THESIS

ASSESSING THE SUITABILITY FOR URBAN STREAM REHABILITATION IN FORT COLLINS BASED ON WATERSHED, HYDROLOGIC, AND BENTHIC MACROINVERTEBRATE INDICATORS

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY STEVEN K. ROZNOWSKI ENTITLED “ASSESSING THE SUITABILITY FOR URBAN STREAM REHABILITATION IN FORT COLLINS BASED ON WATERSHED, HYDROLOGIC, AND BENTHIC MACROINVERTEBRATE INDICATORS” BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

ASSESSING THE SUITABILITY FOR URBAN STREAM REHABILITATION IN FORT COLLINS BASED ON WATERSHED, HYDROLOGIC, AND BENTHIC MACROINVERTEBRATE INDICATORS

Development in urban areas generally increases the proportion of a watershed that is covered by impervious surfaces. This added impervious area causes both the quantity and peak rate of stormwater runoff to increase thereby altering the natural flow regime in receiving streams and causing changes in sediment transport. Such changes in hydrology and sediment load can adversely affect benthic macroinvertebrates residing in channel beds.

This study assesses the degree to which watershed development has impacted urban streams in Fort Collins, Colorado and recommends areas for rehabilitation that are most likely to benefit from watershed or in-stream modification. Fort Collins has recently begun implementing best management practices (BMPs) to help control stormwater runoff from developed areas. Locations and coverage of BMPs along with other measures of urbanization are compared to available stream flow and shear stress data which are in-turn related to benthic macroinvertebrate indicators. By drawing comparisons between these parameters, the effectiveness of stormwater BMPs can be assessed. This al-

lows for recommendations to be made which direct stream rehabilitation efforts in the City.

The impacts of irrigation flows in the Fort Collins area were found to limit the effectiveness of BMPs. This irrigation influence made trends difficult to establish between benthic macroinvertebrate indicators and watershed characteristics. However, as evidenced by recent improvements in macroinvertebrate indicators at one location, the combination of BMPs and in-stream improvement can create habitat suitable for rich macroinvertebrate communities provided irrigation flows are controlled. Therefore, the locations with large portions of the watershed protected by water quality BMPs and relatively little irrigation impact are targeted as prime locations for in-stream rehabilitation. For areas with low levels of water quality control, it is suggested that water quality BMPs be added before in-stream rehabilitation is undertaken.

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1.0 INTRODUCTION

1.1 Background

The City of Fort Collins, Colorado is a rapidly developing urban area in the Front Range region east of the Rocky Mountains. Best management practices (BMPs) have been implemented in the city to control stormwater flowing from developed areas since they became a requirement in 1997 (City of Fort Collins, 1984, rev. 1997). Many of these BMPs have water quality features which help attenuate the flows of small storms that occur frequently. Recent research suggests that this control of low flow, particularly that of the half-year storm, may have a direct link to the quality of habitat for benthic macroinvertebrates (Booth et al., 2004; Pomeroy, 2007).

Within the City of Fort Collins, seven stream gages measure flow on three urban creeks of varying levels of development. Additionally, benthic macroinvertebrate data has been collected in several of the City's creeks by Hoffman (1998) and Zuellig (2001). A follow-up benthic macroinvertebrate study in April of 2010 supplemented the prior studies to reflect changes in land use and development that have occurred since the studies by Hoffman (1998) and Zuellig (2001).

1.2 Objectives

The primary objective of this study was to use benthic macroinvertebrate indicators of stream health to help direct rehabilitation efforts on the urban creeks in Fort Collins. Research has suggested that solutions to protect aquatic environments require not only adequate in-stream habitat but also control of upland runoff (Konrad & Burges, 2001; Booth et al., 2004; Pomeroy, 2007). Therefore, a range of metrics pertaining to watershed alteration, hydrologic effects observed in streams, and sediment transport were used to assess the impact of urban development on benthic macroinvertebrate communities in receiving streams. Through this analysis, a link could be made between various aspects of urban development and the resulting effects on receiving streams. By creating this link, recommendations could be made as to whether remediation should be focused on watershed or in-stream improvements and specific locations could be identified that would be most receptive to sustainable improvement.

1.3 Organization of Report

In Section 2.0, a review of literature is offered which discusses research that has previously been done on stream and watershed metrics, alteration, and health. Section 3.0 outlines the specific approach used in this study to determine what effects urban development in Fort Collins, Colorado is having on stream habitat. The results of the study are then shown and discussed in Section 4.0. Conclusions and recommendations for stream improvement are explained in Section 5.0.

2.0 LITERATURE REVIEW

A review of literature pertaining to stream health classification and stream metrics shows that there is a vast array of methods and techniques for assessing the relative health of streams. Making such an assessment is often a difficult proposition due to the large number of factors that influence stream health. There have been efforts to determine a single metric that reflects the maximum possible number of factors influencing stream health. Furthermore, a useful stream health metric should be applicable to streams with varying local climatic and environmental factors. Determination of such a metric has been done with varying degrees of success.

2.1 Stream Metric Analysis

Several studies have been performed to determine which stream metrics are most helpful in assessing stream health. Olden & Poff (2003) provided a comprehensive overview of 171 hydrologic indicators from 420 different sites. This study looked at the transferability of stream metrics among any of six different stream types which included "harsh intermittent," "intermittent flashy or runoff," "snowmelt," "snow and rain," "superstable or stable groundwater," and "perennial flashy or runoff." Hydrologic metrics were found to be the most easily transferable among perennial streams. Additionally, the study sought to analyze stream metrics from previous studies and determine those that most closely reflected the biologic health of streams while eliminating redundant metrics. Metrics were grouped based on which hydrologic characteristic they described. Metrics included flow magnitude, frequency, duration, timing, and rate of change. These groups encompass metrics used in most relevant studies of the relationship between stream flow and stream health (Booth & Jackson, 1997; Poff et al., 1997; Booth et al., 2004; Sprague et al., 2006; Pomeroy, 2007; DeGasperi et al., 2009). Through the use of a principal component analysis (PCA) approach, Olden & Poff (2003) grouped metrics into categories that were independent of one another and described large portions of variation observed in flow regime. Most of the variation in flow regime could be explained using two to four hydrologic metrics from different principal component axes (Olden & Poff, 2003). Though this work provided guidance for selecting hydrologic metrics, it did not discount the value of local conditions, intuition, and proper judgment. While historically emphasis was placed solely on control of water quality and storm magnitude, considering all aspects of the flow regime has been shown to be necessary to adequately protect aquatic ecosystems from human development (Poff et al., 1997). Therefore, metrics that address several different aspects of the flow regime are preferred when assessing the impacts of urban development.

2.2 Watershed Urbanization

Though the effects of urbanization may be seen within a given stream reach, the reason for this impact starts upstream (Konrad & Burges, 2001). Without properly protecting against the effects of urban development, remediation and protection of streams may be difficult or impossible. Therefore, assessment of the impacts of urbanization necessarily focuses on the watershed upstream of receiving streams.

There must be a way of appropriately measuring urbanization to adequately assess the impact of urbanization on stream flow. One of the simplest ways of assessing impact is to use total impervious area (TIA) or effective imperious area (EIA) (Booth & Jackson, 1997; Booth et al., 2004; DeGasperi et al., 2009). TIA is the total area of a given watershed covered by impervious surfaces whereas EIA is the area of impervious surfaces that has a direct hydraulic connection to downstream receiving waters. The underlying assumption of these methods is that urban land use tends to create impervious surfaces, which prohibit infiltration and increase stormwater runoff. Therefore, more urbanized areas will have higher levels of TIA and EIA.

Another way to quantify urbanization is to determine the percentage of a watershed that is covered by urban, agricultural, or natural land uses (Wang et al., 2000; Roy et al., 2003; DeGasperi et al., 2009). In many circumstances, this can be accomplished through aerial photography. The major drawback of this method is that it operates under the general assumption that urbanization is consistent among watersheds. Therefore, this method assumes urbanization in one region produces similar impacts as urbanization in another region without regard for location, type of development, stormwater controls, or various other factors.

In an attempt to more precisely define the level of urbanization, the Urban Intensity Index (UII) was developed by McMahon & Cuffney (2000). This index was designed to incorporate a variety of environmental, landuse, infrastructure, population, and socioeconomic characteristics to quantify urbanization in a given watershed (McMahon & Cuffney, 2000; Sprague et al., 2006; Pomeroy, 2007). The primary limitation of this index has been the availability of high-resolution information. In lieu of the full UII, other metrics have been used that only include a portion of the UII such as population density (Konrad & Booth, 2002).

2.3 Quantifying Stream Health

Stream health has historically been assessed based on chemical water quality parameters (Booth et al., 2004). New research however suggests that the quality of stream habitat may be aptly determined by analyzing benthic macroinvertebrate communities (Lenat, 1988; Lenat & Crawford, 1994; Roy et al., 2003; Booth et al., 2004; Voelz et al., 2005; Sprague et al., 2006; Pomeroy, 2007; DeGasperi et al., 2009). This research covers a vast geographical area of the United States from the Pacific northwest (Booth et al., 2004; Konrad et al., 2005; DeGasperi et al., 2009) to the mountain west (Voelz et al., 2005; Sprague et al., 2006) to the Piedmont of the southeast (Lenat, 1988; Lenat & Crawford, 1994; Roy et al., 2003; Pomeroy, 2007). This research suggests that certain benthic indicators and metrics can be applied to a wide array of locations with varying climatic and geographical traits.

Three of the simplest and most common benthic indicators of stream health are total taxa richness, richness of Ephemeroptera, Plecoptera, and Trichoptera (EPT), and %EPT (Lenat, 1988; Roy et al., 2003; Voelz et al., 2005; Sprague et al., 2006; Pomeroy 2007). Total taxa richness measures benthic macroinvertebrate diversity as the number of different macroinvertebrate taxa found in a given sample. High benthic macroinvertebrate diversity is indicative of good quality aquatic habitat (Sprague et al., 2006). However, total taxa richness is generally only used as a starting point for assessing stream health. EPT richness is the total number of different macroinvertebrate taxa falling into one of the Ephemeroptera (mayflies), Plecoptera (stoneflies), or Trichoptera (caddisflies) taxonomical orders. %EPT is the percentage of the total number of macroinvertebrates collected that fall into one of the EPT orders. EPT are used as indicator taxa because they are considered to be pollution sensitive and are therefore less prevalent in urbanized streams (Lenat & Crawford, 1994; Sprague et al., 2006).

Another common and slightly more comprehensive benthic index is the benthic index of biological integrity (B-IBI; Kerans & Karr, 1994). The B-IBI incorporates 13 individual benthic metrics which include a quantification of EPT taxa (Kerans & Karr, 1994). B-IBI has been used in several studies as an indicator of stream health as it incorporates many other biotic metrics (Kerans & Karr, 1994; Roy et al., 2003; Booth et al., 2004; Pomeroy, 2007; DeGasperi, 2009). Typically, B-IBI has been compared against some measure of urbanization to help quantify the impact of urban development. Such a direct comparison was made by Pomeroy (2007) between the UII and benthic macroinvertebrate health as shown in Figure 2-1. Note that this figure shows two different types of EPT. One of these uses invertebrate samples collected from riffles, known as a richest targeted habitat (RTH) samples, and the other uses samples taken from many different habitats, known as a qualitative multihabitat (QMH) samples.

The resulting negative correlation appears to show a direct inverse relationship between urbanization and the health of benthic macroinvertebrates in receiving waters. However, such a correlation does not describe the physical interaction between urban development and benthic health (Konrad & Booth, 2002; Pomeroy, 2007). Therefore, to fully explain this relationship, other metrics must be found to describe the physical mechanisms of the interaction between urban development and streams. Subsequent sections of this report address such mechanisms which include stormwater flows and sediment transport.

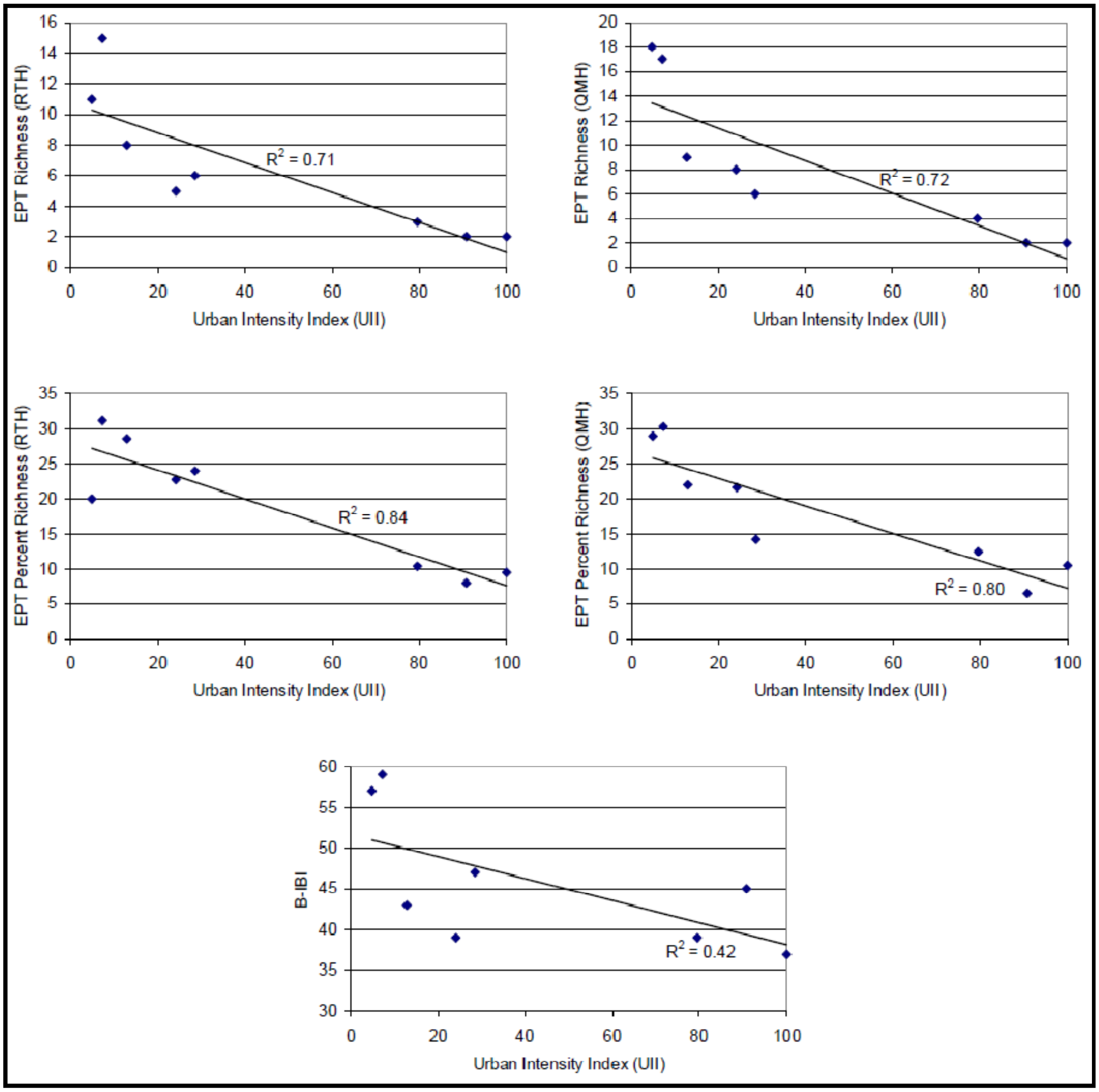

Figure 2-1: Relationship of the Urban Intensity Index to benthic macroinvertebrate sampling data (a) EPT richness (RTH), (b) EPT richness (QMH), (c) EPT percent richness (RTH), (d) EPT percent richness (QMH), (e) Benthic Index of Biotic Integrity (B-IBI). (Source: Pomeroy, 2007)

2.4 Colorado Benthic Studies

Voelz et al. (2005) studied the effects of urbanization on macroinvertebrate communities in the Big Thompson and Cache la Poudre Rivers along the Front Range of Colorado. Among other goals, Voelz et al. (2005) assessed the representativeness of one or a few benthic macroinvertebrate samples compared to long-term averages and concluded that short-term benthic macroinvertebrate study results were not substantially different from the 20-year long-term averages. Short-term data still provided a relatively accurate picture of stream health relative to a reference site (Voelz et al., 2005). The main disadvantage of short-term data was that it could not be used to establish trends of improving or degrading aquatic habitat.

Sprague et al. (2006) studied the South Platte River Watershed which encompasses 62,940 km^2 of the Colorado Front Range including the City of Fort Collins. Within the South Platte River Watershed, 28-subwatersheds were analyzed. In these subwatersheds a maximum value for EPT richness of 16 was found with 21 of the 28 sites having EPT richness values below 10. This indicates that values of EPT above 10 are unlikely in this region and therefore, values near 10 could be considered good.

There have been two relevant studies performed to assess benthic macroinvertebrate communities in Fort Collins, Colorado (Hoffman, 1998; Zuellig 2001). These studies included assessments of benthic macroinvertebrate communities in Spring, Fossil, Clearview, McClellands, and Foothills creeks within the City of Fort Collins. Both studies evaluated a variety of different taxa including Ephemeroptera and Trichoptera. Neither study included Plecoptera and therefore only assessed ET rather than EPT. It was noted that Plecoptera were not included as they have been extirpated from small urban Colorado Front Range streams (Hoffman, 1998; Zuellig, 2001; Sprague et al., 2006).

