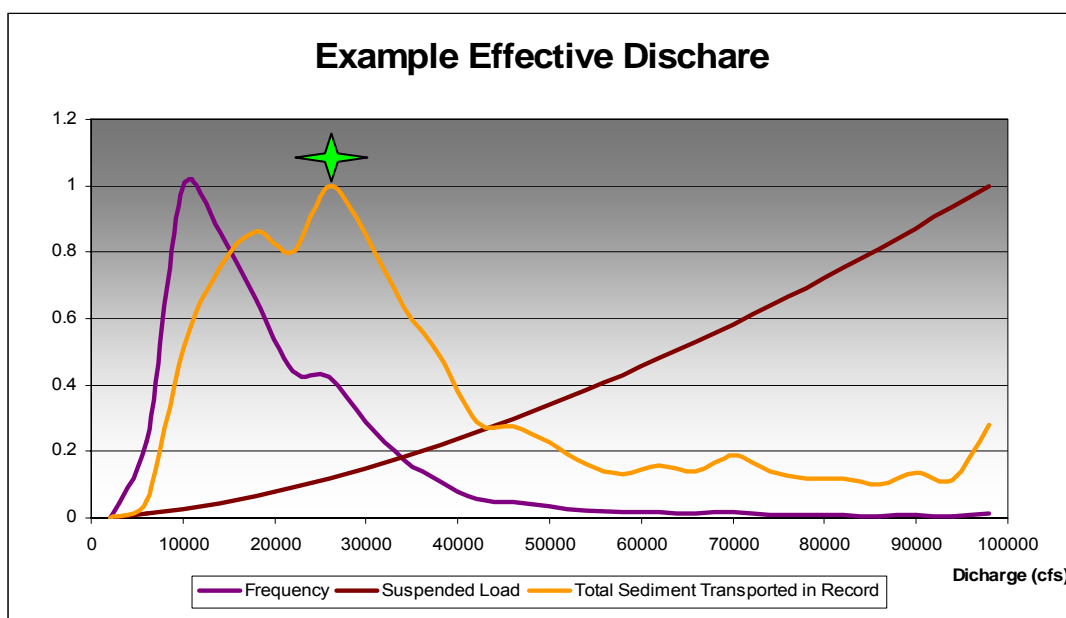


**Figure 5-5 Effective and Bankfull Discharge (Goodwin 2004)**

The relationship between effective discharge and bankfull discharge indicates channel stability. When they are equal the channel is stable (A). If the effective discharge is contained within the bankfull discharge, the channel is incising (B). If the effective discharge is not contained, the channel deposits sediment (C)

Effective discharge is calculated from discharge data and sediment discharge data. As the field site is at a gauging station, a reliable record of daily discharge values exists from 1973 to 2005. However, measurements of sediment discharge were not available. To estimate the sediment transported at each observed discharge, a regression analysis can be used (Goodwin 2004). There is very little quantitative sediment transport information for Silver Creek, particularly downstream of the preserve, making this regression difficult. The best information available for the regression, were sediment loads measured by Manuel et al. (1979) in the 1970s. These values were upstream of Purdy Dam, and therefore to be applicable downstream, the relationship between sediment and discharge at this point, is assumed to be similar.

A model can then be used to calculate the effective discharge from the sediment transport and discharge data. The Effective Discharge Model was developed by Prof. Peter Goodwin at the University of Idaho and utilizes Microsoft Excel. The inputs for the model are the discharge record and the parameters for the sediment regression. Discharge is divided into 25 class intervals and the total sediment load is calculated from the sediment regression, discharge value and frequency of discharge. The total sediment load can then be plotted against discharge values, with the maximum value representing the effective discharge. An example is shown in Figure 5-6. The discharge value can then be assessed against the bankfull discharge to determine the whether the channel is in equilibrium or experiencing incision or deposition.

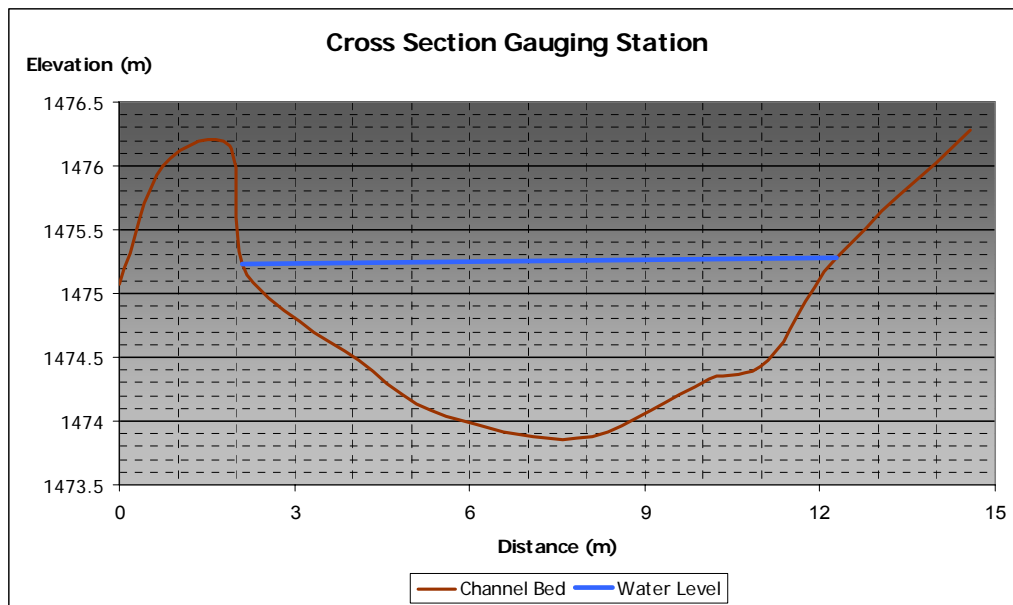


**Figure 5-6 Example Effective Discharge**

This graph demonstrated the process for determining effective discharge. The frequency of each flow is multiplied by the corresponding sediment load value to give total sediment transported. The maximum value, shown here in green, is the effective discharge.

### 5.1.4 Results

A lack of data availability prevented effective discharge calculations being made. The cross-section measured at the gauging station in May 2006 is presented in Figure 5-7. These dimension allowed for the calculation of cross-sectional area of bankfull discharge; however, the setback was that discharge values on the day of measurement were not available during the time of this study. Data at this gauging station is not collected in real time, and although values until April 2006 became available, the May 2006 values were still being collected as of the end of June 2006. This prevented the effective discharge being calculated and analysis of channel stability being conducted. However, once the discharge data becomes available, analysis by The Nature Conservancy is possible from this framework (Appendix D).



**Figure 5-7 Gauging Station Cross-section**

The cross-section at the gauging station was measured. The cross-sectional area can be determined, but more information is required for effective discharge analysis

## 5.2 Discussion

Cross-sections within the catchment provide information about the sediment transport capacity and stability of Silver Creek. Results from field measurement in May 2006 have identified that depending on the sediment particle size, significant deposition or transportation of sediment occurs. Although results could not be generated, the effective discharge approach provides a useful framework for analysis of channel stability. For both methods, further research is required to confirm and expand on the conclusion of this study.

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### 5.2.1 Sediment Transport

Analysis of the Rouse Equation calculation indicates that the sediment transport characteristics are dependent on the sediment particle size. Material finer than 0.0625mm (classified as very fine sand) has an even distribution in the water column and is therefore transported through the system. Conversely, coarser sand material is transported lower in the water column, resulting in deposition. The particle size of sediment input must therefore be identified before significant conclusions can be made. Measuring these properties require further investigation. Manuel et al. (1979) identified that deposited sediment particle size decreased downstream, with up to 75% of sediment in Silver Creek being greater than 0.052mm. This value is for particle sizes taken from sediment cores, and therefore, it therefore it represents deposited material. It is likely to under-represent finer material, which may not be deposited in the stream. Although they were not quantified, observations during field work indicated the sediment in the channel is finer silt material.