Hoffman (1998) took three replicate samples at each of five sites using a Surber square-foot bottom sampler (Merritt et al., 2008). These quantitative samples were repeated monthly from March 1994 to February 1995. In 1996, four replicate samples were taken at five sites (one of which matched a site used in 1994) using the Surber sampler. This was repeated monthly from May through August. Three of the four samples from each site were quantitatively analyzed and the remaining sample was analyzed using a 200 organism count rapid assessment.

Zuellig (2001) collected three one-minute kick net samples (Merritt et al., 2008) at 25 locations on seven different urban creeks in Fort Collins. These samples were collected in early July during the summers of 1999 and 2000 and then analyzed for macroinvertebrates using rapid bioassessment protocols (Barbour et al.,1999). 200-count subsamples were used in the rapid bioassessment.

For these benthic studies in the Colorado Front Range, undeveloped reference streams were unavailable. Settlement and agriculture had impacted the entire Front Range area since the 1860s and therefore, predevelopment conditions could not be established (Voelz et al., 2005). Furthermore, natural benthic aquatic insect diversity along the Front Range of Colorado is relatively low compared to other regions of North America (Ward et al., 2002). Therefore, values of benthic macroinvertebrate indicators in the Colorado Front Range tend to be lower than those found in similar studies in other areas of North America.

2.5 Erosion and Sediment Transport

In addition to impacting the health of benthic macroinvertebrate communities, urbanization can have significant impacts on the rate and severity of erosion in streams. Urbanization, benthic health, and in-stream erosion are likely related because flow from urban areas can cause instability in aquatic habitat (Roesner & Bledsoe, 2003). Studies which assess the erosion and sediment transport in urbanized streams focus on the mitigation of adverse effects through stormwater control measures (Bledsoe, 2002; Rohrer, 2004; Pomeroy, 2007). Specifically, computer models are used to determine the amount of excess shear, the amount of shear stress exerted beyond the critical shear value, in a stream. Critical shear stress is determined as the shear value above which incipient motion of particles occurs (Julien, 1998). Implementing stormwater detention allows storm peaks to be controlled and excess shear to be reduced, thereby reducing sediment transport in the stream (Rohrer, 2004). As demonstrated by Figure 2-2, Roher (2004) found that the use of BMPs and stormwater control measures can decrease the load of stream sediment. In this figure, “Existing” represents a relatively undeveloped watershed. “Dev. Uncont.” shows the sediment load for the same watershed with a medium-density residential development that does not use stormwater controls. The “Over Control” scenario uses the same watershed as the “Dev. Uncont.” scenario but adds detention and a stormwater outlet designed to restrict flow from the 100-year runoff event for developed conditions to that of the 2-year peak for undeveloped conditions. In the “Over Control + BMP” scenario, the same over control outlet is used and an additional low-flow outlet is added so as to treat the water quality capture volume (WQCV). Finally, the “Peak Shaving + BMP” scenario uses a BMP outlet for discharge of the WQCV along with controls designed to restrict the post-development 2- and 100-year flows to the undeveloped 2- and 100-year peak rates respectively.

It should be noted however, that though detention can help match the flow frequency curve to predevelopment conditions, the flow duration curve will increase. Since urbanization and impervious land cover decreases infiltration, the total volume of stormwater increases. This means that detention, that is intended to match predevelopment flow frequency by discharging at a slower rate, must also discharge for a longer time due to the increased volume (Edgerly, 2006).

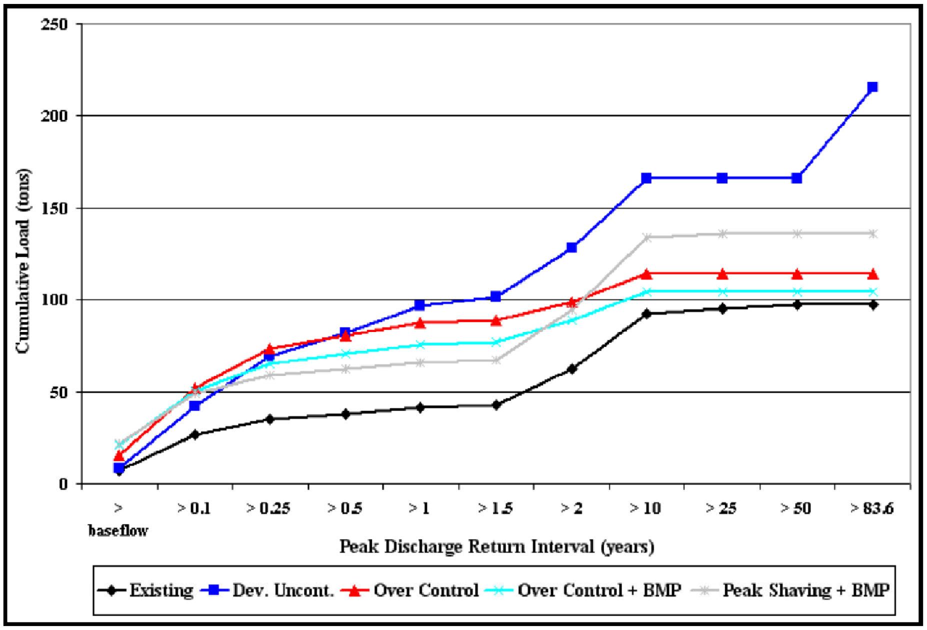

Figure 2-2: Cumulative medium sand load by return interval: Fort Collins. (Source: Rohrer, 2004)

2.6 Correlating Stream Health to Hydrology

Various studies attempt to assess how urban development and the resultant stormwater runoff impacts receiving streams. Many studies have attempted to correlate measures of urbanization directly to stream health (Booth & Jackson, 1997; McMahon & Cuffney, 2000; Roy et al., 2003). However, urbanization is difficult to quantify and there are many aspects that may be difficult or impossible to account for (Nehrke & Roesner, 2004). Addition of detention facilities and BMPs further confound attempts to quantify the impact of urbanization. For example, impervious area has been used because it impacts in-stream hydrology and habitat. However, if detention is incorporated, the effects on the receiving body would likely be lessened (Booth & Jackson, 1997; Roesner et al., 2001). Though imperviousness may indicate something about urbanization's effect on receiving waters, it is not a direct cause-effect relationship. Instead, a more fundamental cause for biotic degradation must be found if in-stream effects of urbanization are to be minimized.

Recently, studies have focused on stream hydrologic metrics to determine the impact of urbanization on the health of stream benthic macroinvertebrate communities, the idea being that changes in hydrology may directly impact in-stream biota (Poff et al., 1997; Konrad & Booth, 2002; Olden & Poff, 2003; Booth et al., 2004; Konrad et al., 2005; Pomeroy, 2007; DeGasperi et al., 2009). Uncontrolled urbanization will cause substantive changes in the hydrology of receiving bodies. However, implementation of appropriate controls may lessen the impact of urbanization by matching pre- and post-development hydrology (Poff et al., 1997; Roesner et al., 2001; Nehrke & Roesner, 2004; Rohrer, 2004; Pomeroy, 2007). Difficulty arises from finding particular stream metrics that best represent the impact of hydrology on benthic macroinvertebrate communities (Olden & Poff, 2003).

Some research makes a direct correlation between flow data and stream health (Konrad & Booth, 2002; Booth et al, 2004; Konrad et al., 2005; Pomeroy, 2007; DeGasperi et al, 2009). Poff et al. (1997) noted five distinct aspects of the flow regime that impact stream health: magnitude, frequency, duration, timing, and rate of change. Common metrics such as mean, peak, or low flows (Konrad & Booth, 2002) can be used; however, these only address one aspect of the flow regime. Other metrics have been found to be more useful because they address several different aspects (Konrad & Booth, 2002; Booth et al., 2004; Konrad et al., 2005; Pomeroy, 2007; DeGasperi, 2009).

Metrics incorporating flow magnitude, frequency, and duration have gained favor in recent research for establishing a relation between hydrology and benthic macroinvertebrate health (Konrad & Booth, 2002; Booth et al, 2004; Konrad et al., 2005; Pomeroy, 2007; DeGasperi et al, 2009). Urbanization and increased uncontrolled impervious area will typically cause increased runoff volumes, rates, and frequency of high flow events (Booth & Jackson, 1997). However, the duration will decrease (system will become "flashy") as runoff can travel more quickly in pipes and on impervious surfaces than via groundwater or as surface runoff from natural land (Booth & Jackson, 1997). Storm flashiness can be quantified through the use of a continuous flow record. The fraction of time during which a given threshold flow is exceeded can be calculated for a period of record. This fraction of time can then be used to indicate how flashy streams are relative to one another. The difference between different time-fraction metrics is in the value of the threshold.

A metric called the T_{Qmean} defines the storm threshold as the annual mean flow for a given stream (Konrad & Booth, 2002). Therefore, T_{Qmean} is the fraction of the year that daily mean discharges exceed the annual mean discharge for a given stream (Konrad & Booth, 2002; Booth et al., 2004; Konrad et al., 2005). Edgerly (2006) found that the use of daily mean discharge rather than a shorter time-step resulted in overestimation of T_{Qmean}. Therefore, T_{Qmean} should be calculated from time steps smaller than an entire day. Regardless of the time step used, as flashiness increases, values of T_{Qmean} would be expected to decrease. Though peak magnitudes increase in flashy systems, the same peaks occur in a shorter duration. This metric has been used with some success in several studies relating benthic health to hydrology (Konrad & Booth, 2002; Booth et al., 2004; DeGasperi, 2009). However, Pomeroy (2007) did not find a strong correlation between benthic health and the T_{Qmean}. Additionally, Edgerly (2006) found that the T_{Qmean} may not be appropriate for small watersheds (10 ha) due to the inherent flashiness of small systems with short times of concentration.

Another metric that has been developed to assess flashiness as a fraction of time is the $T_{0.5}$ (Booth et al., 2004; Konrad et al., 2005; Edgerly, 2006; Pomeroy, 2007). The $T_{0.5}$ is a fraction (or percent) of time metric that uses the $Q_{0.5}$ as a flow threshold. The $Q_{0.5}$ is defined as the peak storm flow which can be expected to be met or exceeded on average twice per year. As with other time-fraction metrics, the $T_{0.5}$ would be expected to decrease in flashy urban streams. Booth et al. (2004) found that the $T_{0.5}$ and T_{Qmean} were appropriate indicators of benthic macroinvertebrate health as shown in Figure 2-3.

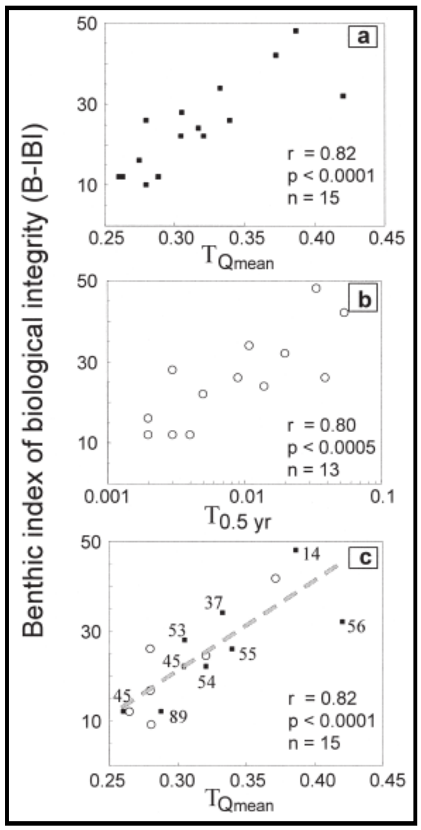

Figure 2-3: Relationship between B-IBI and (a) T_{Qmean} and (b) $T_{0.5}$. In (c), numbers indicate local urban land cover percentage (sites plotted as circles lack local land cover data). (Source: Booth et al., 2004)

The half-year storm was selected because it was hypothesized to have both geo-morphic and biological significance (Booth et al., 2004). Though the $Q_{0.5}$ has been used in several studies, the method of determination varies. Typically, the $Q_{0.5}$ is calculated from a partial duration series of historical data. Booth et al. (2004) used gage data from

13 sites in the Puget Sound region of Washington to calculate the $Q_{0.5}$. Pomeroy (2007) used a similar partial duration series approach in the Piedmont region of North Carolina. Pomeroy (2007) used United States Geological Survey (USGS) stream gage data to calculate the $T_{0.5}$ for 12 to 18 month periods. Rainfall data for the same region was then used to calculate flows with the Storm Water Management Model (SWMM) developed by the U.S. Environmental Protection Agency (EPA). These simulations reported values of the $T_{0.5}$ for periods of record up to 20 years. The relationship between the $T_{0.5}$ and various benthic indices are shown for the 1.5-year gage data in Figure 2-4.

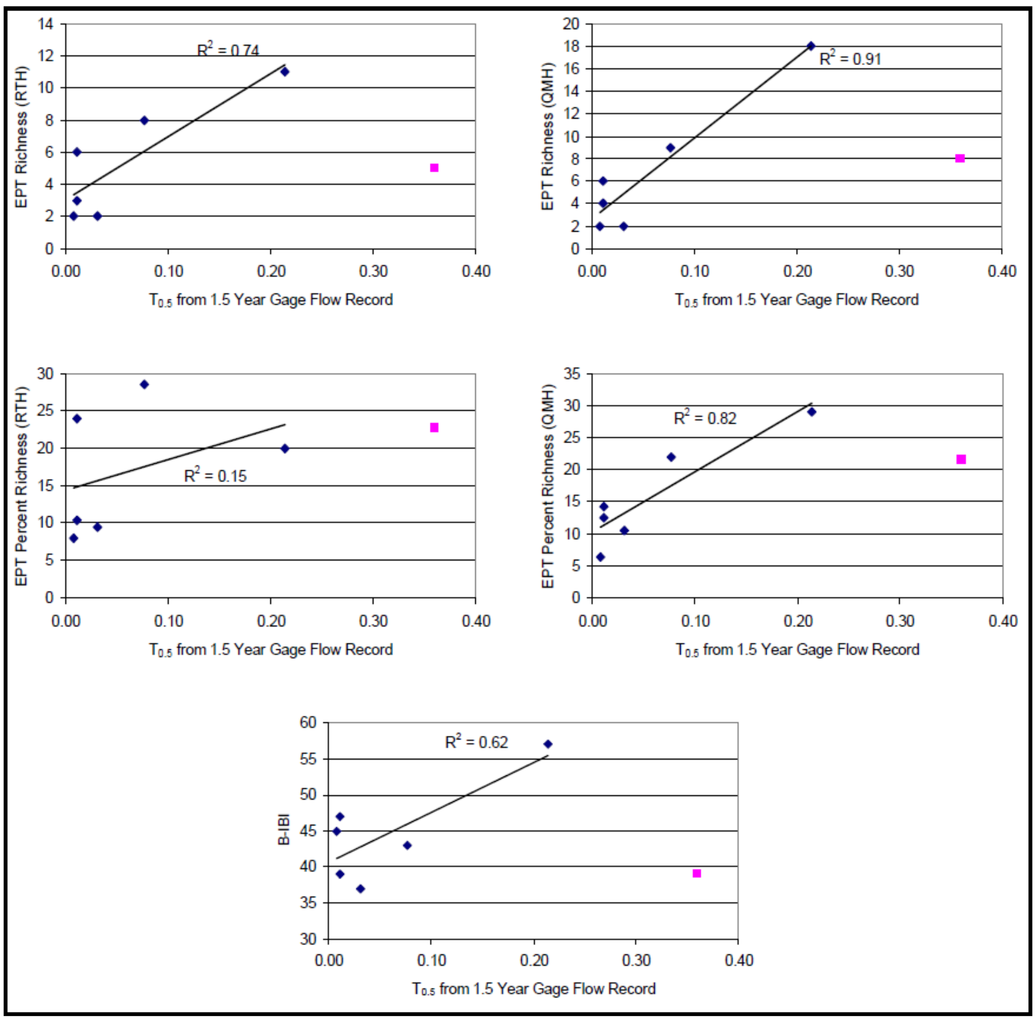

Figure 2-4: Relationship of $T_{0.5}$ calculated from the 1.5-year gage flow record to benthic macroinvertebrate sampling data (a) EPT richness (RTH), (b) EPT richness (QMH), (c) EPT percent richness (RTH), (d) EPT percent richness (QMH), (e) Benthic Index of Biotic Integrity (B-IBI). (Source: Pomeroy, 2007)

In addition to relating the $T_{0.5}$ to benthic health, Pomeroy (2007) also showed that the $T_{0.5}$ was sensitive to urbanization. Figure 2-5 shows the relationship found between the $T_{0.5}$ and the UII developed by McMahon & Cuffney (2000). Here, a negative logarithmic correlation was found between the UII and the $T_{0.5}$ calculated from model results for various periods of record.

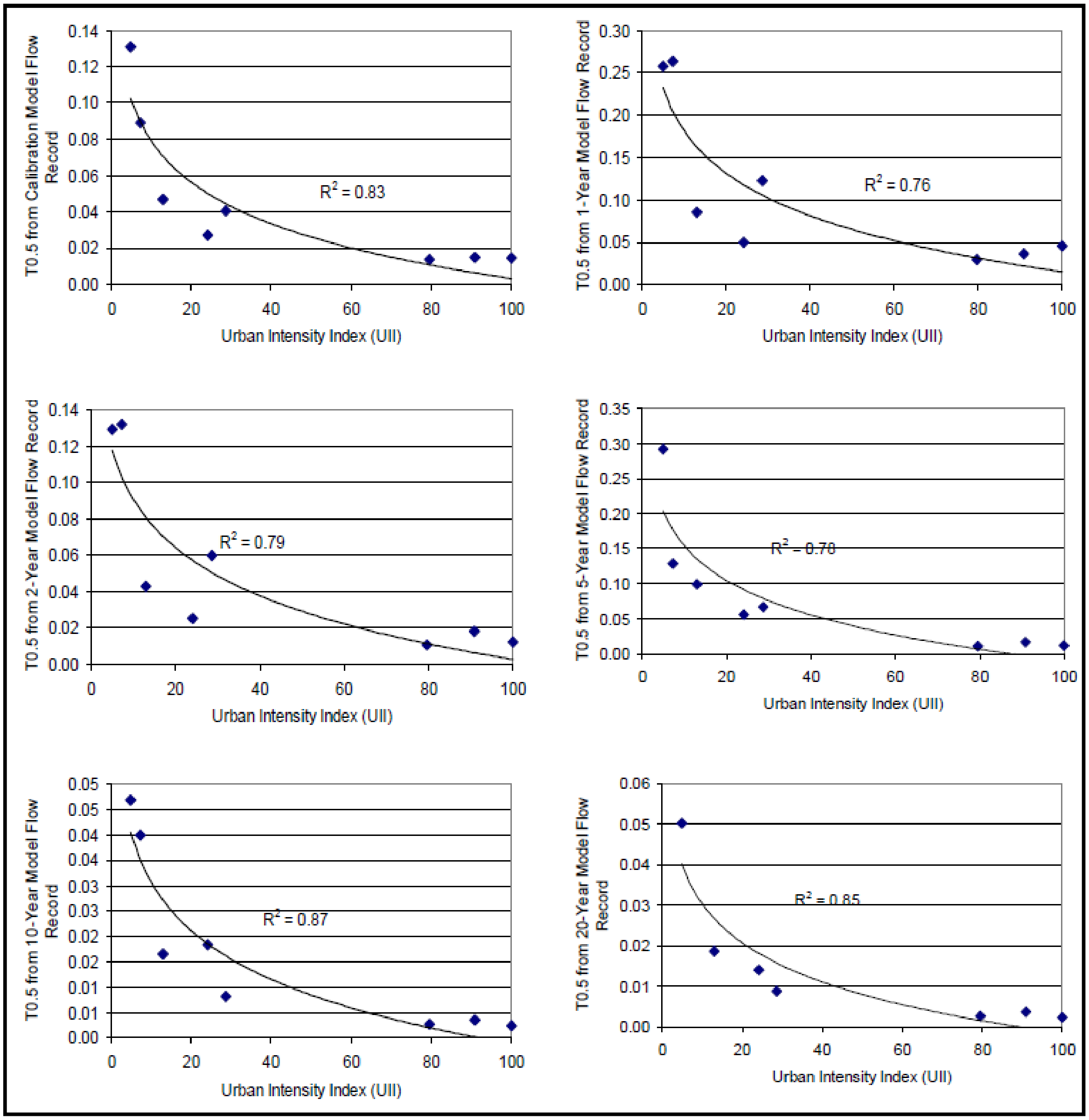

Figure 2-5: Relationship of the Urban Intensity Index to the $T_{0.5}$ calculated from (a) the calibration period, (b) 14-year model flow record, (c) 2-year model flow record, (d) 5-year model flow record, (e) 10-year model flow record, and the (f) 20-year model flow record. (Source: Pomeroy, 2007)

Since the $T_{0.5}$ is inversely related to UII and positively related to benthic invertebrate health, it can be concluded that a negative relationship exists between urbanization as indicated by the UII and the health of benthic macroinvertebrates. Pomeroy (2007) made this connection as shown previously in Figure 2-1. Though there is a discernable relationship between UII and benthic health, there is not a practical application for the use of UII to direct rehabilitation or preventive measures to protect benthic macroinvertebrates (Pomeroy, 2007). Instead, the $T_{0.5}$ is needed as it can be controlled and manipulated by the use of stormwater controls.

2.7 Controlling Flow

If stream flow metrics are to be useful, there must be a way of adequately regulating them so as to match predevelopment conditions. To achieve this, mitigation efforts must start in upland areas at the source of runoff (Konrad & Burges, 2001). It has been determined that control of peak flows is not enough to prevent significant changes in stream hydrology produced by urban development (Roesner et al., 2001; Nehrke & Roesner, 2004; Booth et al., 2004; Rohrer, 2004; Pomeroy, 2007). Nehrke & Roesner (2004) suggest the use of staged detention pond outlets to better control the entire spectrum of storm events. Not only will this prevent damage to the geomorphic characteristics of receiving waters, but the use of detention BMPs will likely remove many of the pollutants produced by urban runoff (Roesner et al., 2001).

The use of stormwater controls to manipulate the $T_{0.5}$ was demonstrated by Edgerly (2006) in Fort Collins, Colorado and Atlanta, Georgia however calculation of the $Q_{0.5}$ varied fundamentally in this study. In this study, the $T_{0.5}$ was calculated relative to an historical $Q_{0.5}$ rather the $Q_{0.5}$ from current data to create a modified version of the $T_{0.5}$.

Edgerly (2006) did this because for a small watershed, the study showed that the threshold for determining the half-year storm increased with urbanization thereby causing the $T_{0.5}$ to remain unchanged. Therefore, a constant value of $Q_{0.5}$ (historical value) was needed in order to observe changes in urban development. Also, instead of comparing the $T_{0.5}$ directly to benthic health, Edgerly (2006) analyzed the effects of different urban stormwater controls on the $T_{0.5}$. Figure 2-6 shows the results of the study done by Edgerly (2006) with the modified $T_{0.5}$.

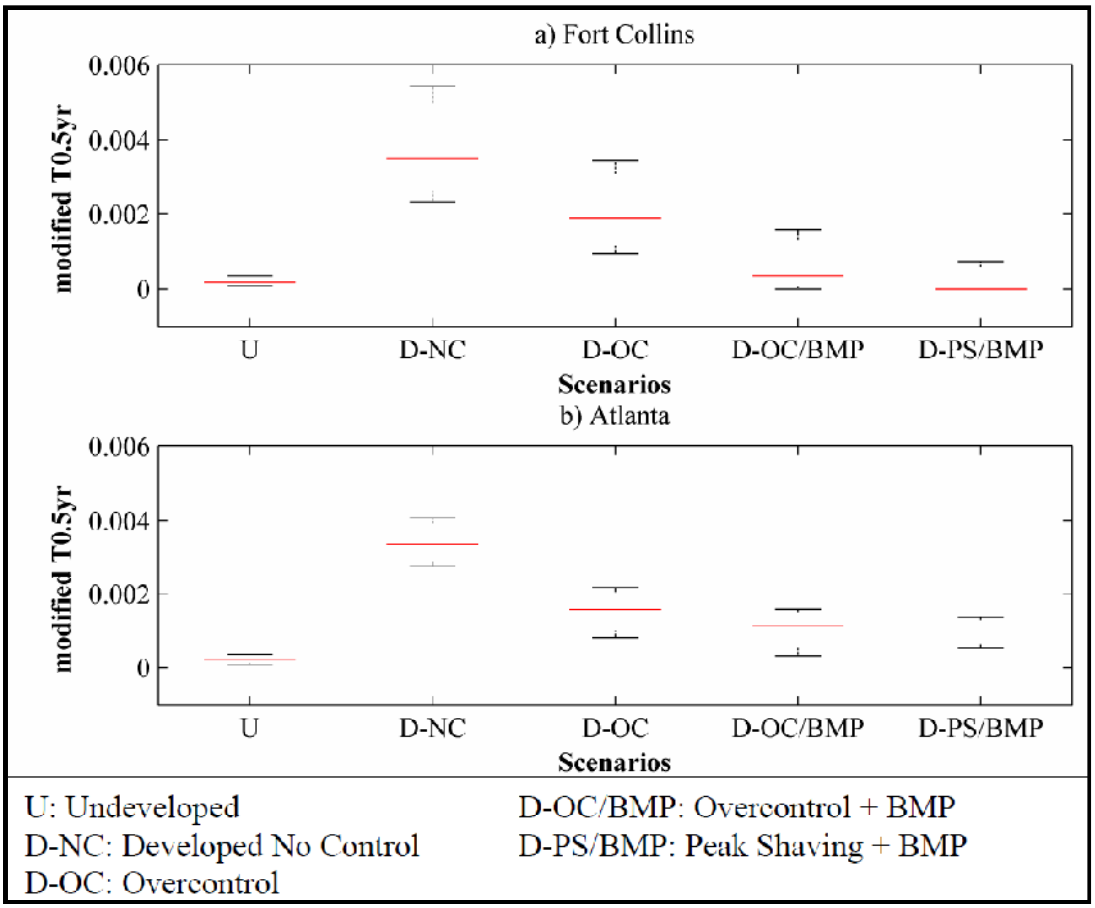

Figure 2-6: Median and interquartile range values of *modified* $T_{0.5yr}$ for multiple scenarios of development in Fort Collins, Colorado and Atlanta, Georgia. (Source: Edgerly, 2006)

It is important to note that due to the difference in the way $T_{0.5}$ was calculated, $T_{0.5}$ values in this study ***increased*** which contrasted the study by Pomeroy (2007) where $T_{0.5}$ ***decreased*** with urbanization (see Figure 2-5). The increase shown by Edgerly (2006) occurred because flows were only compared to historical values of the $Q_{0.5}$ and therefore higher levels of urbanization necessarily lead to higher flow peaks ***and*** durations. When the $Q_{0.5}$ is allowed to move to match current data however as done by Booth et al. (2004) and Pomeroy (2007), the $T_{0.5}$ becomes a measure of flashiness rather than simply an indicator of increased flow.

Though the $T_{0.5}$ indicates a biologically relevant hydrologic parameter, stormwater BMP controls should focus on the reduction of post-development peak flow magnitudes and frequencies to those of undeveloped conditions (Roesner et al., 2001). Rohrer (2004) showed that BMP controls placed on detention facilities can have an impact on peak flow frequency. BMP low flow and peak shaving controls were found to decrease the frequency of high flows for a modeled site using either Fort Collins, Colorado or Atlanta, Georgia rainfall data. An example of this is shown below for the Fort Collins model in Figure 2-7.

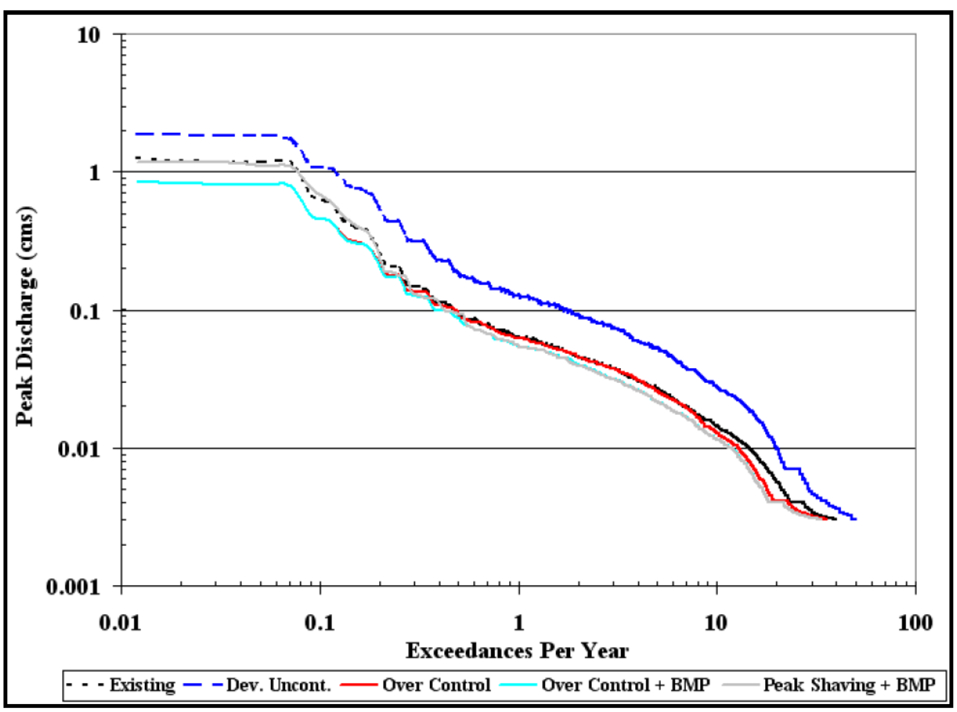

Figure 2-7: Peak flow exceedance frequency, full watershed: Fort Collins. (Source: Rohrer, 2004)

The findings of Rohrer (2004) in Georgia and Colorado were corroborated by Pomeroy (2007). Figure 2-8 shows the effect of stormwater detention on peak discharges for the Morgan Creek watershed in the North Carolina Piedmont. For this figure, channel geometry remained constant and urban development was mitigated to near rural conditions through the use of detention. The use of stormwater controls help mitigate the effects of urban development by causing the urban scenario's peak flow exceedance curve to more closely match that of the rural scenario.

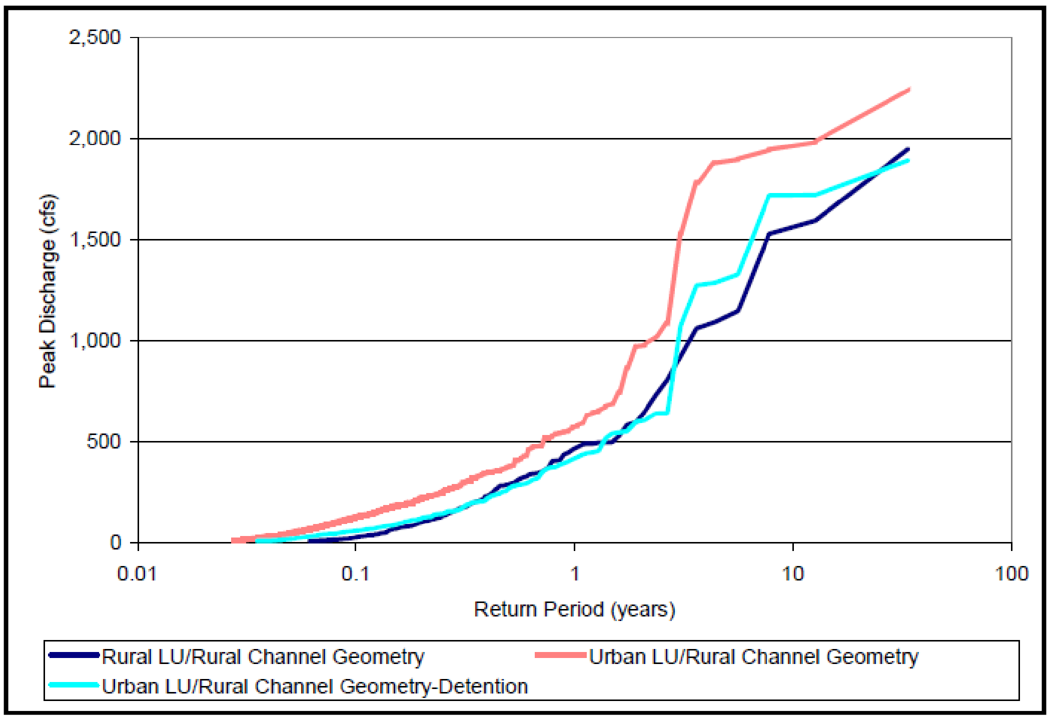

Figure 2-8: Effects of detention on peak flow frequency exceedance curves in Morgan Watershed with rural channels. (Source: Pomeroy, 2007)

In addition to decreasing the frequency of peak flows, Rohrer (2004) found that stormwater controls could decrease the duration of high flows. Again, this was done for rainfall data from both Fort Collins and Atlanta. The flow duration curve in Figure 2-9 plots discharge against the percent of time that a given discharge is exceeded for the Fort Collins model.

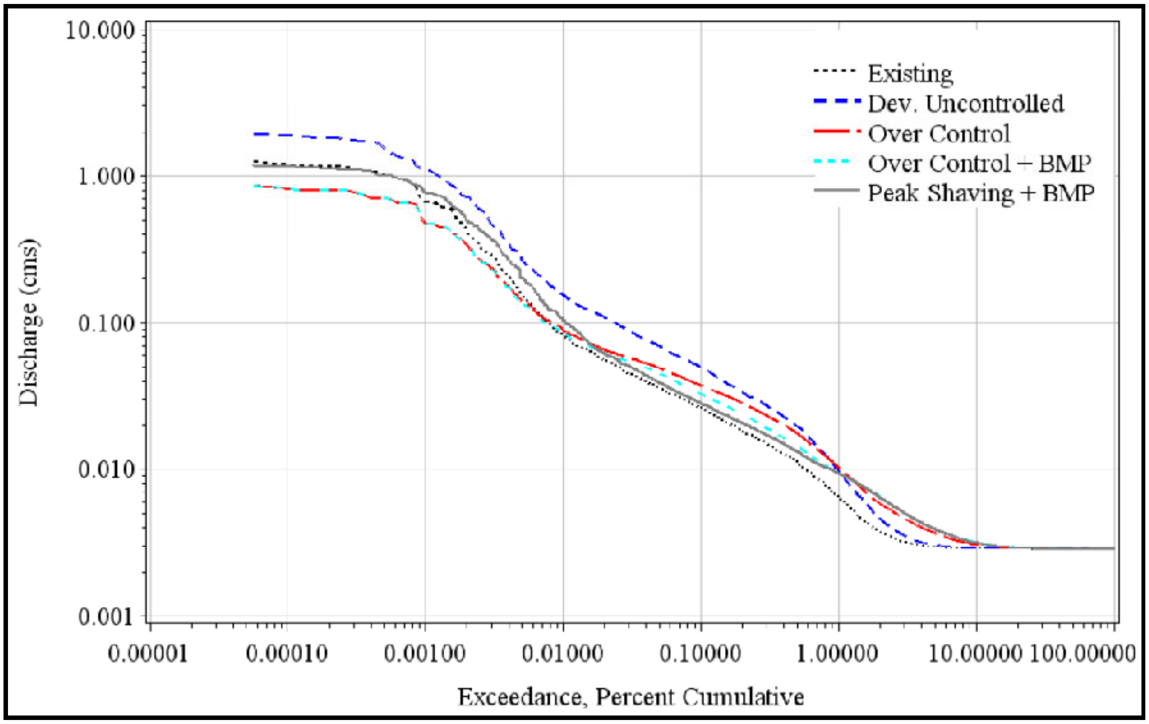

Figure 2-9: Discharge duration, full watershed: Fort Collins. (Source: Rohrer, 2004)

Any restoration efforts on impaired aquatic systems should focus on mimicking natural hydrology (Roesner et al., 2001). Purely physical restoration techniques or restoration measures that focus solely on one species' habit and preferred flow characteristics will likely be unable to establish a healthy aquatic habitat (Poff et al. 1997). Even if physical changes are made, deteriorated hydrologic conditions will cause habitat problems to reoccur unless hydraulic controls are able to prevent negative hydrologic impacts of urbanization. Such adverse impacts from uncontrolled development are evidenced by the erosion caused by flow frequency and flow duration curves that are above critical thresholds of shear. Figure 2-10 shows the results of the analysis done by Rohrer (2004) on the Fort Collins watershed where shear stress is plotted against the percent of time a given shear stress is exceeded. The figure shows that for gravel bed streams, stormwater controls reduce the period of time for which shear stress exceeds the critical shear stress relative to the uncontrolled development scenario.