If the field observations are correct, and sediment entering the channel is fine material, the current channel morphology supports sediment transportation rather than deposition. The consistency of results throughout the creek indicates that fine sediment from agricultural fields or other sources is transported through the system. This supports the theory that sediment input in Silver Creek equals sediment output as suggested by Manuel et al. (1979). Furthermore, the transport capacity of the stream supports the finding of channel stability from the aerial photograph analysis. As material is transported through the system, deposition of fine sediment and transportation of coarser deposited material does not occur. However, with limited quantitative data on changes in sediment storage this cannot be confirmed. Without sediment particle size information, the Rouse Equation data is limited to describing transport capacity for varying particle sizes rather than the overall transport capacity and any implications on channel stability.

The sediment concentration profiles from the Rouse Equation emphasize the role of vegetation in sediment deposition. For all sediment particle sizes, a considerable concentration of sediment is transported near the channel bed, and therefore, any obstructions to flow near the channel bed can reduce flow velocities, encouraging deposition of sediment. Therefore, in Silver Creek the aquatic vegetation contributes to the quantity of sediment that is deposited within the stream. The flow heights measured in the fields ranged from 0.1 to 0.75m and submerged vegetation can

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occupy a significant portion of that height, leading to deposition of a significant portion of the suspended sediment. Further investigation of the impact under increased and decreased flow heights is required to understand the overall role of vegetation in sediment deposition; however, these results point to it having a substantial contribution.

The effective discharge analysis provides another analysis of channel stability to compliment the sediment transport capacity results. The appropriate data could not be obtained to calculate effective and bankfull discharges for comparison. Had data been available, the location for this analysis may have not been ideal to look at stability of Silver Creek. The impacts from dam construction vary upstream and downstream of the impoundment, and channel adjustments do not necessarily occur over the same time scale. Therefore, downstream stability may not be indicative of stability upstream. Further investigation of effective discharge upstream of the dam would be more beneficial in assessing channel stability, and confirming findings from the historical information.

### **5.2.2 Further Research**

Further research is required to determine the exact transport characteristics of Silver Creek. The results of the Rouse Equation have provided the framework for establishing transport characteristics but the exact sediment particle size measurements are required. This data would provide the ability to assess the whether the channel is experiencing further sediment deposition. A more comprehensive approach would be to calculate the total quantity of sediment that can be transported in the stream and compare this to the total quantity of sediment input. The latter is determined as described in 4.3.2. The Rouse Equation is capable of calculating total sediment transport capacity if the bed load concentration is known. With an absolute value of  $C_a$  the actual concentrations would be represented in the concentration profiles rather than the relative concentrations, and integrating over the depth of the profile generates the total sediment transport capacity for that cross-section. Finally, as sediment fall velocity is dependent on temperature, further research is required to determine whether there are any seasonal variations in transport capacity.

The Effective Discharge analysis demands further data to evaluate the channel stability. With the discharge data, the channel stability could be assessed at the gauging station. A superior approach though is to calculate Effective Discharge and compare to Bankfull Discharge upstream of Purdy

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Dam. This methodology could be applied at several locations to obtain examine channel stability throughout the channel network. Although discharge is only measured at the gauging station, the discharge could be scaled to any point in the catchment using a ratio of drainage areas. Field studies could then be conducted to establish the relationship between transported sediment and discharge at these points to determine the effective discharge. Once this value has been documented, regular measurements of the bankfull discharge would be a useful indicator of channel stability. Effective Discharge analysis could be incorporated into a monitoring strategy.

### **5.3 Conclusion**

Sediment concentration profiles calculated from the Rouse Equation indicate that Silver Creek's transport capacity is high for fine, silt material and low for coarse, sand material. Therefore, fine material is transported through the system, while sand is deposited. Further research is required to determine the exact particle size of transported sediment and identify the general sediment transportation characteristics. Field observations and previous studies indicate the material is fine sediment, indicating the channel is in a stable form, without further deposition. To assess channel stability an effective discharge analysis was conducted. The lack of availability of data prevented calculation of effective discharge and conclusions about channel stability were not possible. This approach would be useful for a monitoring regime and quick field calculations of channel stability.

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## Chapter 6: Remediation

The existence of sediment within Silver Creek has been widely acknowledge, and increasingly there have been increasing calls for remediation efforts to remove it (The Nature Conservancy 2003). The available historical information indicates that a considerable quantity of sediment has been delivered to the creek since the introduction of agriculture and dam construction. However, in more recent times, the creek has featured a stable morphology, and transportation of fine sediment exceeds deposition. Based on these findings, the creek has reached its capacity of sediment storage, and further sedimentation is unlikely. Further research is required to characterize the particle size of suspended sediment input and determine the sedimentation rates throughout the creek which would verify that there is no net storage in the creek. If Silver Creek is at its maximum capacity and in equilibrium with the surrounding catchment, remediation would not necessarily be required.

The current sediment stored within the creek does not represent the natural conditions of the stream and in certain conditions, is detrimental to the fish population. Owing to the abundance of insects in the stream, the fish population is not limited by food supply; however, it has been identified that fish are susceptible to habitat alterations (The Nature Conservancy 2003). A study of surface water temperatures in 2004 established that there is a significant increase in temperature in Kilpatrick Pond towards Purdy Dam, and then higher temperatures downstream of the dam (Watershed Sciences Inc. 2006). The changes in temperature behind the dam and in Kilpatrick Pond are attributed to reduced water depth from sedimentation. The water temperature characteristics, combined with low flow conditions and summer temperatures, create an unsuitable habitat, leading to a decline in the fish population. Remediation is therefore required for the current sediment conditions, particularly in Kilpatrick Pond, to eliminate this threat to the fish population. The most frequently mentioned remediation methods for Silver Creek are sediment dredging and dam removal.

### **6.1 Dredging**

Sediment dredging is the most popular remediation technique, and has been used previously in Silver Creek to address sedimentation. Dredging involves using mechanical equipment to remove sediment, which is then transported and deposited offsite. There are several methods for

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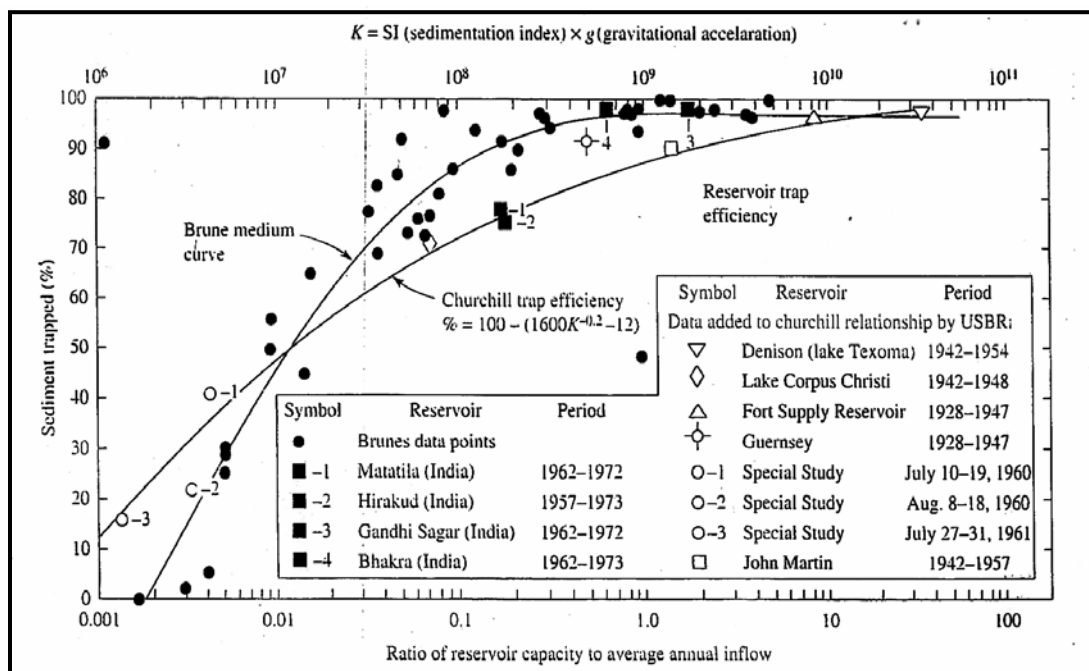
removing the sediment, with the most frequent being suction dredgers, which suck sediment through a long tube, and bucket dredgers, which scoop sediment from the channel. Dredging is a successful technique in that it guarantees sediment removal, eliminates it from moving downstream and provides an immediate solution. For these reasons, it is often popular with the general public (The Nature Conservancy 2003). However, there are many negative consequences to this technique.