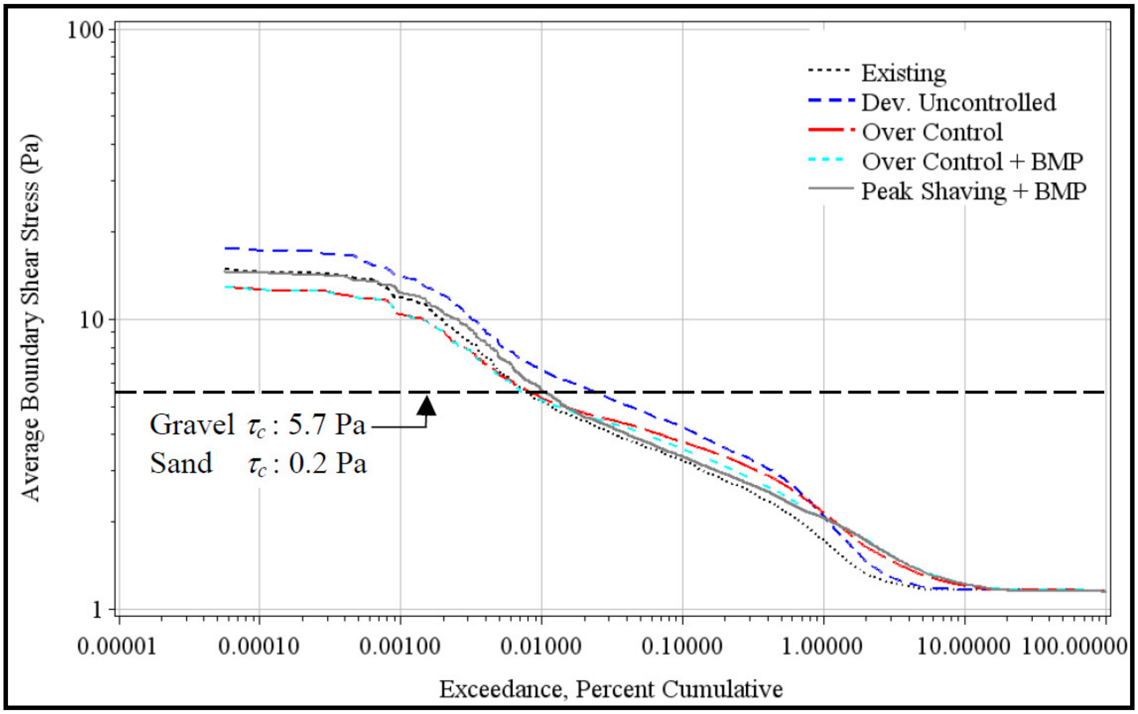

Figure 2-10: Average boundary shear stress, full watershed: Fort Collins. (Source: Rohrer, 2004)

Modeled results of shear and flow exceedance showed the importance of matching post-development hydrology to pre-development. If such changes in hydrology are to be mitigated, stormwater controls must be implemented to control both peak flow frequency and duration. Pomeroy (2007) recommended that this be done by sizing stormwater facilities to control the 100-, 10-, and 2-year peak flows (peak shaving) in conjunction with an extended detention water quality feature to match pre-development hydrology.

2.8 Calculating Hydrologic Metrics

Determination of storm recurrence intervals is necessary for the calculation of many of the aforementioned hydrologic metrics including the $T_{0.5}$. Cunnane (1978) gives the following plotting formula:

$$\boldsymbol{F_i} = (\boldsymbol{i} - \quad)/(\boldsymbol{N} + 1 - 2 \quad) \tag{2-1}$$

In the above equation, $\boldsymbol{F_i}$ is the return frequency of a given flow (events per year), $\boldsymbol{i}$ is the rank of a given storm event taken from a series of peaks (ranked in descending order), $\boldsymbol{N}$ is the total number of storm peaks, and α is the plotting position that varies from 0.375 to 0.44 (typically 0.4).

To determine the storm peaks needed in Equation 2-1, partial duration series can be used rather than using only annual maximum values (Langbein, 1949; Beguería, 2005). If annual maximum values are used, several large events would be missed if they occurred within a single year. The advantage of a partial duration series is that all storm peaks will be ranked and incorporated into the flow frequency analysis regardless of the time increment. Differences between the annual maximum and partial duration series approaches are most readily observed for relatively small, frequent storms (Langbein, 1949). This is because large peaks will likely be observed using either method, whereas smaller storms will be more likely to be incorporated by the partial duration series method. To use a partial duration series, a threshold value must be set to distinguish between minor fluctuations in baseflow and storm events (Beguería, 2005). If this threshold value is set too high, uncertainty is increased as the number of events observed becomes limited. If the threshold is set too low, peaks may not be independent and therefore be part of the same storm.

3.0 APPROACH AND METHODOLOGY

The purpose of this study is to use available information and known correlations between hydrology and benthic macroinvertebrate indicators of stream health to guide stream rehabilitation efforts in the City of Fort Collins, Colorado. For rehabilitation efforts to be effective, appropriate hydrology must be present. If in-stream modification is performed in impaired hydrologic systems, it is unlikely to be sustainable and is therefore a poor investment. For those stream systems with poor hydrology, stormwater controls should be placed upstream prior to modifying the physical characteristics of receiving streams. This study seeks to identify methods for directing stream improvements to areas with the highest potential for positive environmental impacts.

The papers and articles discussed in the literature review suggested a correlation between stream health, stream hydrology, and watershed urbanization. Therefore, metrics describing each of these relevant stream attributes are assessed in this report. As discussed in the literature review, benthic macroinvertebrate data are available from two previous studies performed in Fort Collins, Colorado. Data from these studies are coupled with stream gage data from the City's Flood Warning System gage stations. The degree and effect of urbanization is quantified through the use of geographic information system (GIS) maps. Data for these maps comes from various sources and will be discussed in greater detail later in this report.

3.1 Study Area

The City of Fort Collins, Colorado is situated in the Front Range area east of the Rocky Mountains as shown in Figure 3-1. Recent urban development has caused rapid growth in the City whose population has increased from just under 119,000 in 2000 to over 136,000 in 2008 (U. S. Census Bureau).

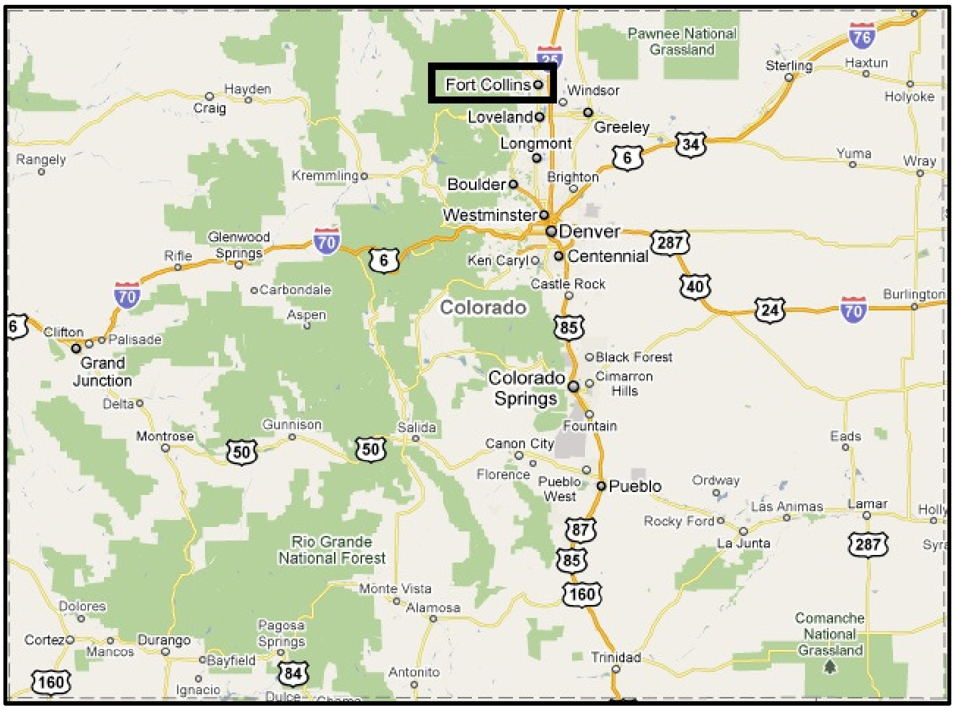

Figure 3-1: Location map of Fort Collins, Colorado. (Source: Google Maps)

Because of the relatively arid climate in the region, irrigation is necessary to support agriculture. Starting in the 1860's, several irrigation canals were constructed to deliver water to the region (Watrous, 1911, p. 71-72). These canals draw water from the Cache la Poudre River and flow from north to south through the City. Additionally, there are two major creeks that flow from west to east through Fort Collins. Spring Creek originates at Horsetooth Reservoir and flows through the northern part of the City while Fossil Creek drains much of the southern part of the City. Boxelder Creek, which enters the Cache la Poudre River from the north, drains a vast area but a relatively small portion of Fort Collins. Several smaller creeks including Foothills Creek, McClellands Creek, and Clearview Creek also flow from west to east through the City. Figure 3-2 shows this system of creeks and canals in the City of Fort Collins.

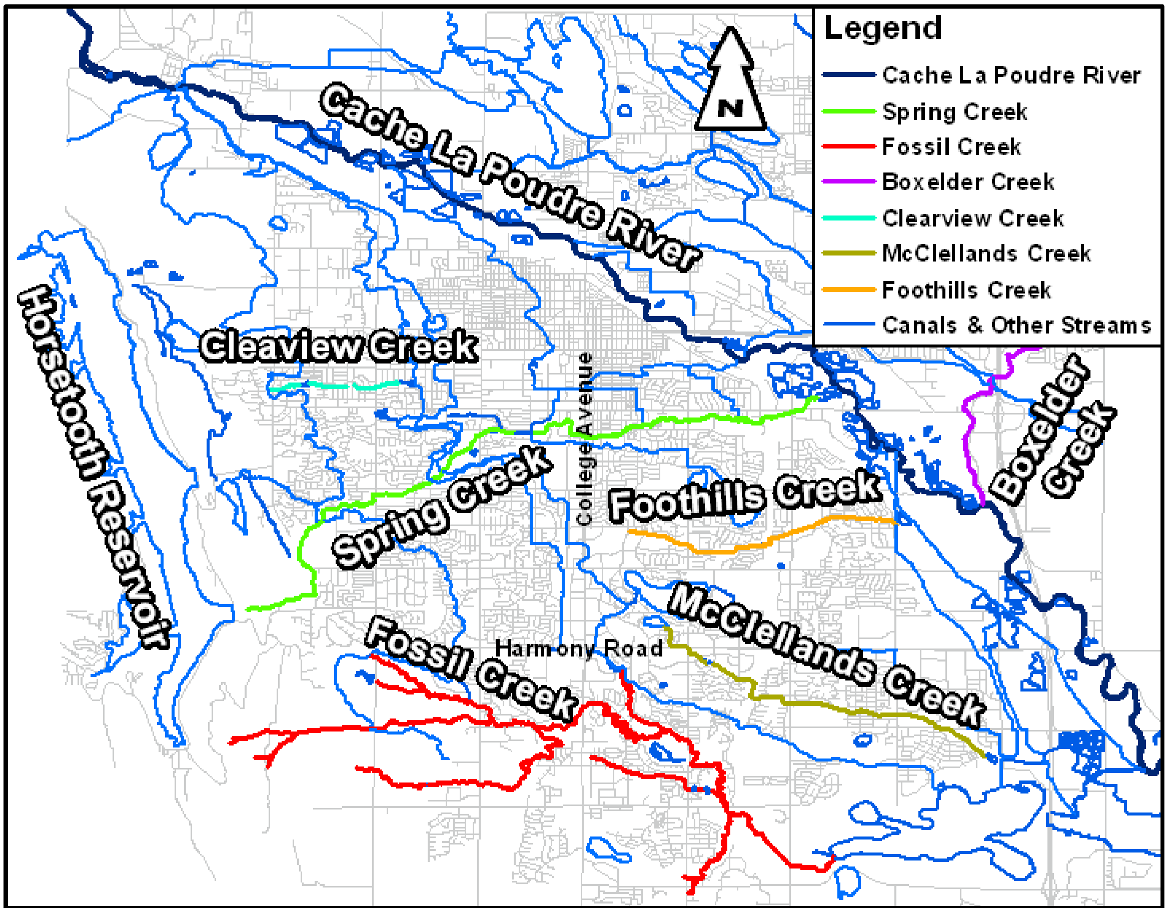

Figure 3-2: Map of urban creeks in Fort Collins, Colorado. (Source: Fort Collins Utilities GIS)

The Fort Collins area is no longer dominated by agriculture as was historically the case. Urbanization first occurred in the northeast part of town and spread to the southern reaches of the City. This has caused each of the creeks to have different watershed characteristics. The specific characteristics of each watershed are discussed below.

3.1.1 Spring Creek

The area near the confluence of Spring Creek and the Cache la Poudre River was the first area of Fort Collins to be developed and is referred to by locals as "Old Town."

This area was first developed in the 1860's (Watrous, 1911, p. 226). The campus of the Agricultural College of Colorado, presently Colorado State University (CSU), was established in 1870 (Watrous, 1911, p. 138). The campus encompassing nearly 2.0 km^2 (0.8 mi^2) drains to Spring Creek. Fort Collins expanded around the university and Old Town and therefore, of the three major creeks, Spring Creek is the most densely urbanized. At the time of development, neither flood controls nor stormwater BMPs were used to attenuate or treat runoff entering Spring Creek. Though some recent construction and retrofit designs now include stormwater controls, much of the development in the 26.9 km^2 (10.4 mi^2) Spring Creek Watershed still flows freely into the creek (Fort Collins Utilities GIS, 2009).

The creek itself has been trained and channelized through much of Fort Collins. In-line flood-control detention has been added at several locations along the length of the creek. Furthermore, a system of in-line detention ponds is located at the creek's outlet to the Cache la Poudre River. These ponds are reclaimed gravel pits acquired by the City in 1996 as part of the Cattail Chorus Natural Area (City of Fort Collins, 1999).

3.1.2 Fossil Creek

The Fossil Creek Watershed is less developed than Spring Creek. Furthermore, urban development in this area is relatively recent. Much of the 42 km^2 (16 mi^2) watershed remains undeveloped pastureland and those areas that were developed after 1997 incorporate stormwater quality BMPs. The creek flows through several residential developments and a golf course before emptying into the Fossil Creek Reservoir. The reservoir then discharges into the Cache la Poudre River via a canal. Upstream reaches of Fossil Creek are characterized by gently sloping banks with grassy vegetation. Further downstream, the channel has become incised by high flows from irrigation canals and development occurring prior to 1997.

3.1.3 Boxelder Creek

Boxelder Creek enters the Cache la Poudre River downstream of the urban Old Town area of Fort Collins and its watershed extends north into Wyoming. The watershed is by far the largest, encompassing an area of roughly 700 km^2 (270 mi^2). Relatively little urban development has occurred in this watershed. Much of the region is covered by irrigated agricultural development. Substantial gullying and degradation can be seen in some reaches of the channel, particularly in agricultural areas. Deep incision has created steep banks in areas where vegetation and stream flow have been altered by agriculture.

3.1.4 Clearview Creek

Clearview Creek is the smallest of the creeks analyzed with a total contributing area of about 2.9 km^2 (1.1 mi^2). It is located in the northwest region of Fort Collins in a largely residential area. The creek empties into the Avery Park detention pond before discharging to the New Mercer canal. The channel is small (less than one meter wide) and meanders through Avery Park and residential developments.