The disadvantages of dredging are the high costs involved; destruction of vegetation and removal of benthic organisms (Beach 1994; Gob et al. 2005; Ryding 1982). Dredging costs are high due to the expensive equipment used in the procedure and high costs involved in the disposal of the sediment. Depending on the scale of the project, dredging can often cost hundreds of thousands of dollars (Klahr 2006 pers. comm.). In the dredging process heavy equipment on the banks and in the channels can damage or destroy riparian vegetation, whilst submerged vegetation is removed with the sediment (Hupp 1992). Without this vegetation, banks are exposed to further erosion, and fish that depend on the vegetation for cover, lose their habitat (The Nature Conservancy 2003). Similarly, benthic organisms are removed with the sediment, disturbing the ecology of the stream (Klahr 2006 pers. comm.). Another problem associated with dredging is the disruption to waterfowl. A study by Einarsson (1993) found that the number of ducks diving for food significantly decreased around areas where dredging was taking place. Whilst Einarsson's study is significant for Silver Creek with its large bird population, the study identified ongoing dredging activity rather than the outcomes of dredging to be the source of problem.

More significantly dredging is not a permanent solution. Removing sediment from a river disrupts the morphological balance with the surrounding environmental conditions and sediment supply. Therefore, the channel will adjust its morphology to the new conditions, through either channel incision, bank erosion and generally through further deposition of sediment (Knighton 1998; Arnaud-Fassetta 2003). The impacts of dredging often migrate downstream, as the entire channel adjusts towards equilibrium conditions. Behind dams, the effects are localized. Dredging sediment upstream of a dam increases the storage capacity of the reservoir and decreases the discharge of water and sediment over the dam. Consequently, the reservoir features accelerated deposition until the previous quantity of sediment is stored (Yang 1996). The economic feasibility of dredging is generally determined by the time scale of this reservoir infilling process.

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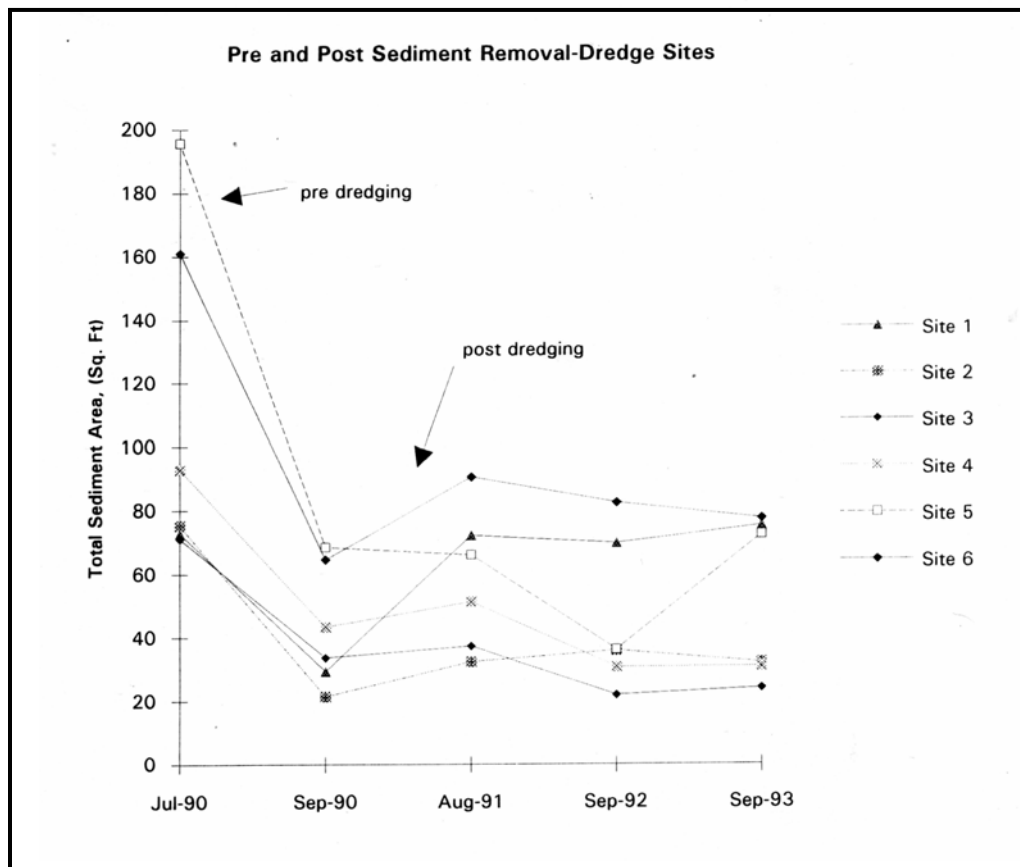
The amount of time taken for a reservoir to reach its sediment storage capacity is determined by the dimensions of the reservoir; sediment characteristics; and the rate of sediment deposition (Yang 1996). The ratio of deposited sediment to the sediment inflow into the reservoir is termed the trap efficiency of the system. Trap efficiency is determined from sedimentation rates in the reservoir. Numerous studies have led to empirical relationships between reservoir characteristics and trap efficiency being developed. Figure 6-1 illustrates a trap efficiency curve developed by Churchill (Churchill 1948) for small reservoirs and settling basins. Calculating the ratio of reservoir capacity to average annual inflow provides the percentage of sediment that is deposited in the reservoir. To determine the quantity of sediment deposited, the total sediment input to the stream is required, which can be calculated using a number of different methods. For example, if bed load concentrations were available, the Rouse Equation could be integrated to give the total sediment input into the stream. With the annual quantity of sediment deposited into the stream, the length of time required for the reservoir to infill calculated knowing the sediment storage capacity of the reservoir. Although Yang (1996) cautions that trap efficiency decreases continuously as sediment is deposited, and new calculations of reservoir capacity are required as sediment deposition occurs.



**Figure 6-1 Trap Efficiency Curves (Churchill 1948)**

The percentage of sediment transported into the dam that is deposited can be determined from the ratio of reservoir capacity to average annual inflow. The curves were developed from a study of small dams.