3.1.5 McClellands Creek

McClellands Creek drains roughly 8.7 km^2 (3.4 mi^2) immediately north of Fossil Creek in the southeastern part of town. The creek ultimately flows into a detention pond before it empties into the Fossil Creek Reservoir Inlet canal. It should be noted that a portion of the flow immediately upstream of the detention pond is diverted over the Fossil Creek Reservoir Inlet canal for irrigation purposes. Much of the watershed contributing flow to McClellands Creek is residential or agricultural. Development near the upstream end of the creek tends to be older and incorporate fewer BMPs than does that at the downstream end.

3.1.6 Foothills Creek

Foothills Creek is situated between Spring and McClellands creeks and like McClellands Creek, discharges into the Fossil Creek Reservoir Inlet canal. The 4.7 km^2 (1.8 mi^2) watershed has the most urban development of any of the creeks in Fort Collins. The creek itself tends to be well-channelized with minor incision in places.

3.2 Site Analysis

This study analyzed 12 different sites for various parameters to assess the impact of watershed characteristics on the quality of receiving streams. Each of the 12 sites was located on one of the streams described above. A map with specific locations of each site is shown in Figure 3-3 with corresponding site descriptions in Table 3-1. Photographs of each site are included in Appendix A. The parameters available at each of these sites will be discussed in greater detail in the following sections.

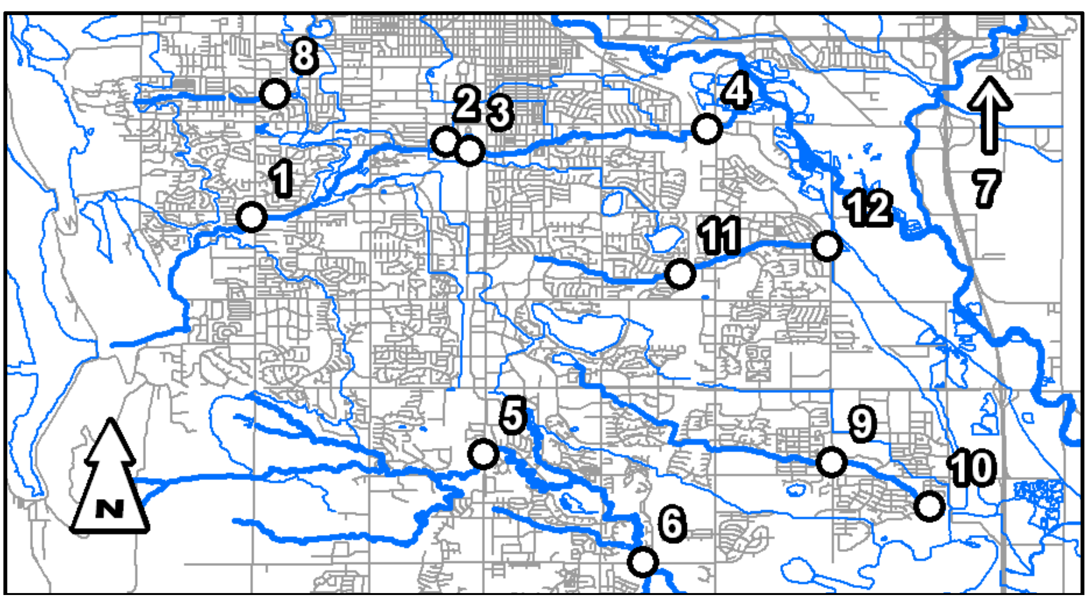

Figure 3-3: Sites assessed in stream study of Fort Collins, Colorado. Site #7 on Boxelder Creek is located several miles north of the top map boundary. (Source: Fort Collins Utilities GIS)

Table 3-1: Location of each site assessed for the urban stream study in Fort Collins, Colorado.

Site ID	Creek Name	Location
1	Spring	Taft Hill Road
2	Spring	Centre Avenue
3	Spring	Burlington Northern RR
4	Spring	Timberline Road
5	Fossil	College Avenue
6	Fossil	Trilby Road
7	Boxelder	County Road 56
8	Clearview	Castlerock Drive
9	McClellands	Ziegler Road
10	McClellands	Fossil Cr. Res. Inlet
11	Foothills	Union Pacific RR
12	Foothills	Ziegler Road

3.3 Stream Gage Data

Gage data gathered from the City of Fort Collins' Flood Warning System was used to assess in-stream hydrology at various places throughout the City. These gages provided roughly nine years of continuous flow records at four locations on Spring Creek, two on Fossil Creek, and one on Boxelder Creek. Figure 3-4 shows the location of these gages throughout Fort Collins. It should be noted that the gage located on Boxelder Creek was north of the City and was therefore not shown. Gage data at these locations was generally collected in hourly increments. To protect the gages from freezing, the stream gages were not left in the streams year-round. Instead, gages were removed each fall and reinstalled the following spring.

Each of the below gage locations used a pressure transducer to measure water depth. This was converted to a flow rate using a head-discharge relationship developed for each particular location. In many cases, urban development has changed channel geometry and therefore, these rating curves have been adjusted over time.

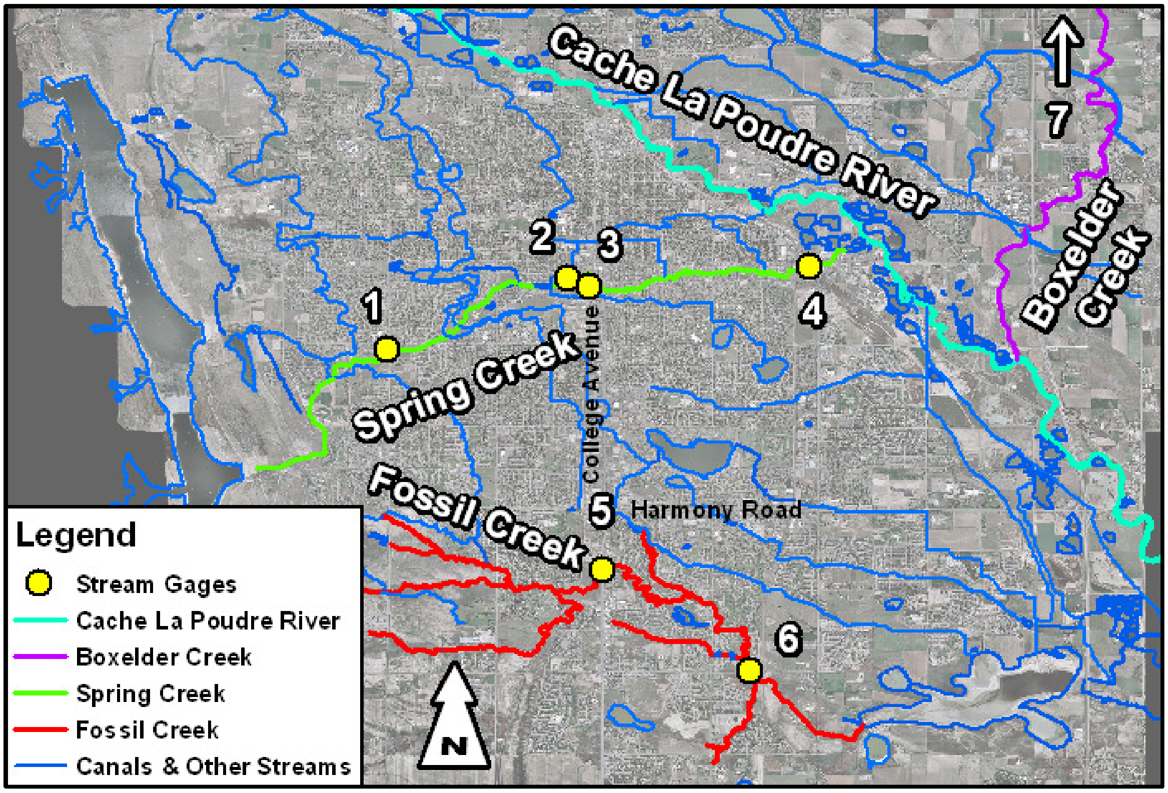

Figure 3-4: Map of stream gages on creeks in the City of Fort Collins, Colorado. (Source: Fort Collins Utilities GIS)

3.4 Hydrologic Metric Calculation

This study focuses on the $T_{0.5}$ metric as used by Booth et al. (2004), Konrad et al. (2005), and Pomeroy (2007). Values of the $T_{0.5}$ metric were calculated for each of the stream gages in Fort Collins. Because stream gages were removed each fall and redeployed each spring, only summer data (May through September) was consistently available and the number of years of record was reduced from nine years to roughly four years. To maintain consistency, only data from May 1st through September 30th was used for each year.

To calculate the $T_{0.5}$, the peak flow for the half-year storm ($Q_{0.5}$) was determined using a partial duration series (Langbein, 1949; Cunnane, 1978). In calculating the partial duration series, it was necessary to set a threshold to define storm flow. To mitigate the effects of baseflow, the threshold value for each gage was adjusted as high as possible while still remaining low enough to identify a sufficient number of storms to determine the half-year storm based on Cunnane (1978). The peak values used in the partial duration series were taken as the highest value of a series of data points above the storm threshold. Peak flows were ranked from highest to lowest and the $Q_{0.5}$ was determined using the plotting position formula suggested by Cunnane (1978). The $T_{0.5}$ was found as the percent of time that flow exceeded the calculated $Q_{0.5}$ at a given gage. It should be noted that the percent of time was determined based on the total time that the gages were operating (May through September each year) and not on the total nine years during which the gages were deployed.

In some instances, peak values appeared which were near the threshold value and occurred within a few hours of one another. It was observed that several of these were two peaks within the same storm event. To maintain independence of storm events as required by a partial duration series, an inter-event time was incorporated which defined the dry period necessary between storm flows to consider storm events to be independent. Values of the inter-event time found in literature varied depending on the source. Pomeroy (2007) used a 6-hour inter-event time to ensure independence was achieved. Konrad et al. (2005) required that peaks be separated by 20 days to ensure independence. With such a large disparity between these two sources, a sensitivity analysis was performed to determine the effect of inter-event time on the $T_{0.5}$. The results of this analysis are shown below in Table 3-2. Based on this analysis, an inter-event time of 48 hours was selected. The rationale for this selection was twofold. First, $T_{0.5}$ values were generally stable around this value of inter-event time. Second, 48 hours was a hydrologically reasonable value. The City of Fort Collins used Volume 3 of the Denver Urban Drainage and Flood Control District (UDFCD) Urban Storm Drainage Criteria Manual for water quality control guidance. The manual required that an emptying time of 40 hours be used for extended detention facilities (UDFCD, 1999). Therefore, with an inter-event time of 48 hours, extended detention facilities should have been given time to empty completely and streams would have returned to near baseflow conditions. Based on this reasoning, peak flows occurring greater than 48 hours apart were assumed to have been independent.

Table 3-2: Values of $T_{0.5}$ hydrologic metric calculated using varying inter-event times for stream gage locations in Fort Collins, Colorado.

	Inter-event Time (hours)									
Gage	**0**	**6**	**12**	**24**	**48**	**72**	**96**	**120**	**240**	**480**
1	0.02%	0.02%	0.02%	0.03%	0.03%	0.03%	0.03%	0.03%	0.03%	0.04%
2	0.06%	0.07%	0.07%	0.09%	0.09%	0.09%	0.25%	0.25%	0.25%	0.25%
3	0.10%	0.10%	0.10%	0.11%	0.11%	0.11%	0.11%	0.11%	0.11%	0.11%
4	0.03%	0.06%	0.06%	0.06%	0.06%	0.06%	0.06%	0.06%	0.10%	0.10%
5	0.13%	0.27%	0.27%	0.27%	0.27%	0.27%	0.30%	0.30%	0.30%	0.30%
6	0.15%	0.26%	0.26%	0.29%	0.46%	0.46%	0.49%	0.49%	0.54%	0.54%
7	1.48%	1.51%	1.51%	2.02%	2.06%	2.30%	2.30%	4.19%	4.78%	9.76%

3.4.1 Data Gaps

Data collected from the Fort Collins Flood Warning Gage were generally continuous with measurements being made at least on an hourly basis. However, there were several gaps present in the data. These may have been due to problems with stream obstructions (beaver dams, floatable debris, etc.), gage calibration, equipment malfunction, or routine maintenance. If data were judged to be substantially out of the normal range, the data were removed and the period of time used in $Q_{0.5}$ calculation was reduced as described below. This occurred for the entire period of May-September 2009 at Gage #3. At this location, a large beaver dam was constructed immediately downstream of the gage shortly after it was installed in the spring. This resulted in depth recordings that were substantially higher than those that occurred under normal baseflow conditions.

Another significant gap existed in the data from Gage #1. This gage was not installed during 2002 and therefore no data were available. Additionally, data from 2004 were sparse indicating a gage malfunction. During that year, 107 data gaps of over 12 hours were identified. The entire year of 2004 was removed to account for this.

At Gage #4, construction was done on the bridge immediately downstream of the gage during the summer of 2006. For this construction to proceed, the gage had to be removed for the months of July, August, and September. Therefore, no data were available at Site #4 for these months.

3.5 Shear Stress and Sediment Transport

In addition to the $T_{0.5}$, shear stress was also calculated from data taken from the Fort Collins Flood Warning Gages. For this calculation, average boundary shear stress was calculated using Equation 3-1 (Julien, 1998, p. 41).

$$_0 = \quad \cdot \boldsymbol{R_h} \cdot \boldsymbol{S_f} \qquad (3\text{-}1)$$

In the above equation, $\boldsymbol{\tau_0}$ is the average boundary shear stress, γ is the unit weight of water, $\boldsymbol{R_h}$ is the channel's hydraulic radius, and $\boldsymbol{S_f}$ is the friction slope of the water surface.

Hydraulic radius was determined as the cross-sectional area of the channel at a given flow divided by the wetted perimeter. These values were based on a field study conducted by CSU in April 2010. Typical stream cross-sections are shown in Appendix B. It should be noted that cross-sections were taken only for Sites #1-3 and #5-7. Site #4 was not surveyed because shear stress could not be readily determined as the gage at this site was located downstream of a weir. Therefore, flow depth in the channel upstream could not have been determined based on gage measurements.

In calculating boundary shear, bed slope was substituted in place of friction slope. This substitution required the assumption that flow was steady and uniform. Though backwater effects and inconsistencies in flow were likely to have existed, this assumption was necessary to determine shear based solely on water depth measured by the Flood Warning Gages.

Average shear stress was calculated for each of the cross-sections and is shown in Table 3-3. It should be noted that the cross-sections measured at the six gages were only applicable to the most recent channel configuration. Therefore, if channel modifications were done, only those years after the modifications could be used with the current cross-sections. Furthermore, even if a channel was not modified, only data from the most recent years (2007-2009) were used to determine shear stress. This was done so that the cross-sections were not subject to historical natural changes that may have occurred. In addition to average shear stress, Table 3-3 also lists the years of available record used to calculate shear. As with the $T_{0.5}$, only May through September data were used in order to maintain consistency. The implication of these findings will be discussed in greater detail in Section 4.4.

Table 3-3: Average boundary shear stress calculated based on channel cross-sections surveyed in 2010. Average shear stress was determined using the most current gage data available as indicated by the time frame listed.

Site	τ_0 (Pa)	Years
1	1.69	2009
2	3.59	2007-2009
3	3.32	2007-2008
5	1.11	2007-2009
6	2.57	2007-2009
7	5.65	2007-2009

3.5.1 Sediment Transport

Sediment transport is a function of both shear stress and some channel characteristic; generally grain size or a value of critical shear stress. There are numerous equations commonly used to determine sediment transport in streams. Since this study focuses on stream health indicated by benthic macroinvertebrates residing in bed sediments, bedload transport equations were used to assess the impact of shear stress.

Two common bedload equations, the Meyer-Peter and Müller equation and the Einstein and Brown equation for high shear stresses, determine the magnitude of sediment transport by raising the Shield's parameter (τ_*) to the 1.5 power (Julien 1998, p.161-162). Shield's parameter is defined by Equation 3-2 below (Julien 1998, p. 162).

$$\tau_* = \frac{\tau_0}{(\gamma_s - \gamma)\cdot \boldsymbol{d_s}} \qquad (3\text{-}2)$$

In the above equation, $\boldsymbol{\tau_0}$ is the average boundary shear stress, $\boldsymbol{\gamma_s}$ is the unit weight of bed sediment, γ is the unit weight of water, and $\boldsymbol{d_s}$ is the average sediment size in the bed material. The primary caveat with the use of τ_* as an indicator of sediment transport is that the aforementioned equation only applies to non-cohesive sediments. In several of the Fort Collins streams, cohesive soils were found therefore, sediment transport could not be determined simply based on sediment size.

However, if sediments were assumed to be similar and have similar shear resistance, the sediment transport equations mentioned above would solely be a function of $\tau_0^{1.5}$. This would mean that $\tau_0^{1.5}$ would be directly proportional to the sediment transport rate and the relative rates of sediment transport between creeks could be observed by comparing values of $\tau_0^{1.5}$. Table 3-4 shows the average values of $\tau_0^{1.5}$ for each of the six gages surveyed. The same period of record described in Table 3-3 was used for this calculation. As before, the implication of these findings will be discussed in Section 4.4.

Table 3-4: Average values of the sediment transport parameter, $\tau_0^{1.5}$, for each of the surveyed stream gage locations. The transport parameter was calculated based on the most current gage data available as indicated by the period of record listed.