Dredging work has previously been conducted in Silver Creek system, although at a significantly smaller scale than Kilpatrick Pond. The previous work was conducted on Stalker Creek, both within the preserve and on private property in 1990. Measurements of total sediment cross-sectional area were taken at six sites to monitor the success of the dredging program. The results are presented in Figure 6-2. Dredging removed between 50% and 70% of the sediment at these sites. The cross-sections were remeasured annually from 1991-1993 and demonstrated varying trends. Sites #2, #3, #4 and #6 all experienced relatively consistent sediment levels over the three years while site #5 featured a continued decrease in sediment storage for 2 years, followed by a return to post dredging conditions. Site #1, the furthest upstream, had returned to pre-dredging conditions by 1993. These results for sites #2-#5 indicate that dredging was successful. Given that one of the sites returned to pre-dredging sediment levels within 3 years, it is difficult to judge whether it is successful over the long term. Remeasuring these cross-sections for present conditions would provide a better indication of the level of success achieved by the 1990 dredging.



**Figure 6-2 Dredging Monitoring**

The cross-sectional area in Stalker Creek for pre and post dredging conditions show for most sites there has been a decrease in sediment storage. Site #1 had returned to pre-dredging conditions by the completion of this monitoring.

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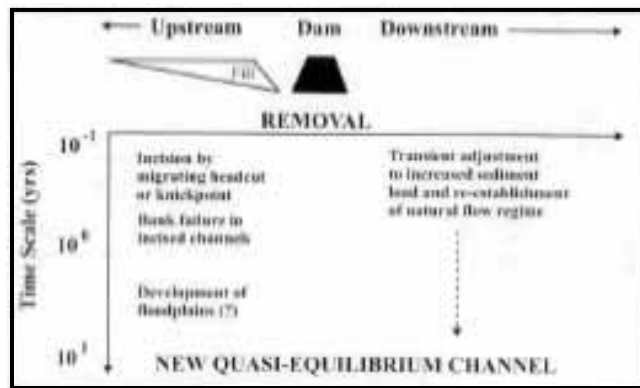
## **6.2 Dam Removal**

The flow of sediment and water is restricted downstream of a dam. This has a severe impact on the morphology of rivers. Many dams, including Purdy Dam, that were constructed in the late 1800s and early 1900s, are now being considered for removal owing to the cost of maintenance and repair (Hart & Poff 2002). Dam removal has considerable impacts on the morphology of the stream both upstream and downstream since flow is no longer impeded and sediment is remobilized. Further scientific studies are required to predict how different types of rivers will respond to dam removal; however, general responses are well understood (Hart & Poff 2002; Pizzuto 2002)

Upstream of the dam, the impounded sediment is incised, creating a new channel, and downstream, the increased sediment load leads to deposition and a re-establishment of the natural channel morphology. With dam removal, flows generally return to natural conditions and the channel upstream will also adjust to this environment and form an equilibrium channel. This process involves channel incision; formation of a new flood plain and in weak soils bank failure (Pizzuto 2002). Channel incision entrains sediment and as the dam no longer restricts sediment movement, there is a significant increase in sediment load downstream. Corresponding to this sediment load, the channel adjusts to a natural morphology, balanced with the surrounding environmental conditions (Pizzuto 2002).

Dam removal is a long term solution to sediment removal and it leads to the creation of a natural channel morphology. The time it takes to achieve this form determines whether it is a suitable option. The rate of incision upstream of the removed dam is poorly documented, although several studies record changes continuing for several decades (Pizzuto 2002). As the sediment incision upstream occurs over time, the downstream adjustments occur over similar timescales, and are highly variable. An illustration of the geomorphic process and timescales for dam removal is presented in Figure 6-3. The exact timescale of all the modifications depends on the environmental characteristics of the site; the dam properties; and the design and process of dam removal (Pizzuto 2002). Immediate and complete removal of the dam can result in rapid erosion upstream and excessive sedimentation downstream, which causes problems associated with increased sediment load (2.3.1). Pizzuto (2002) identified that “controlled lowering” can minimize the potential downstream impacts.

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**Figure 6-3 Timescales of Geomorphic Processes after Dam Removal**

Geomorphic processes that occur after dam removal and their corresponding time scales are described. The timescales for change are highly variable and depend on the sediment characteristics and dam dimensions amongst other variables.

Along with changes to the hydrodynamics and geomorphology, dam removal impacts the river ecology (Stanley & Doyle 2002). Removing the dam potentially allows flushing flows to return. These flows are capable of removing fine sediment from gravel streams, which is beneficial for spawning and has a positive impact on the fish population (Richter et al. 1997). Dam removal also eliminates obstructions for fish passage upstream and creates a diversity of stream habitats (Bednarek 2001). There are also potential negative impacts as Pollard (2004) identified that downstream of dams excessive silt can reduce the functional diversity of invertebrates, and significant changes in the aquatic and riparian vegetation can occur (Hart & Poff 2002).

Although it potentially provides a long term solution to sedimentation issues, and the river returns to a natural morphology, dam removal is not a popular solution with the general public. Decisions affecting the future of small dams are determined in the “court of public opinion”, rather than being based on scientific studies (Johnson & Graber 2002). Johnson and Graber (2002) provide a review of public concerns, suggesting that dam removal and restoration opportunities are only possible with public support. In some cases, even when the removal costs were less than the costs of repair, communities were reluctant to remove old and obsolete dams (Hart & Poff 2002). Another issue is that laws designed to protect ecosystems often restrict ecological restoration projects such as dam removal and dredging (Hart & Poff 2002).

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### **6.3 Discussion**

Sediment dredging and dam removal are both viable options for remediation of the excessive sediment storage. For Silver Creek, the specific environmental characteristics, historical changes and current sediment transportation characteristics affect the suitability of each method. Selecting either option requires an assessment of the geomorphological, ecological, economic and social impacts. Based on the current data available, there is also a requirement for further research.

#### **6.3.1 Remediation Techniques**

The two remediation techniques considered in this report offer solutions on different timescales. Dredging is an immediate solution with some doubt over long term results. Removing the dam and remobilizing the sediment can take several decades to reach an equilibrium morphology, which prompts negative public opinion. For Silver Creek there is uncertainty over the preferable remediation technique.

There is uncertainty over whether dam removal would lead to impounded sediment scouring from Kilpatrick Pond. Since the introduction of agriculture, surface diversions and ground water extraction have altered the hydrology and their impact on the system remains unknown (Brown 2001). In Kilpatrick Pond, the irrigation diversion near Purdy Dam has altered the hydrodynamics by providing a secondary outlet from the pond. The impact is that discharge from the Pond after dam removal being less than in pre-agricultural conditions. The contemporary hydrodynamics need to be established to determine whether dam removal and resultant discharges from the Pond are sufficient to scour out the sediment from Kilpatrick Pond. The design of dam removal is also significant given the quantity of sediment in Kilpatrick Pond and potential impacts downstream. In the short-term dam removal is a considerably more cost-effective solution than dredging, but its effectiveness requires further research.

The limitation of dredging in the short-term is the riparian vegetation damage from heavy equipment. Previous work using suction dredging on Stalker Creek had little impact on the vegetation though. Whether this method is suitable for Kilpatrick Pond, and whether the impacts on vegetation can be mitigated needs to be determined.

Over the long term, the effectiveness of dredging and impacts from dam removal are unknown. The viability of dredging is determined by how long it will take before the sediment returns and

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therefore the quantity of sediment entering Kilpatrick Pond. Although the historical information and sediment transport characteristics, indicate that Silver Creek currently experiences little deposition of fine sediment and is in a stable form this is disrupted by the dredging. Dredging is not directed at the causes of sedimentation within the catchment, but at removing the end product in the channel. So the sediment supply and the characteristics that support deposition (i.e. the Dam) remain, and eventually the channel will experience excess sediment storage once more. The timescale of this requires further investigation. Based on the historical information, particularly the 1951 aerial photograph, the time frame for Kilpatrick Pond to reach maximum sediment capacity is likely to be less than 70 years given that a stable morphology has achieved by the 1950s. For the current conditions the time required to achieve sediment storage capacity may be significantly longer because the riparian vegetation has stabilized the channel banks and sediment supply from the agricultural fields may be exhausted. This emphasizes the significance of quantifying the erosion rates and sediment input within the catchment. Previous dredging monitoring on Stalker Creek does not provide an indication as no long term monitoring was conducted.

The final morphology of the channel if the dam was removed and the time scale to adjust to the equilibrium form are difficult to predict. Increasing the discharge from Kilpatrick Pond would replace the slow moving water body with a faster flowing narrower channel upstream of the dam and higher water levels downstream. Due to the irrigation diversions, it may not return to the pre-agricultural conditions. However, the final morphology will represent a channel in equilibrium with surrounding environmental characteristics and remove the excess sediment and distribute it downstream. This will improve the habitat for fish with a passage where the dam was and a deeper channel upstream with lower summer temperatures than are currently experienced. A potential problem with dam removal concerns the material that is deposited in the pond. Sediment within the pond was deposited in the early 1900s and therefore may contain toxic chemicals, such as pesticides, that were used for agriculture early last century (Milligan 2006 pers. comm.). Although no data exists to confirm this, it requires investigation as remobilizing this sediment could cause more significant problems than the sedimentation issues.

Along with the geomorphic and ecological considerations are the economic and social interests. Dredging the sediment from Kilpatrick Pond is a preferable method as it offers an instantaneous solution and retains the current conditions in the creek. Dam removal is less desirable as it

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removes the slow moving body of water behind the dam and replaces it with a deeper, narrower channel. This provides a better habitat for fish, but it is not ideal for fishing, particularly the fly fishing which attracts many thousands of visitors annually. Consideration must also be given for the fact the dam is privately owned and not within the preserve boundary. Removing it would impact the irrigation diversion that diverts from the pond is not an insignificant issue. From an economic perspective though, dam removal is a more cost effective solution as dredging work would have to be repeated in the future.

Based on the information presented in this report, correctly designed and managed dam removal, represents a better geomorphic and ecological solution than dredging. From a recreational and fly fishing perspective, this is an inappropriate solution given the potential changes to the creek. The information in this report is insufficient to determine the impacts of either remediation method and further research is required to obtain valuable information for decision-making.

### **6.3.2 Further Research**

Further research is required to determine the impacts and effectiveness of these remediation methods. A detailed study of the hydrodynamics and the influence of the irrigation canal are necessary to establish whether removing the dam will scour out the sediment and predict the type of channel that will result. This could be accomplished using a 2D hydrodynamic model such as Mike-21 to calculate shear stress and evaluate whether sediment is entrained (Goodwin 2006 pers. comm.). The benefit of using a 2D model is that the planform of the resulting channel could then be approximated. Along with this, the downstream impacts require a detailed investigation, not only of the geomorphic changes, but also the ecological implications. This requires an estimation of the quantity of sediment moving downstream. Finally, these impacts need to be linked to the design of the dam removal, and an investigation into the most appropriate design, that limits the negative impacts, needs to be established.

The feasibility of dredging is primarily determined by the amount of time required for the sediment to completely infill again. This can be calculated using the trap efficiency curves outlined in 6.1. Data is required to determine the characteristics of the sediment input to the pond, the quantity of sediment, dimensions of Kilpatrick Pond and inflow to the pond. These could be measured using field monitoring or calculated using transport equations and comparisons with other datasets. The erosion rates and quantity of sediment input also needs to be established to

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determine whether erosion rates are as high as historical times. Finally, the dredging method that has the least impact on the riparian and aquatic vegetation must be identified.

The most suitable method for alleviating the sediment problem must account for the geomorphic, ecological, economic and social concerns. Accounting for these different aspects, and assessing the success over a long time scale requires using sustainability frameworks. There is scope here to develop an Index of Sustainable Functionality (ISF) to determine which remediation method is suitable, and it provides a framework for monitoring ongoing conditions (Imberger et al. 2005).

#### **6.4 Conclusion**

Although the historical information and sediment characteristics suggest that further sedimentation is unlikely, the current sediment problem in Silver Creek requires attention. Two remediation methods have been considered and their benefits and impacts compared. Dredging is popular solution with the general public, and it provides an immediate solution to the excess sediment in the creek. Dredging is not effective over the long term since the sediment will return. Dam removal is another possible solution that will allow the channel to adjust towards an equilibrium form. This a more desirable solution over the long term, particularly in a geomorphic and ecological sense; however, it would remove the backwater in Kilpatrick Pond which is popular for recreational use. Further research is required to determine the impacts of each approach to aid in deciding which one is appropriate for Silver Creek.

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## Chapter 7: Conclusion

The aims of this project were to investigate the causes of excess sedimentation in Silver Creek; determined the channel stability and transport characteristics; and consider possible remediation techniques. The following conclusions were established from the review of historical information, field investigations and GIS analysis:

- There is insufficient current data to quantify a sediment budget for Silver Creek. Sediment input data is either outdated or inappropriate and sediment yield, output data, has not been collected. Numerous cross-sections provide information on sediment storage but they have not been regularly or consistently measured.
  - Agriculture within the catchment is the likely cause of the increased sediment load in the creek. Clearing of native vegetation and flood irrigation techniques have increased surface runoff and erosion. The scale and timing of the sedimentation problem corresponds with the introduction of agriculture.
  - The construction of the dam on Kilpatrick Pond has increased sediment deposition within the channel. The dam has reduced downstream flow of water and sediment, creating a backwater area featuring excessive deposition. Increased sediment depths downstream towards the dam indicate its role in sediment storage. These problems are common for many dams in the United States.
  - Aquatic vegetation plays a significant role in sediment deposition. Submerged plants reduce stream velocity, increasing deposition of sediment. Nutrient runoff from agricultural fields increased aquatic plant growth and subsequent deposition. Remediation efforts by the Nature Conservancy have targeted this problem.
  - Construction of irrigation channels has altered the hydrology and sediment dynamics within the catchment. Impacts from surface diversions and groundwater extraction are yet to be determined. Modifications of natural channels to create irrigation canals and drains have contributed to the increased sediment load. Although at a smaller scale than vegetation clearing from agriculture.
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- Analysis of aerial photographs indicates minimal changes to the Silver Creek channel from 1951 to 2003. This may signify the channel has attained a stable morphology by the 1950s. The photographs also demonstrate an increase in vegetation in the catchment during that time. The lack of gully formation indicates surface sheet erosion is the likely process of increased sediment delivery to the creek.
  - Fine sediment would be transported through the system and coarser sediment is deposited. Calculation of sediment concentration profiles using the Rouse Equation indicate that silt concentration is evenly distributed in the water column and transported by suspension. Sand is transported near the channel bed and is more likely to deposit. Similar results were identified in all cross-sections that were surveyed.
  - The particle size of the sediment load needs to be determined to characterize the transport capacity of Silver Creek. It is suspected that the material is predominantly silts. If this is confirmed, the channel has a high transport capacity and a stable form.
  - A lack of data availability prevented analysis of channel stability using an effective discharge approach. It would provide a useful preliminary assessment of channel stability in future monitoring.
  - Increased water temperatures in Kilpatrick Pond indicate that the current level of sediment stored in the creek has detrimental impacts that require remediation. Assessment of channel stability is required to determine the extent of remediation efforts.
  - The feasibility of dredging is determined by the time required for the Kilpatrick Pond to return to current sediment storage levels. This can be determined using trap efficiency curves for small dams. Dredging does not address the sources or favorable conditions of excessive sedimentation within the creek. It is an effective short term solution as it guarantees immediate sediment removal and has public support.
  - The effectiveness of dam removal in remobilizing the entrained sediment is unclear as the irrigation diversion from Kilpatrick Pond has altered the hydrodynamics. If this method is
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effective, the channel will adjust towards natural conditions in the long term. This would be beneficial for the river ecology. Removing the backwater behind Purdy Dam would have a negative impact on the recreational value of Silver Creek.