Site	$\tau_0^{1.5}$ ($Pa^{1.5}$)	Years
1	2.27	2009
2	7.65	2007-2009
3	6.15	2007-2008
5	1.21	2007-2009
6	4.29	2007-2009
7	14.28	2007-2009

3.6 GIS Analysis of BMPs

The City of Fort Collins in the summer of 2009 inventoried its BMPs through the use of GIS mapping. This map classified the way in which BMPs were used to control stormwater as either flood control only, water quality control only, flood control with water quality features, or no stormwater controls. In addition to the sites with stream gages, five other sites were used for the analysis of stream health and BMP coverage as shown in Figure 3-3. It should be noted that BMP analysis was not performed at Site #7 on Boxelder Creek as it was north of the City and BMP data were not available.

3.6.1 Watershed Delineation

Through detailed analysis of the Fort Collins GIS map, those areas contributing ultimately to either Spring, Fossil, Clearview, McClellands, or Foothills creeks were delineated. This was done using existing watershed boundaries in conjunction with detailed stormwater pipe maps. Contributing areas for each creek were broken down into subwatersheds for each site. The area contributing to each site can be seen below in Figure 3-5.

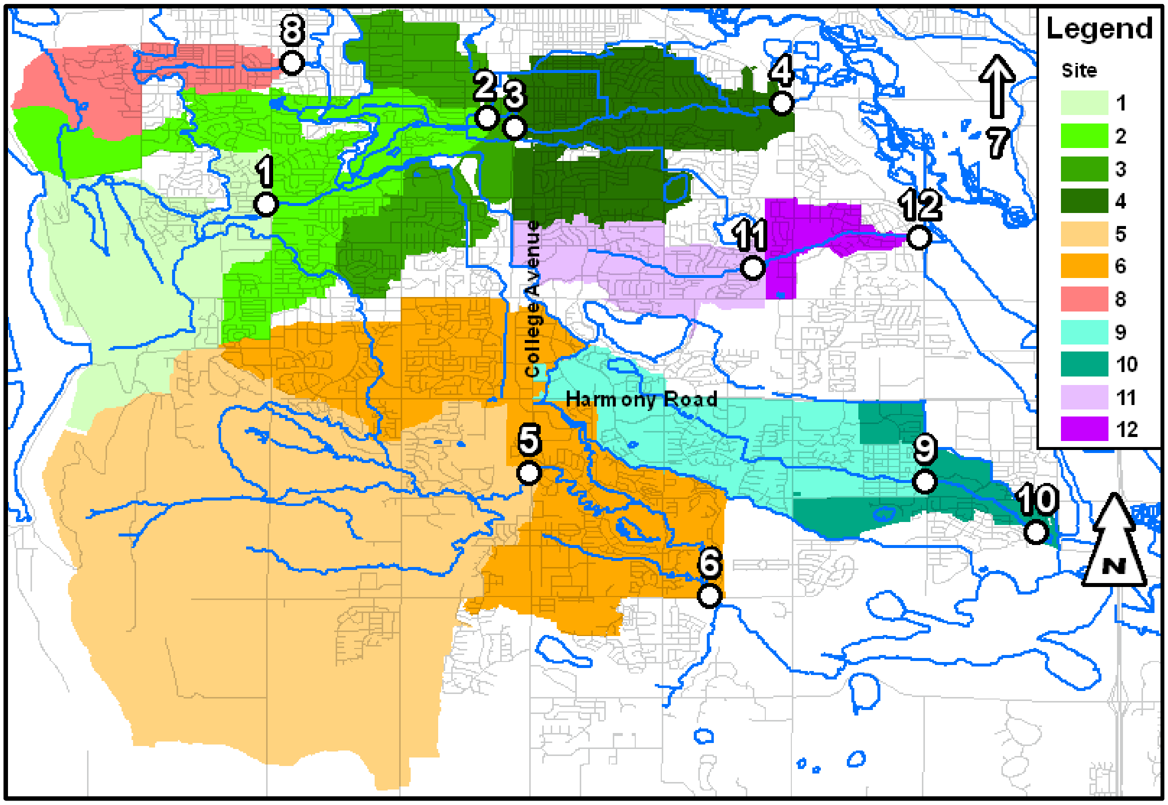

Figure 3-5: Map of sub-watershed areas contributing to each of the stream study sites in Fort Collins Colorado. Note that the watershed areas of upstream sites (lighter color) also contribute to downstream sites (darker color) on the same creek. (Source: Fort Collins Utilities GIS)

In the process of determining the boundaries of the above watersheds, special attention had to be paid to the numerous irrigation canals traversing the City from north to south. Figure 3-6 shows the major canals in Fort Collins. Every canal is supplied by flow diverted from the Cache la Poudre River. As can be seen from Figure 3-6, each of these canals intersects Spring Creek or Fossil Creek. A more detailed assessment of how the canals influence the creeks is provided in the following sections. It should be noted that the current Fort Collins stormwater manual (City of Fort Collins, 1984, rev. 1997) does not generally permit discharges from urban areas into irrigation canals. Since 1984, discharge to canals has only been permitted when a variance is obtained for such a discharge or where discharge to a canal is required by water rights law.

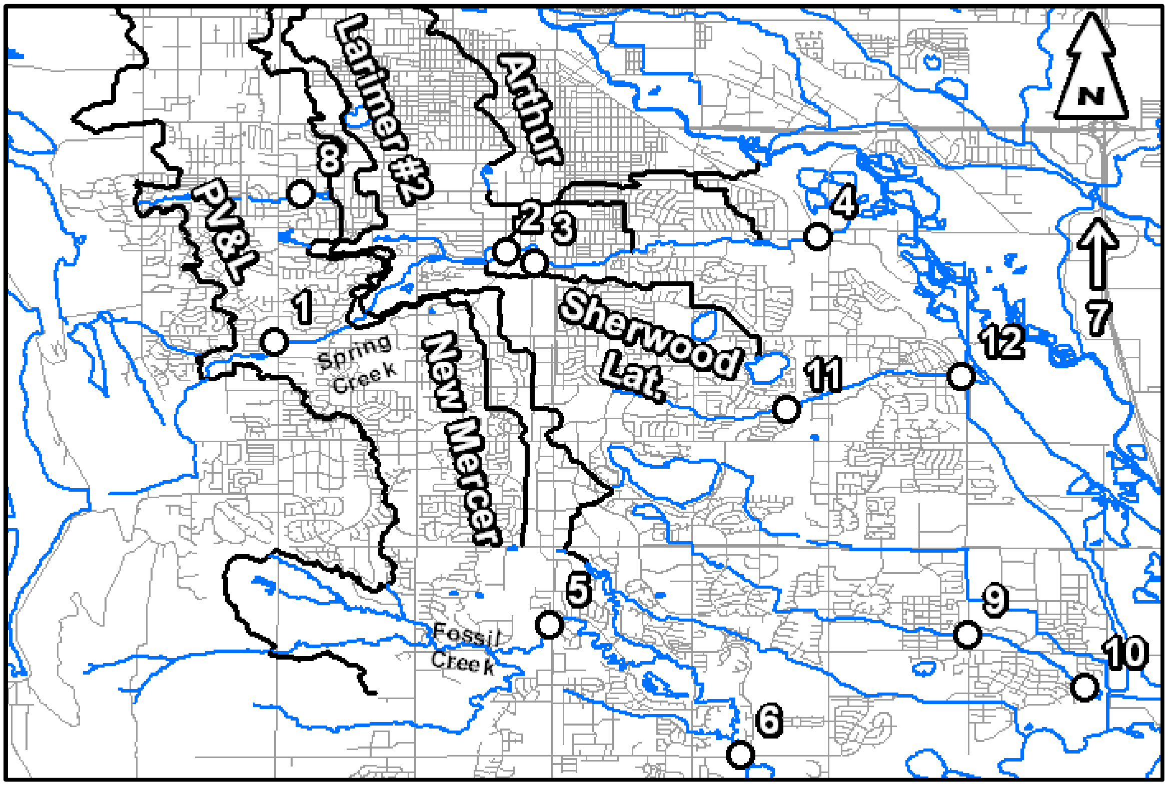

Figure 3-6: Map of canals influencing flow in Spring Creek and Fossil Creek in Fort Collins, Colorado. (Source: Fort Collins Utilities GIS)

3.6.1.1 PV&L Canal

The Pleasant Valley and Lake (PV&L) Canal conveys flow over Spring Creek. Therefore, except during large storms, flow from Spring Creek and the canal do not commingle. The PV&L Canal ultimately discharges at the upstream end of Fossil Creek. Because the canal carries flow from north of the city limits, precise areas contributing to the canal cannot be readily determined. Furthermore, flow in the canal cannot be attributed to a contributing area because it is diverted directly from the Cache la Poudre River. Since this diversion rather than storm flow is the main contributor of water to the canal, flow in the canal should be generally stable and therefore is assumed to act as a baseflow during the summer months (May to September). Areas contributing to the canal upstream of Spring Creek are not included in the watershed of Fossil Creek.

3.6.1.2 New Mercer Canal

As with the PV&L Canal, the New Mercer Canal primarily carries flow that is diverted from the Cache la Poudre River. However, this canal does physically comingle with Spring Creek. Here, flow from Spring Creek enters the canal and water is allowed to leave the canal and re-enter the creek via a sluice gate as shown in Figure 3-7.

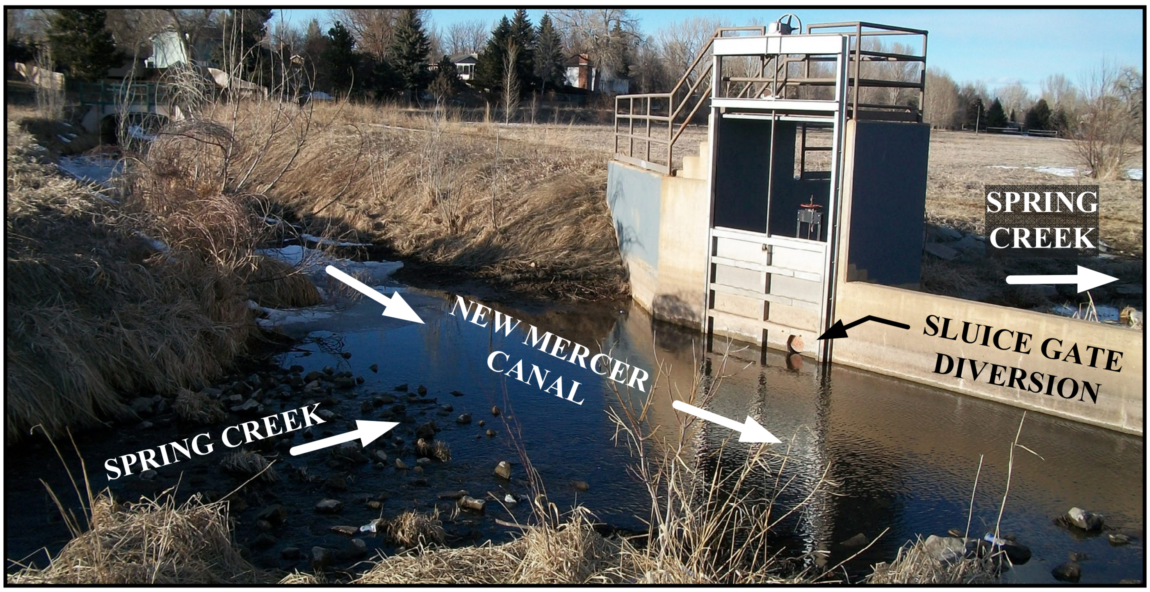

Figure 3-7: Confluence of flow at Spring Creek and New Mercer Canal. Flow comingles in the New Mercer Canal before being discharged to Spring Creek via a sluice gate.

The City of Fort Collins adjusts the sluice gate so as to allow equal flow entering and leaving the canal via Spring Creek (Lochra, 2010). However, this is an inexact process as there is not a flow monitor on the slice gate. Gages on Spring Creek and the New Mercer Canal are not spaced closely enough to determine with any certainty the water balance at this confluence. Therefore, flow from the New Mercer Canal is assumed not to add or remove flow from Spring Creek.

Downstream of the intersection with Spring Creek, the New Mercer Canal continues south and flows into the Fairway Estates Reservoir where flow is split. A portion of the flow goes through the Fairway Estates Reservoir and then discharges over a dam into

Mail Creek and eventually into Fossil Creek. Another portion of the flow from the New Mercer Canal never enters Fossil Creek and is instead diverted directly to the Mail Creek Ditch upstream of the Fairway Estates Reservoir. Additionally, gage data at the Fairway Estates Dam indicate that flow over the dam is well-regulated and therefore acts as base flow. Because of this base flow characteristic and the disconnect created by the Fairway Estates Dam, flow contributing to the upstream portions of the New Mercer Canal are not included in the Fossil Creek watershed.

3.6.1.3 Larimer County #2

The Larimer County #2 Canal flows immediately east of the New Mercer Canal. As with the PV&L Canal, flow in the Larimer County #2 Canal crosses over Spring Creek and the two do not comingle except during large storms. Therefore, areas contributing to the Larimer County #2 Canal are not included in the Spring Creek watershed. At the downstream end of the canal, the Larimer County #2 Canal joins with the New Mercer Canal before entering the Fairway Estates Reservoir. Hence, like the New Mercer Canal, areas contributing to the Larimer County #2 Canal are not included in the Fossil Creek watershed.

3.6.1.4 Arthur Canal & Sherwood Lateral

The Arthur Canal flows from the north and splits ultimately into four different branches. Of these, three enter Spring Creek at various locations. The most upstream branch enters Spring Creek upstream of Site #2 at a regional wet detention pond. Flow from the pond exits either via a weir to Spring Creek or via a sluice gate to the Sherwood Lateral. Flow at this point is not measured by a stream gage and therefore cannot be quantified.

The next most downstream branch is known as the Pitkin Lateral and enters Spring Creek between Sites #3 and #4. Further downstream, the canal splits again and the Emigh Lateral enters the Creek upstream of Site #4. The remaining branch of the canal discharges directly to the Cache la Poudre River. Since there are no gages on any of these canal branches, flow to Spring Creek cannot be determined quantitatively. Because of this and because new developments do not discharge to the canal, flow in the canal is assumed to be unaffected by storms and acts as a baseflow. Therefore, it is not included as part of the Spring Creek watershed delineation.

3.6.2 BMP Data Layer

Though the City of Fort Collins' GIS layer determined the type of BMP treatment for each site in the City, it did not distinguish between those areas that were developed without stormwater controls and those areas that had no stormwater controls because they had not yet been developed. Since BMPs were intended to mimic natural conditions, undeveloped areas should not have been treated in the same manner as those areas that have been developed without stormwater controls. Therefore, through site visits and visual inspection of aerial photography, areas that did not contain urban development were separated as being "undeveloped." The final composite map of the areas treated by each type of BMP is shown below in Figure 3-8. Much of the southern and western portions of the city contributing to the upstream ends of Fossil and Spring Creeks remained undeveloped. In contrast, the northeast portion of town near the downstream end of Spring Creek was densely developed with relatively few stormwater controls. The distribution of BMP coverage by watershed is detailed below in Table 3-5.

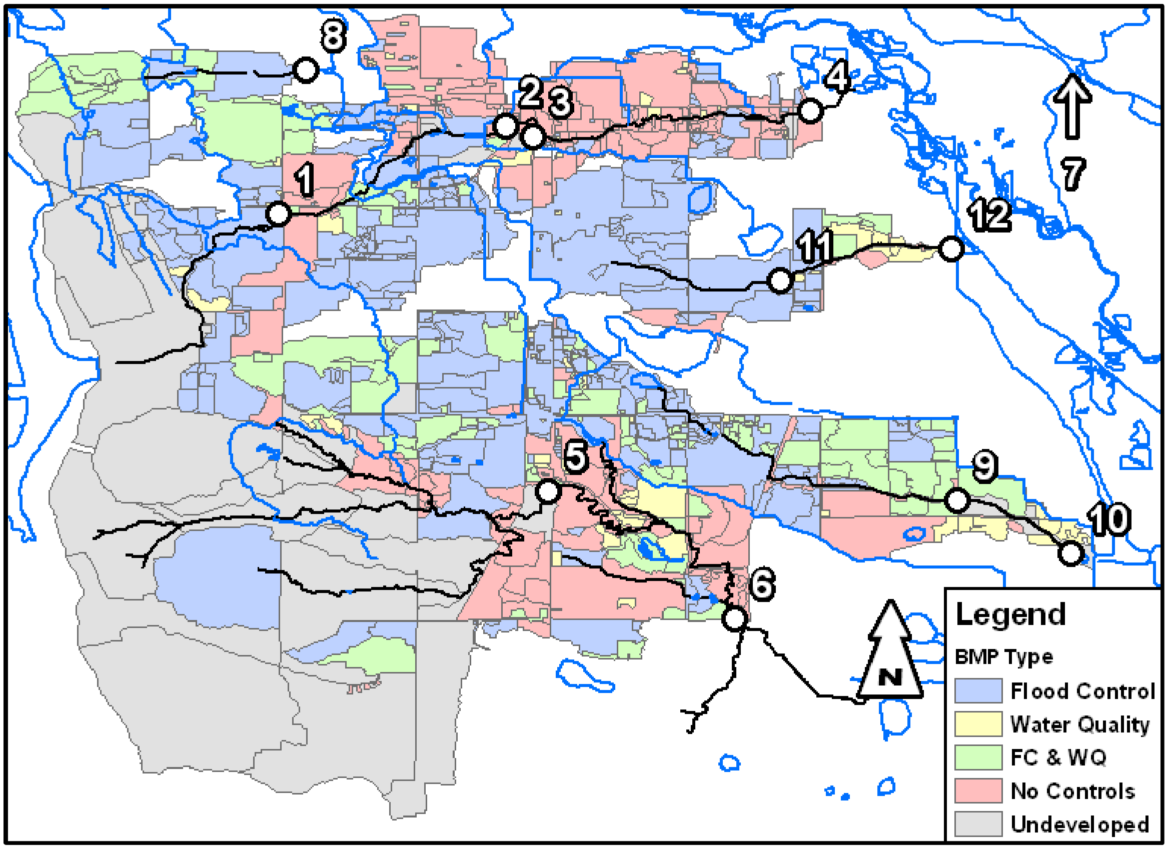

Figure 3-8: Map of best management practices used to treat runoff contributing to urban creeks in Fort Collins, Colorado. (Source: Fort Collins Utilities GIS)

Table 3-5: Relative distribution of best management practices among each of the 12 sites assessed in Fort Collins, Colorado.