## **7.1 Further Research**

The study of sediment dynamics in Silver Creek has identified a number of areas that require investigation to further the understanding of increased sedimentation; provide greater detail of historical changes and aid in decision making for management. The following are recommendations for further research:

- A long term field monitoring program is required to update the findings of Manuel et al. (1979). Measuring sediment depth at the same locations and determining the suspended sediment concentration from the tributaries would provide an indication of changes to the sediment storage and input since the introduction of the preserve.
  - Measurement or modeling of sediment yield from the agricultural fields. This is the ultimate source of sediment in the catchment and has not been investigated. The erosion rates could be determined in the field, or catchment wide sediment input estimated using a WEPP model. The latter would allow for historical changes to be evaluated.
  - Future monitoring of sediment depths in channels would allow for quantification of sediment storage. This could be achieved through regularly taken cross-section using consistent techniques at set locations. Measuring the cross-sections against a datum or using a differential GPS would provide greater accuracy of changes.
  - Determine historical sedimentation rates in the creek. Taking sediment cores and dating deposited organic material throughout the system would provide historical rates of deposition and changes in storage over time.
  - Further analysis of aerial photographs between 1951 and 2003 may identify sensitive changes that were not identified in the low contrast early photograph.
  - Establish the conditions in the catchment between the 1880s and 1950s. Oral histories of local farmers and comparison of historical photographs with current conditions would provide useful information.
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- Measurement sediment load particle size in Silver Creek and its tributaries. This allows the transport characteristics to be determined from the Rouse Equation sediment concentration profile framework that has been developed.
  - Calculate the total transport capacity of the stream by evaluating the bed load concentrations. Sediment characteristics and bed load transport equations are required for this calculation. The total transport capacity can be compared with the total sediment input to predict whether further deposition will occur.
  - Assess seasonal variations in the transport capacity. Sediment fall velocity is dependent on temperature, which fluctuates in Silver Creek. Measurements of cross-sections and stream temperatures during different seasons would allow for this analysis.
  - Obtain discharge values for the gauging station and perform an effective discharge evaluation of the creek. This methodology would also be useful in assessing channel stability upstream on the dam, and could be achieved by monitoring discharge and sediment concentrations.
  - The time it will take for Kilpatrick Pond to completely infill after dredging requires calculation. The trap efficiency curves provide a framework for this assessment. Field investigations could provide the reservoir dimensions and sediment input data required.
  - The hydrodynamics of Kilpatrick Pond require investigation to determine whether removing the dam will scour out the sediment. Modeling using a 2D hydrodynamic model such as Mike-21 would be a suitable method. The estimated resulting channel could then be modeled using DYRESM to determine whether it will provide suitable temperatures for fish habitat.
  - Determine the downstream impacts of dam removal. Sediment scoured from Kilpatrick Pond poses a threat to the downstream channel if released it moves downstream in large quantities. The ideal design for dam removal to minimize these impacts requires further research.
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## References

- Abrahams, A. D. 1984, 'Channel Networks; a Geomorphological Perspective', *Water Resources Research*, vol. 20, no. 2, pp. 161 - 188.
- Acornley, R. M. & Sear, D. A. 1999, 'Sediment Transport and Siltation of Brown Trout (*Salmo trutta* L.) Spawning Gravels in Chalk Streams', *Hydrological Processes*, vol. 13, pp. 447 - 458.
- Ahnert, J. 1970, 'Functional Relationship Between Denudation, Relief, and Uplift in Large Mid-Latitude Drainage Basins', *American Journal of Science*, vol. 268, pp. 243 - 263.
- Allan, J. D. 2004, 'Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems', *Annual Review of Ecology, Evolution, and Systematics*, vol. 35, no. 1, pp. 257 - 284.
- Allen, R. 2006, *Professor, University of Idaho*.
- Anderson, J. E., Ruppel, K. T., Glennon, J. M., Holte, K. E. & Rope, R. C. 1996, *Plant Communities, Ethnoecology, and Flora of the Idaho National Engineering Lab. Idaho Falls, ID*, National Research Foundation.
- Angelier, E. 2003, *Ecology of Streams and Rivers*, Science Publishers, Inc., Enfield.
- Arnaud-Fassetta, G. 2003, 'River Channel Changes in the Rhone Delta (France) Since the end of the Little Ice Age: Geomorphological Adjustments to Hydroclimatic Change and Natural Resource Management', *Catena*, vol. 51, pp. 141 - 172.
- Baxter, R. M. 1977, 'Environmental Effects of Dams and Impoundments', *Annual Review of Ecology and Systematics*, vol. 8, no. 1, pp. 255 - 283.
- Beach, T. 1994, 'The Fate of Eroded Soil: Sediment Sinks and Sediment Budgets of Agrarian Landscapes in Southern Minnesota, 1851-1988', *Annals of the Association of American Geographers*, vol. 84, no. 1, pp. 5 - 28.
- Bednarek, A. T. 2001, 'Undamming Rivers: A Review of the Ecological Impacts of Dam Removal', *Environmental Management*, vol. 27, no. 6, pp. 803 - 814.
- Bouma, N. A. & Imeson, A. C. 2000, 'Investigation of Relationships Between Measured Field Indicators and Erosion Processes on Badland Surfaces at Petrer, Spain', *Catena*, vol. 40, no. 2, pp. 147 - 171.
- Brandt, S. A. 2000, 'Classification of Geomorphological Effects Downstream of Dams', *Catena*, vol. 40, no. 4, pp. 375 - 401.
- Brockway, C. E. & Kahlow, M. A. 1994, *Hydrological Evaluation of the Big Wood River and Silver Creek Watersheds Phase I*, University of Idaho, Moscow.
- Broekhuizen, N., Parkyn, S. & Miller, D. 2001, 'Fine Sediment Effects on Feeding and Growth in the Invertebrate Grazers *Potamopyrgus antipodarum* (Gastropoda, Hydrobiidae) and *Deleatidium* (Ephemeroptera, Leptophlebiidae)', *Hydrobiologia*, vol. 457, pp. 125 - 132.
- Brown, A. L. 2001, *Augmented Flows in Silver Creek*, Ketchum.
- Campbell, I. A. 1989, 'Badlands and Badland Gullies', in *Arid Zone Geomorphology*, ed. D. S. G. Thomas, Belhaven Press, London, pp. 159 - 183.
- Castelin, P. M. & Chapman, S. L. 1972, *Water Resources of the Big Wood River and Silver Creek Area, Blaine County, Idaho*.
- Chakrapani, G. J. 2005, 'Factors Controlling Variations in River Sediment Loads', *Current Science*, vol. 88, no. 4, pp. 569 - 575.

- Church, M. 2006, 'Bed Material Transport and the Morphology of Alluvial River Channels', *The Annual Review of Earth and Planetary Science*, vol. 34, pp. 325 - 354.
- Churchill, M. A. 1948, 'Discussion of "Analyses and Use of Reservoir Sedimentation Data"', in *Proceedings of the Federal Inter-Agency Sedimentation Conference*, ed. L. C. Gottschalk, Denver, Colorado. Cited by Yang, C. T. 1996, *Sediment Transport Theory and Practice*, McGraw-Hill, New York.
- Chutter 1968, 'On the Ecology of the Fauna of Stones in the Current in a South African River Supporting a very Large Simulium (Diptera) Population', *The Journal of Applied Ecology*, vol. 5, no. 3, pp. 531 - 561.
- Clark, E., Webb, B. W. & Ladle, M. 1999, 'Microthermal Gradients and Ecological Implications in Dorset Rivers', *Hydrological Processes*, vol. 13, pp. 423 - 438.
- Colby, B. R. 1963, *Fluvial Sediments: A Summary of Source, Transportation, Deposition, and Measurement of Sediment Discharge*, U. S. Govt. Print. Off, Washington.
- Daniel, J. R. K. 1981, 'Drainage Density as an Index of Climatic Geomorphology', *Journal of Hydrology*, vol. 50, no. 1-4, pp. 147 - 154.
- Dietrich, W. E. & Dunne, T. 1978, 'Sediment Budget for a Small Catchment in Mountainous Terrain', *Zeitschrift fuer Geomorphologie*, vol. 29, pp. 191 - 206.
- Edwards, T. K. & Glysson, G. D. 1999, *Field Methods for Measurement of Fluvial Sediment*, 3, USGS, Reston, Virginia.
- Einarsson, A. & Magnúsdóttir, M. L. 1993, 'The Effect of Sediment Dredging on the Distribution of Diving Ducks at Lake Myvatn, Iceland', *Biological Conservation*, vol. 66, pp. 55 - 60.
- Gallart, F., Sole, A., Puigdefabregas, J. & Lazaro, R. 2002, 'Badland Systems in the Mediterranean', in *Dryland rivers: hydrology and geomorphology of semi-arid channels*, eds L. J. Bull & M. J. Kirkby, John Wiley & Sons, Chichester, pp. 299 - 326.
- Gob, F., Houbrechts, G., Hiver, J. M. & Petit, F. 2005, 'River Dredging, Channel Dynamics and Bedload Transport in an Incised Meandering River (The River Semois, Belgium)', *River Research and Applications*, vol. 28, pp. 791 - 804.
- Goodwin, P. 2004, 'Analytical Solutions for Estimating Effective Discharge', *Journal of Hydraulic Engineering*, vol. 130, no. 8, pp. 729 - 738.
- Goodwin, P. 2006, *Professor, University of Idaho*.
- Graf, W. L. 1999, 'Dam Nation: A Geographic Census of American Dams and Their Large-Scale Hydrologic Impacts', *Water Resources Research*, vol. 35, no. 4, pp. 1305 - 1311.
- Graf, W. L. 2001, 'Damage Control: Restoring the Physical Integrity of America's Rivers.' *Annals of the Association of American Geographers*, vol. 91, pp. 1 - 27.
- Gregory, J. S., Beesley, S. S. & Van Kirk, R. W. 2000, 'Effect of Springtime Water Temperature on the Time of Emergence and Size of *Pteronarcys Californica* in the Henry's Fork Catchment, Idaho, U.S.A', *Freshwater Biology*, vol. 45, pp. 75 - 83.
- Gregory, K. J. & Gardiner, V. 1975, 'Drainage Density and Climate', *Zeitschrift fuer Geomorphologie*, vol. 19, no. 3, pp. 287 - 298.
- Griffith, J. S. & Grunder, S. A. 1982, *Sediment Removal as a Means of Stream Habitat Improvement*, Idaho State University, Pocatello.
- Hammond Murray-Rust, D. 1972, 'Soil Erosion and Reservoir Sedimentation in a Grazing Area West of Arusha, Northern Tanzania', *Physical Geography*, vol. 54, no. 3/4, pp. 325 - 343.

- Hart, D. D. & Poff, N. L. 2002, 'A Special Section on Dam Removal and River Restoration', *BioScience*, vol. 52, no. 8, pp. 653 - 655.
- Hauck, F. R. 1947, *Preliminary Observations on Silver Creek and its Headwater Tributaries with Notes on Population Studies and Some Fishing Results*, Idaho Fish and Game Department.
- Hupp, C. R. 1992, 'Riparian Vegetation Recovery Patterns Following Stream Channelization: a Geomorphic Perspective', *Ecology*, vol. 73, no. 4, pp. 1209 - 1226.
- Imberger, J., Mamouni, E.-A. D., Anderson, J., Ng, M.-L., Nicol, S. & Veale, A. 2005, 'The Index of Sustainable Functionality: A new adaptive, multi-criteria measurement of sustainability: Application to Western Australia', *Ecosystems*, vol. 2073.
- Imeson, A. C., Kwaad, F. J. P. M. & Verstraeten, J. M. 1982, 'The Relationship of Soil Chemistry and Physical Properties to the Development of Badlands in Morocco', in *Badland Geomorphology and Piping*, eds R. B. Bryan & A. Yair, Geobooks, Norwich, pp. 47 - 70.
- Irving, R. B. 1956, *Silver Creek Stream Improvement*, State of Idaho, Department of Fish and Game, Boise.
- Johnson, S. E. & Graber, B. E. 2002, 'Enlisting the Social Sciences in Decisions about Dam Removal', *BioScience*, vol. 52, no. 8, pp. 731 - 738.
- Kesel, R. H., Yodis, E. G. & McCraw, D. J. 1992, 'An Approximation of the Sediment Budget of the Lower Mississippi River Prior to Major Human Modification', *Earth Surface Processes and Landforms*, vol. 17, no. 7, pp. 711 - 722.
- Klahr, T. 2006, *Watershed Manager, The Nature Conservancy of Idaho*.
- Knighton, D. 1998, *Fluvial Forms and Processes*, Arnold, London.
- Lawrence, P., Cascio, A. L., Goldsmith, P. & Abbott, C. L. 2004, *Sedimentation in Small Dams: Development of a Catchment Characterisation and Sediment Yield Prediction Procedure*, Department for International Development.
- Leys, K. F. & Werritty, A. 1999, 'River Channel Planform Change: Software for Historical Analysis', *Geomorphology*, vol. 29, pp. 107 - 120.
- Ligon, F. K., Dietrich, W. E. & Trush, W. J. 1995, 'Downstream Ecological Effects of Dams', *BioScience*, vol. 45, no. 3, pp. 183 - 192.
- Madej, M. A. & Ozaki, V. 1996, 'Channel Response to Sediment Wave Propagation and Movement, Redwood Creek, California, USA', *Earth Surfaces Processes and Landforms*, vol. 21, no. 10, pp. 911 - 927. Cited by Knighton, D. 1998, *Fluvial Forms and Processes*, Arnold, London.
- Manuel, C. Y., Griffith, J. S. & Minshall, G. W. 1979, *The Sources and Causes of Sedimentation in Silver Creek, Blaine Co., Idaho*, Idaho State University.
- McLean, D. G. & Church, M. 1999, 'Sediment Transport Along Lower Fraser River; 2, Estimates Based on the Long-term Gravel Budget', *Water Resources Research*, vol. 35, no. 8, pp. 2549 - 2559.
- Milligan, J. 2006, *Professor, University of Idaho*.
- Millman, J. D. & Syvitski, S. P. M. 1992, 'Geomorphic/Tectonic Control of Sediment Discharge to the Ocean: The Importance of Small Mountainous Rivers', *Journal of Geology*, vol. 100, pp. 525 - 544.
- Moglen, G. E., Eltahir, E. A. B. & Bras, R. L. 1998, 'On the Sensitivity of Drainage Density to Climate Change', *Water Resources Research*, vol. 34, no. 4, pp. 855 - 862.
- Montgomery, D. R. & Brandon, M. T. 2002, 'Topographic Controls on Erosion Rates in Tectonically Active Mountain Ranges', *Earth and Planetary Science Letters*, vol. 201, pp. 481 - 489.