Site ID	Creek Name	WQ/FC	WQ only	FC only	None	Undev.
1	Spring	0%	2%	34%	0%	64%
2	Spring	12%	2%	36%	13%	37%
3	Spring	10%	2%	39%	21%	29%
4	Spring	7%	2%	39%	30%	22%
5	Fossil	2%	0%	17%	7%	74%
6	Fossil	9%	2%	22%	16%	51%
8	Clearview	51%	0%	49%	0%	0%
9	McClellands	40%	0%	50%	10%	0%
10	McClellands	34%	6%	39%	17%	5%
11	Foothills	0%	0%	93%	7%	0%
12	Foothills	6%	8%	77%	10%	0%

3.7 Urban Intensity Analysis

The literature review found several methods for quantifying urbanization. Of these, the most comprehensive was found to be the UII developed by McMahon & Cuffney (2000). Sprague et al. (2006) adapted this method to use data that had been made available since the metric's development such as 2000 population and socioeconomic data. This study followed the five basic steps used by Sprague et al. (2006) which were modified from the original UII. UII calculation was done for each of the watersheds delineated in the GIS analysis of BMPs. A set of 83 different watershed characteristics were analyzed falling into one of five categories: environmental, land use, infrastructure, population, and socioeconomic characteristics. A complete listing of data sources and UII parameters is shown in Appendix C. Metrics were selected based on those used by McMahon & Cuffney (2000) and Sprague et al. (2006).

The raw calculated values for each of these watershed characteristics were then adjusted proportionally such that the values for the set of watersheds ranged from 0-100. As suggested by Sprague et al. (2006), Sprearman's rank correlation coefficients were calculated to relate each of the variables to watershed area and population density. Only those characteristics that were strongly correlated to population density (absolute value of Spearman $\rho \geq 0.5$) and weakly correlated to basin area (absolute value of Spearman $\rho \leq 0.5$) were retained for analysis in the final UII. These retained variables and corresponding correlation coefficients are shown below in Table 3-6.

To make increasing levels of urbanization correspond to increasing values of UII, any watershed metrics which were negatively correlated with population density were subtracted from 100 so they increased with population density. Finally, all of the retained UII component values were averaged and the composite UII was adjusted proportionally so that it ranged from 0-100. Values for this composite UII are tabulated below in Table 3-7.

Table 3-6: Retained Urban Intensity Index variable. "ρ Area" is the Spearman correlation coefficient with respect to watershed area and "ρ Pop" is the Spearman correlation coefficient with respect to population density. Characteristics were retained if ρ Area ≤ 0.5 and ρ Pop ≥ 0.5.

ρ Area	ρ Pop	Landuse Characteristics	
-0.08	0.51	LU21_AB	Proportion of watershed with devel. open space on well-drained soils
-0.47	0.69	LU21_CD	Proportion of watershed with devel. open space on poor-drained soils
-0.33	0.68	LU22_AB	Proportion of watershed with low intensity devel. on well-drained soils
-0.22	0.60	LU23_AB	Proportion of watershed with med. intensity devel. on well-drained soils
-0.47	0.51	LU23_CD	Proportion of watershed with med. intensity devel. on poor-drained soils
-0.47	0.71	LU24_CD	Proportion of watershed with high intensity devel. on poor-drained soils
-0.44	0.92	MRLC_21	Watershed area in Developed, Open Space(square miles)
-0.48	0.74	MRLC_24	Watershed area in Developed, High Intensity (square miles)
0.35	-0.58	MRLC_41	Watershed area in Deciduous Forest (square miles)
0.23	-0.70	MRLC_81	Watershed area in Pasture/Hay (square miles)
0.00	-0.68	MRLC_82	Watershed area in Row Crops (square miles)
0.34	-0.83	MRLC_95	Watershed area in Emergent Herbaceous Wetlands (square miles)
0.33	-0.69	BUF_11	Total area (square miles) of MRLC 11 within buffer
0.40	-0.54	BUF_81	Total area (square miles) of MRLC 81 within buffer
		Population Characteristics	
0.29	-0.59	AGESTR2000	Age structure of population (pop. under 18/pop. over 18)
0.32	-0.79	POP90_2000	Population change 1990-2000 (proportion) (P2000DEN)
0.26	-0.55	URBSPRWL	Urban sprawl index [(urban land area/2000 pop.)*10,000]
		Socioeconomic Characteristics	
0.37	-0.71	PPLFAM	Average Family Size: 2000
0.24	-0.61	PPLHSE	Average Household Size: 2000
0.37	-0.84	HSE95_2000	Percent of Housing Units Built 1995 to March 2000: 2000
-0.49	0.95	URBNPPL	Percent of Persons Who Live in Urban Areas: 2000

Table 3-7: Final Urban Intensity Index for each of 12 stream study watersheds in Fort Collins, Colorado.

	Final Adjusted UII											
Site	1	2	3	4	5	6	7	8	9	10	11	12
UII	21	65	83	92	0	14	16	62	44	32	100	87

3.8 Benthic Macroinvertebrate Data

For the purposes of this study, benthic stream health is presumed to be indicated by ET richness and %ET. Therefore, each of the aforementioned watershed and stream characteristics will be used to relate urban development to the quality of benthic macroinvertebrates as indicated by ET richness and %ET.

3.8.1 Historical Benthic Assessments

Two previous studies have evaluated the structure of benthic macroinvertebrate communities in Fort Collins streams (Hoffman, 1998; Zuellig, 2001). Locations where benthic information was available were matched to the sites shown in Figure 3-3. Figure 3-9 shows which benthic data were available for each of the sites. At sites with stream gages, benthic data were deemed to match a particular gage if they were within approximately 0.5 km of the gage and no major tributaries, hydraulic structures, or stormwater inputs were between the benthic sampling location and the gage. Hoffman (1998) studied benthic macroinvertebrates at five locations which corresponded to the location of study sites and Zuellig (2001) recorded benthic data at eight locations which matched study sites.

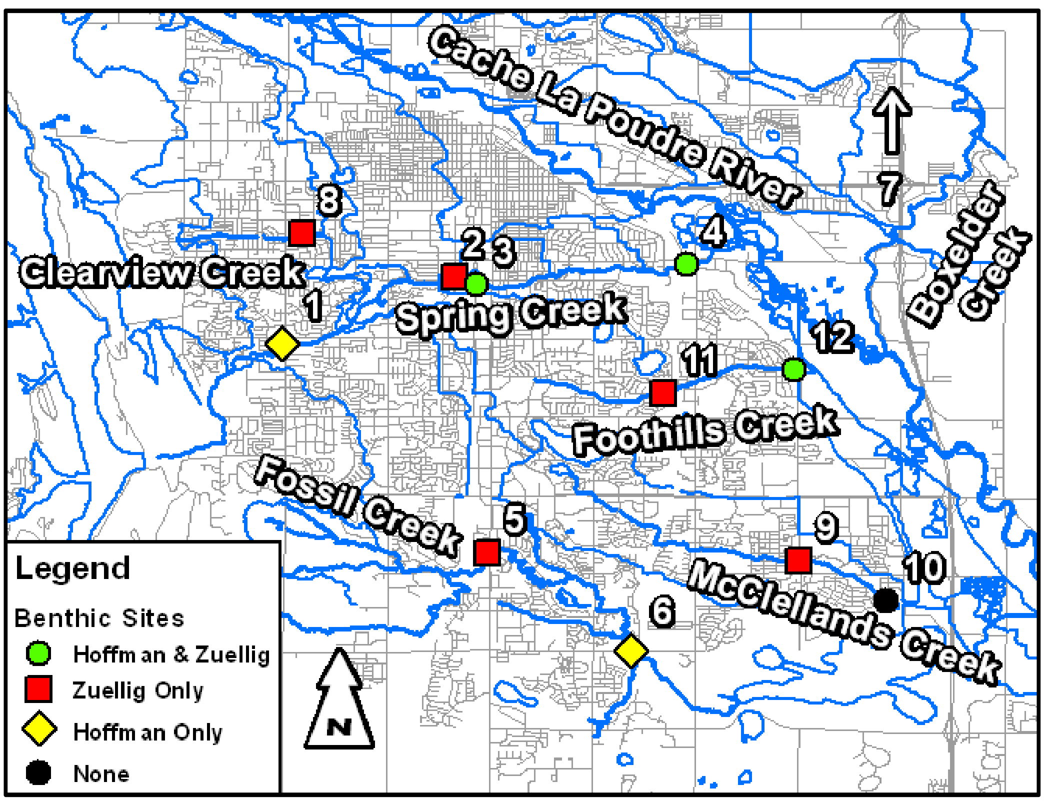

Figure 3-9: Stream gage locations with corresponding benthic macroinvertebrate data from Hoffman (1998) and Zuellig (2001). No benthic macroinvertebrate data were available at Site #7 on Boxelder Creek. (Source: Fort Collins Utilities GIS)

As was noted in the literature review, Zuellig (2001) used rapid bioassessment techniques (Barbour et al., 1999) for samples collected in July of 1999 and 2000. Hoffman (1998) collected samples monthly over the course of a year during 1994 and 1995 and over four months in the summer of 1996. Furthermore, Hoffman (1998) used both rapid and quantitative assessments to analyze benthic communities. To maintain consistency between the two studies, only data from July 1994 and 1996 were used from Hoffman (1998). Additionally, rapid assessment results were used rather than the quantitative assessment when available to better relate to the study conducted by Zuellig (2001).

3.8.2 Updated Benthic Sampling

In addition to the historical benthic macroinvertebrate assessments from Hoffman (1998) and Zuellig (2001), sampling of 12 sites was commissioned by the City of Fort Collins, Colorado which was completed in April of 2010. This sampling was performed to ascertain if ET richness or %ET had changed as a result of changes in land use since the study done by Zuellig (2001). Benthic macroinvertebrate sampling was done using the same methods employed by Zuellig (2001). ET and %ET were determined at each sample site based on 200 organism samples. Macroinvertebrate samples were taken as three, one-minute kick net samples at each site. Sample analysis was performed based on the procedure set forth in the EPA's "Rapid Bioassessment Protocols" (Barbour et al., 1999).

A total of 12 sites were sampled for macroinvertebrates, several of which had been previously sampled. Sites were selected to maximize the amount of information available. Sites with Flood Warning Gage data, existing benthic studies, and GIS BMP information were preferred over those without such data available. Additionally, sites were chosen with varying degrees of urbanization and BMP coverage. Table 3-8 shows what data were available at each of the sites from Figure 3-3. Detailed descriptions of each of the sample sites and the rationale for sampling are included in the following sections.

Table 3-8: Macroinvertebrate, gage, and best management practices data available for each of 12 sites assessed in Fort Collins, Colorado stream assessment.

Site ID	Creek Name	Location	Macroinvertebrate Data Hoffman[1]	Zuellig[2]	2010	Gage Data	BMP Data
1	Spring	Taft Hill Road	X		X	X	X
2	Spring	Centre Avenue		X	X	X	X
3	Spring	Burlington Northern RR	X	X	X	X	X
4	Spring	Timberline Road	X	X	X	X	X
5	Fossil	College Avenue		X	X	X	X
6	Fossil	Trilby Road	X		X	X	X
7	Boxelder	County Road 56			X	X	
8	Clearview	Castlerock Drive		X	X		X
9	McClellands	Ziegler Road		X	X		X
10	McClellands	Fossil Cr. Res. Inlet			X		X
11	Foothills	Union Pacific RR		X	X		X
12	Foothills	Ziegler Road	X	X	X		X

[1]Hoffman (1998), [2]Zuellig (2001)

3.8.2.1 Site #1

The best opportunity for drawing relevant correlations came from incorporating the maximum number of relevant metrics (BMP coverage, benthic macroinvertebrate data, and $T_{0.5}$). One such point was at the most upstream Flood Warning Gage which was located immediately upstream of Taft Hill Road. At this point, BMP, stream flow, and benthic macroinvertebrate data were available. The channel here intercepted flow from a regional detention pond. Areas immediately adjacent to the stream were well vegetated and significant channel degradation was not observed.

3.8.2.2 Site #2

As with Site #1, this location had a stream gage and BMP data making it suitable for a benthic macroinvertebrate study. A Flood Warning Gage was located immediately upstream of the Centre Avenue Bridge at this site. Existing benthic macroinvertebrate data were available from the report by Zuellig (2001). It was noted in the report that the Centre Avenue Bridge was under construction during the summer of 1999 causing siltation in the creek which may have skewed benthic macroinvertebrate results. Therefore, new benthic macroinvertebrate sampling at this site was done to reflect current conditions. Approximately 0.3 km upstream of this site, Spring Creek was regulated by an in-line wet detention facility. The creek itself showed little degradation and was separated from the surrounding park by a small buffer strip of shrubs and grasses.

3.8.2.3 Site #3

Site #3 was located at a Flood Warning Gage near the Burlington Northern and Santa Fe Railroad crossing immediately west of College Avenue. Benthic data from both Zuellig (2001) and Hoffman (1998) were available at this point. The gage was approximately 0.7 km downstream of Site #2 and therefore may also have been affected by the construction of the Centre Avenue Bridge in 1999. The stream at this point was well-channelized and made a right angle turn before flowing through three culverts under the railroad. Construction of a bicycle path near the creek was done in the fall of 2009 which could have contributed sediment to the creek.

3.8.2.4 Site #4

The fourth location on Spring Creek was located at the upstream side of the railroad crossing immediately upstream of the Timberline Road Bridge near the Coterie Natural Area. A Flood Warning Gage provided flow data at this site and existing benthic data were again available from both Zuellig (2001) and Hoffman (1998). Data from these studies appeared to have been uncharacteristically high at this point and new sampling was performed to determine if ET richness or %ET had changed. Furthermore, this provided another location where benthic macroinvertebrate data could be compared to both BMP coverage and the $T_{0.5}$. The channel here was well-defined and was buffered by a grass natural area. However, the stream segment immediately upstream showed substantial incision and bank degradation.

3.8.2.5 Site #5

This site was located immediately upstream of College Avenue on Fossil Creek in the Redtail Grove Natural Area. The channel was well-defined and was buffered by a wide grass area. Steep banks indicated that substantial incision had occurred in the area. This may have been attributed to flow from the PV&L Canal entering the creek upstream. Additionally, a Flood Warning Gage was located at this point. According to ET richness and %ET values found by Zuellig (2001), this location had the highest ET richness and %ET of all of the sites associated with stream gages. This corresponded to the BMP analysis which showed this as one of the least developed of the gauged areas. New benthic macroinvertebrate sampling was done to determine if irrigation flows or recent development beginning in the area had affected the local aquatic ecosystem.

3.8.2.6 Site #6

A Flood Warning Gage was located at this site on Fossil Creek immediately upstream of Trilby Road. The only benthic macroinvertebrate data that were applicable to this site were from Hoffman (1998) which indicated that ET richness and %ET were slightly lower than that found upstream. Development in this area was generally newer than that found along Spring Creek and included more water quality BMPs. Despite these BMPs, the channel here was deeply incised. This was likely due to irrigation flows entering from Mail Creek (from New Mercer Canal and Larimer #2 Canal) upstream of the site. Comparison of 2010 ET richness and %ET data to the 1998 data was done to determine if the stream health had been affected by BMPs or if irrigation flows had caused persistent degraded conditions.

3.8.2.7 Site #7

This site was located north of the City of Fort Collins at County Road 56. A Flood Warning Gage monitored flow in this largely agricultural region. There was relatively little urban development in the watershed however there was no BMP map available for the area. No historic benthic macroinvertebrate data were available on Boxelder Creek though the $T_{0.5}$ was the highest of the seven gauged locations. The channel here was surrounded by high grassy banks and meandered through agricultural fields. High levels of ET richness and %ET were expected based on existing hydrology. However, new benthic macroinvertebrate sampling was done to determine if there were adverse impacts from agricultural runoff or irrigation flows entering upstream of the gage.

3.8.2.8 Site #8

Site #8 was on Clearview Creek in the Canal Importation Basin in the northwestern portion of Fort Collins at the inlet to the Avery Park Detention Pond immediately upstream of Castlerock Drive. The channel was well defined with grass-covered banks as it meandered through Avery Park. Approximately 50% of the watershed had stormwater quality control. Additionally, benthic data were available at this location from Zuellig

(2001). This area was not thoroughly developed when Zuellig's study was completed and new benthic macroinvertebrate sampling was done to determine if the effects of the present development had been appropriately mitigated. Though no gage data existed, this site was assessed to further the relationship between benthic macroinvertebrate indicators of stream health and water quality BMP coverage.