- Moreland, J. A. 1977, *Ground Water - Surface Water Relations in the Silver Creek Area, Blaine County, Idaho*, U.S. Geological Survey, Boise.
- Norman, L. 1998, *Estimates of the Economic Impact of Recreation at the Silver Creek Preserve*, Idaho State University, Pocatello.
- Phillips, J. D. 2003, 'Toledo Bend Reservoir and Geomorphic Response in the Lower Sabine River', *River Research and Applications*, vol. 19, pp. 137 - 159.
- Pizzuto, J. 2002, 'Effects of Dam Removal on River Form and Process', *BioScience*, vol. 52, no. 8, pp. 683 - 691.
- Pollard, A. I. & Reed, T. 2004, 'Benthic Invertebrate Assemblage Change Following Dam Removal in a Wisconsin Stream', *Hydrobiologia*, vol. 513, pp. 51-58.
- Prosser, I. P., Rutherford, I. D., Olley, J. M., Young, W. J., Wallbrink, P. J. & Moran, C. J. 2001, 'Large-scale Patterns of Erosion and Sediment Transport in River Networks, with Examples from Australia.' *Marine & Freshwater Research*, vol. 52, no. 1, pp. 81 - 99.
- Rapp, A., Axelsson, V., Berry, L. & Hammond Murray-Rust, D. 1972, 'Soil Erosion and Sediment Transport in the Morogoro River Catchment, Tanzania', *Physical Geography*, vol. 54, no. 3/4, pp. 125 - 155.
- Renwick, W. H., Smith, S. V., Bartley, J. D. & Buddemeier, R. W. 2005, 'The Role of Impoundments in the Sediment Budget of the Conterminous United States', *Geomorphology*, vol. 71, no. 1-2, pp. 99 - 111.
- Richter, B. D., Baumgartner, J. V., Wigington, R. & Braun, D. P. 1997, 'How Much Water Does a River Need?' *Freshwater Biology*, vol. 37, no. 1, pp. 231 - 249.
- Rouse, H. 1937, 'Modern Conceptions of the Mechanics of Fluid Turbulence', *Transactions of the American Society of Civil Engineers*, vol. 102, pp. 463 - 541. Cited by Yang, C. T. 1996, *Sediment Transport Theory and Practice*, McGraw-Hill, New York.
- Rovira, A. A., Batallaa, R. J. & Salab, M. 2005, 'Fluvial Sediment Budget of a Mediterranean River: the Lower Tordera (Catalan Coastal Ranges, NE Spain).' *Catena*, vol. 60, no. 1, pp. 19 - 42.
- Ryan, P. A. 1991, 'Environmental Effects of Sediment on New Zealand Streams; a Review', *New Zealand Journal of Marine and Freshwater Research*, vol. 25, no. 2, pp. 207 - 221.
- Ryding, S. 1982, 'Lake Trehorningen Restoration Project: Changes in Water Quality after Sediment Dredging', *Hydrobiologia*, vol. 92, pp. 549 - 558.
- Safran, E. B., Bierman, P. R., Aalto, R., Dunne, T., Whipple, K. X. & Caffee, M. 2005, 'Erosion Rates Driven by Channel Network Incision in the Bolivian Andes', *Earth Surfaces Processes and Landforms*, vol. 30, pp. 1007 - 1024.
- Salins, D. M. 1998, Erosional processes and soil-landform associations: an investigation into the factors controlling the nature of erosion in the upper Irwin River Catchment, Western Australia, Honours, University of Western Australia.
- Schumm, S. A. 1963, 'A Tentative Classification of Alluvial River Channels', *United States Geological Survey Circular*, vol. 477, p. 10. Cited by Knighton, D. 1998, *Fluvial Forms and Processes*, Arnold, London.
- Schumm, S. A. 1967, 'Rates of Surficial Rock Creep on Hillslopes in Western Colorado', *Science*, vol. 155, no. 3762, pp. 560 - 562.
- Schumm, S. A. 1985, 'Patterns of Alluvial Rivers', *Annual Review of Earth and Planetary Sciences*, vol. 13, pp. 5 - 27.
- Schweibert, E. 1977, 'The Anatomy of a Spring Creek', *Fly Fisherman*.

- Stanley, E. H. & Doyle, M. W. 2002, 'A Geomorphic Perspective on Nutrient Retention Following Dam Removal', *BioScience*, vol. 52, no. 8, pp. 693 - 702.
- Snyder, N. P., Rubin, D. M., Alpers, C. N., Childs, J. R., Curtis, J. A., Flint, L. E. & Wright, S. A. 2004, 'Estimating Accumulation Rates and Physical Properties of Sediment Behind a Dam: Englebright Lake, Yuba River, northern California', *Water Resources Research*, vol. 40, no. 11.
- The Nature Conservancy 1975, *Idaho's Silver Creek: A Conservation Program for One of America's Finest Spring Creeks*, The Nature Conservancy, Hailey.
- The Nature Conservancy 1985, *The 1985 Silver Creek Preserve Stewardship Plan (1980-1985)*, The Nature Conservancy, Hailey.
- The Nature Conservancy 1993, *Silver Creek Preserve: A Model for Balancing Stream Conservation, Agricultural Use and Public Recreation*, The Nature Conservancy, Hailey.
- The Nature Conservancy 2003, 'The Silver Creek Symposium', in *Silver Creek: Today and Tomorrow*, The Nature Conservancy, Sun Valley, Idaho, p. 16.
- The Nature Conservancy, *Silver Creek Fact Sheet* [Online], The Nature Conservancy, Available: [http://nature.org/wherewework/northamerica/states/idaho/files/silver\\_creek\\_fact\\_sheet.pdf](http://nature.org/wherewework/northamerica/states/idaho/files/silver_creek_fact_sheet.pdf) [28/11/2005].
- Todd, P. 1997, *Silver Creek Site Conservation Plan and Five Year Plan*, The Nature Conservancy, Hailey.
- Trimble, S. W. 1981, 'Changes in Sediment Storage in the Coon Creek Basin, Driftless Area, Wisconsin, 1853 to 1975', *Science*, vol. 214, pp. 181 - 183.
- Trimble, S. W. 1983, 'A Sediment Budget for Coon Creek Basin in the Driftless Area, Wisconsin, 1853-1977', *American Journal of Science*, vol. 283, pp. 454 - 474.
- Trimble, S. W. 1999, 'Decreased Rates of Alluvial Sediment Storage in the Coon Creek Basin, Wisconsin, 1975-93.' *Science*, vol. 285, no. 5431, pp. 1244 - 1246.
- Trimble, S. W. & Crosson, P. 2000, 'U.S. Soil Erosion Rates - Myth and Reality', *Science*, vol. 289, no. 5477, pp. 248 - 250.
- Tucker, G. E. & Bras, R. L. 1998, 'Hillslope Processes, Drainage Density, and Landscape Morphology', *Water Resources Research*, vol. 34, no. 10, pp. 2751 - 2764.
- Walling, D. E., Russell, M. A., Hodgkinson, R. A. & Zhang, Y. 2002, 'Establishing Sediment Budgets for Two Small Lowland Agricultural Catchments in the UK', *Catena*, vol. 47, no. 4, pp. 323 - 353.
- Watershed Sciences Inc. 2006, *Geo-Rectification of Thermal Infrared Images Near Kilpatrick Pond, Silver Creek, ID*, Corvallis.
- Whiting, P. J. 2002, 'Streamflow Necessary for Environmental Maintenance', *Annual Review of Earth and Planetary Sciences*, vol. 30, no. 1, pp. 181 - 206.
- Wolter, R. N., Todd, P. & Watters, E. 1994, *Silver Creek Preserve Stream Quality Monitoring Summary 1991-1994*, The Nature Conservancy, Hailey.
- Yang, C. T. 1996, *Sediment Transport Theory and Practice*, McGraw-Hill, New York.

# APPENDICES