3.8.2.9 Site #9

This site was located at the upstream side of the Ziegler Road crossing at McClellands Creek. The creek here was well-vegetated with a wide floodplain and meandering thalweg. No gage data were available at this location however BMP and benthic macroinvertebrate data (Zuellig, 2001) were available. The watershed had water quality controls on approximately 40% of its land area, many of which had been constructed after the study by Zuellig (2001) was completed. Also, in-stream improvements had been done in 2000 and 2001 which included the addition of a low-flow channel, installation of drop structures, regrading of banks, and creation of pools and riffles. New benthic macroinvertebrate sampling was done here to determine if these in-stream improvements had the desired positive effect on benthic macroinvertebrate communities.

3.8.2.10 Site #10

The second McClellands Creek sampling location was upstream of the creek's confluence with the Fossil Creek Reservoir Inlet and was approximately 1.5 km downstream of Site #9. Before entering the reservoir inlet, a portion of the creek flow was diverted for irrigation. As no gage data were present here, there was no way of determining the amount of flow being diverted. Therefore, new ET richness and %ET sampling was done upstream of the diversion. The creek at this location flowed through a park area that was bordered by an elementary school to the north and a residential development to the south.

Additional BMP controls between Sites #9 and #10 brought the water quality BMP coverage up to nearly 45%. As this watershed had one of the highest levels of water quality BMP coverage in the City, this location was used to show if the inclusion of water quality controls at the downstream end of the creek have protected stream ecology.

3.8.2.11 Site #11

Site #11 was located on Foothills Creek upstream of the pond immediately west of the Union Pacific Railroad crossing. Previously, benthic macroinvertebrate data had been collected at this site by Zuellig (2001). Here, the creek flowed behind several residential developments. There was a dense vegetated buffer separating the creek from the surrounding area and some channel incision was present. The upstream watershed at had virtually no water quality BMPs however over 90% of the contributing area had flood control. New benthic macroinvertebrate sampling was performed at this location to determine if flood control (rather than water quality) has had any impact on stream health as indicated by ET richness and %ET.

3.8.2.12 Site #12

Downstream of Site #11, Site #12 was located at the Ziegler Road crossing of Foothills Creek. This site was previously sampled by both Hoffman (1998) and Zuellig (2001), however substantial development had occurred (and still is occurring) since these studies were conducted. Though only 13% of the total watershed had water quality control, over 45% of the area between Sites #11 and #12 had been developed with water quality controls. An update of prior benthic macroinvertebrate sampling was done here to determine if the addition of these new BMPs had protected benthic macroinvertebrate communities. The creek itself was channelized and showed some incision. Thick grasses and shrubs buffered the stream from the surrounding residential development.

3.9 Correlating Results

Guiding remediation efforts on Fort Collins streams requires that practical limits be found for BMP coverage. Such coverage limits must be based on stream hydrology and benthic community health. Watershed characteristics such as BMP coverage and urbanization have been shown to directly impact stream hydrology, which in-turn impacts sediment transport and benthic macroinvertebrates. This relationship is further influenced by irrigation inflows, particularly on Spring, Fossil, and Boxelder creeks. The interaction between stream and watershed characteristics is shown graphically in Figure 3-10.

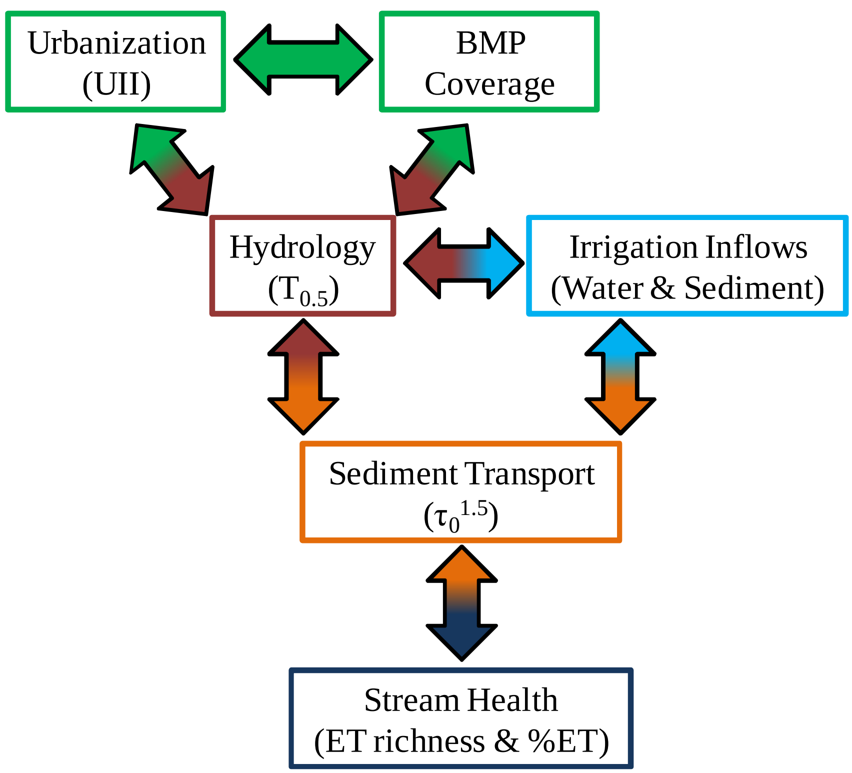

Figure 3-10: Relationship between watershed characteristics and factors affecting stream health.

Though no single watershed characteristic has been shown to have a direct cause-effect relationship with stream health, runoff caused by increasing urban development can be shown to directly alter stream hydrology. This hydrologic alteration is reflected in the $T_{0.5}$ metric. Likewise, hydrology of the stream has been hypothesized to have a direct cause-effect relationship with sediment transport. Because benthic macroinvertebrates reside in the stream bed, sediment transport affects stream health. Therefore, by correlating these different parameters, a link can be found between watershed alteration and stream health.

4.0 DATA ANALYSIS & RESULTS

4.1 Benthic Macroinvertebrates

As explained previously, benthic macroinvertebrates were used to quantify stream health at each of the Fort Collins sites. Table 4-1 shows the values of ET and %ET found for each of the benthic studies. In those locations where benthic data were available from both Hoffman (1998) and Zuellig (2001), values were simply averaged to obtain a composite historic benthic score.

Table 4-1: Fort Collins, Colorado ET richness and %ET data for all available studies.

Site	ET Richness				%ET			
ID	Hoffman[1]	Zuellig[2]	Historic	2010	Hoffman[1]	Zuellig[2]	Historic	2010
1	3		**3**	**2**	3%		**3%**	**25%**
2		2	**2**	**2**		1%	**1%**	**15%**
3	3	2	**2.5**	**2**	7%	17%	**12%**	**6%**
4	4	5	**4.5**	**1**	52%	44%	**48%**	**22%**
5		7	**7**	**2**		83%	**83%**	**9%**
6	4		**4**	**3**	47%		**47%**	**48%**
7				**0**				**0%**
8		2	**2**	**2**		9%	**9%**	**11%**
9		3	**3**	**5**		52%	**52%**	**43%**
10				**2**				**22%**
11		0	**0**	**0**		0%	**0%**	**0%**
12	4	1	**2.5**	**2**	5%	3%	**4%**	**26%**

[1]Hoffman (1998), [2]Zuellig (2001)

Below in Figure 4-1, values for the historic benthic assessment are compared to values obtained in the 2010 study. The dashed line indicates no change in benthic health. Points lying above and left of the line indicate improving conditions while those below and right of the line indicate degrading conditions.

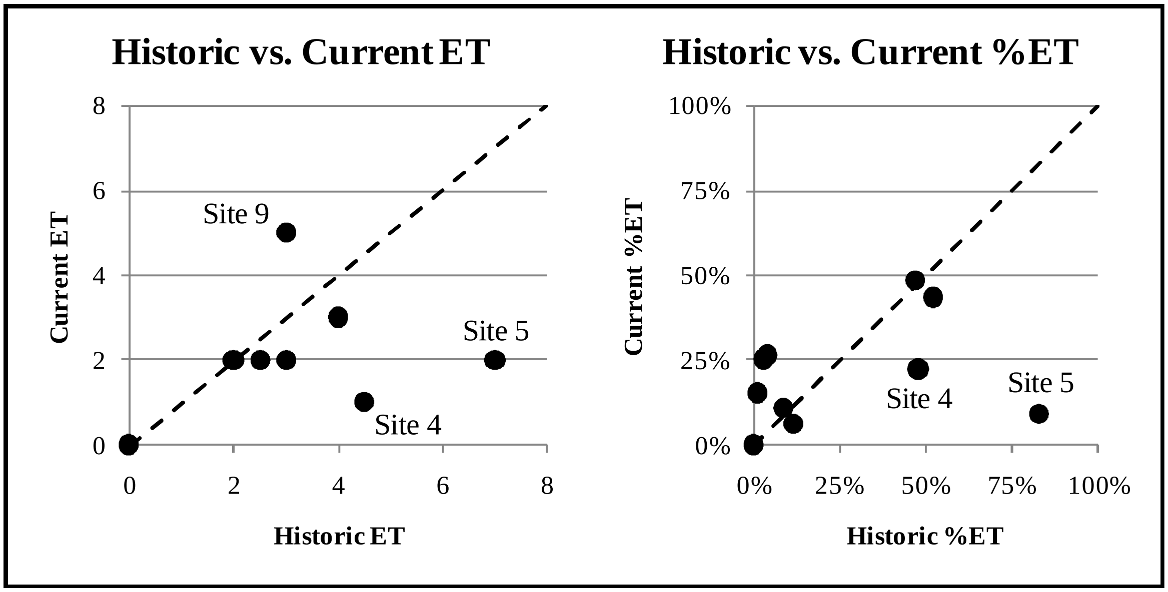

Figure 4-1: Comparison of historic and current ET richness and %ET. Possible improving benthic macroinvertebrate conditions are indicated by points above and left of the dashed line. Possible degradation is indicated by points below and right of the dashed line.

From the above figure, Sites #4 and 5 appear to show that benthic health has degraded since the studies conducted by Hoffman (1998) and Zuellig (2001) as indicated by both ET and %ET. Site #9 showed some improvement in the number of ET taxa however, %ET was slightly lower in the 2010 study. Conclusions regarding the causes of these changes are found in Section 5.0.

4.1.1 Historic Studies

The $T_{0.5}$ values computed using a 48 hour inter-event time shown in Table 3-2 were compared to ET richness and %ET. Figure 4-2 below, relates the historic benthic macroinvertebrate data from Hoffman (1998) and Zuellig (2001) to values of the $T_{0.5}$ metric computed from the entire set of available stream flow data collected from May to September. Both ET richness and %ET were used as benthic indicators. It is important to note that benthic data were not collected at Site #7 by either Hoffman (1998) or Zuellig (2001) and therefore Site #7 is not included on any graph displaying historic benthic data.

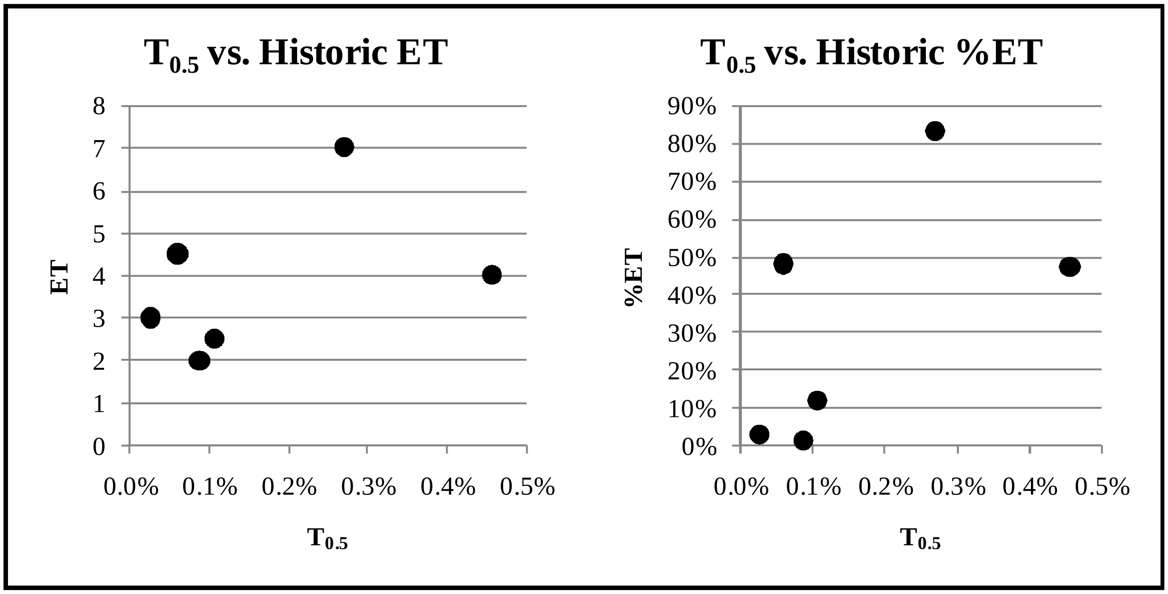

Figure 4-2: $T_{0.5}$ hydrologic metric calculated from the entire period of available gage data compared to ET and %ET values from Hoffman (1998) and Zuellig (2001).

The data indicate that there may be a slight, though weak, positive relationship between $T_{0.5}$ and benthic macroinvertebrate indicators as evidenced by Figure 4-2. On both graphs, the two points with the highest values of $T_{0.5}$ were located on Fossil Creek while the remaining points were on Spring Creek. Because the benthic macroinvertebrate data were collected prior to the installation of the stream gages, recent measurements of stream flow and the $T_{0.5}$ may not have been indicative of the stream conditions present at the time of the historic macroinvertebrate sampling. Therefore, the earliest consistently available stream data were used to compute the $T_{0.5}$. $T_{0.5}$ values were calculated using flow data from only 2001 through 2003 as shown in Table 4-2. As before, these were computed using a 48 hour inter-event time and maximizing the storm threshold. Figure 4-3 uses the $T_{0.5}$ computed from only 2001 to 2003 data in the comparison to stream health measured by the historic benthic studies.

Table 4-2: Values of the $T_{0.5}$ calculated from 2001-2003 gage data using a 48 hour inter-event time.

Gage	**1**	**2**	**3**	**4**	**5**	**6**	**7**
$T_{0.5}$	0.03%	0.57%	0.12%	0.15%	0.23%	0.12%	0.16%

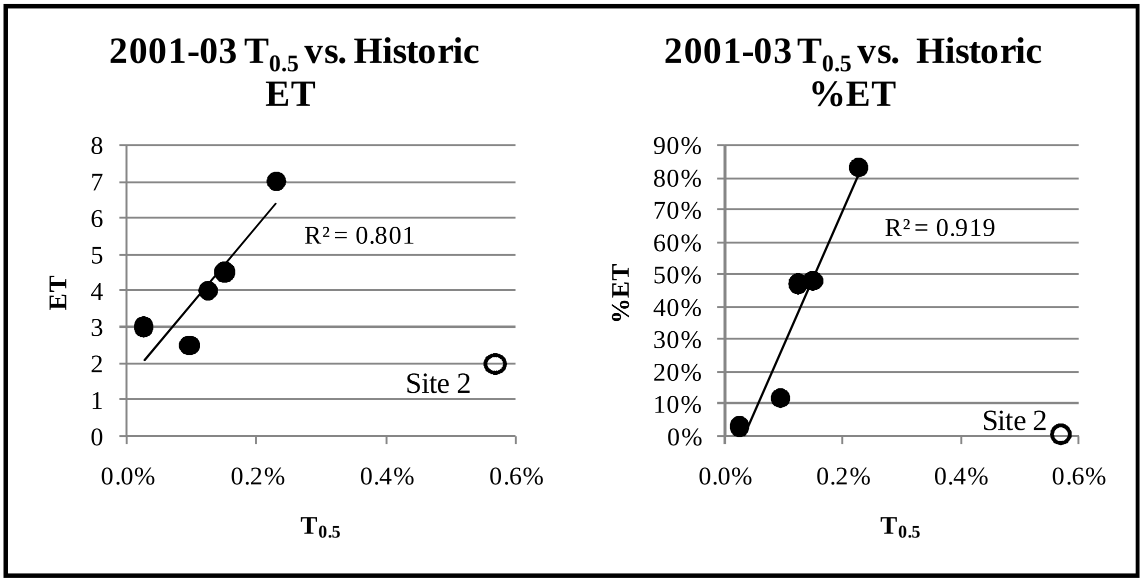

Figure 4-3: $T_{0.5}$ calculated based on 2001-2003 flow data related to historic ET richness and %ET from Hoffman (1998) and Zuellig (2001).

Figure 4-3 shows that values of $T_{0.5}$ measured from 2001-2003 more closely correlate to historic benthic macroinvertebrate data than do values of the $T_{0.5}$ calculated from the entire data set. It should be noted that there was an outlier in the 2001-2003 $T_{0.5}$ data set indicated by the open circle on the graph. This occurred at Site #2 which had a $T_{0.5}$ of 0.57%. At this location, the year 2003 appears to have had a sustained flow over the $Q_{0.5}$ for a period of nearly three days. However the rainfall gage data for this area showed that minimal rain fell during this period (less than 0.30 inches). This indicated that stream blockage may have caused uncharacteristically high depth values thereby artificially increasing the $T_{0.5}$. Additionally, it should be noted that these flow measurements at Site #2 were only over the $Q_{0.5}$ if it was calculated based on 2001-2003 data. These sustained high flows remained below the $Q_{0.5}$ calculated from the entire set of data and therefore caused no problems when calculating the cumulative $T_{0.5}$.

4.1.2 Current Benthic Study

The benthic assessment conducted in April 2010 was compared to values of the $T_{0.5}$ obtained using a 48 hour inter-event time for the entire period of available data as shown in Table 3-2. This comparison is shown graphically in Figure 4-4.

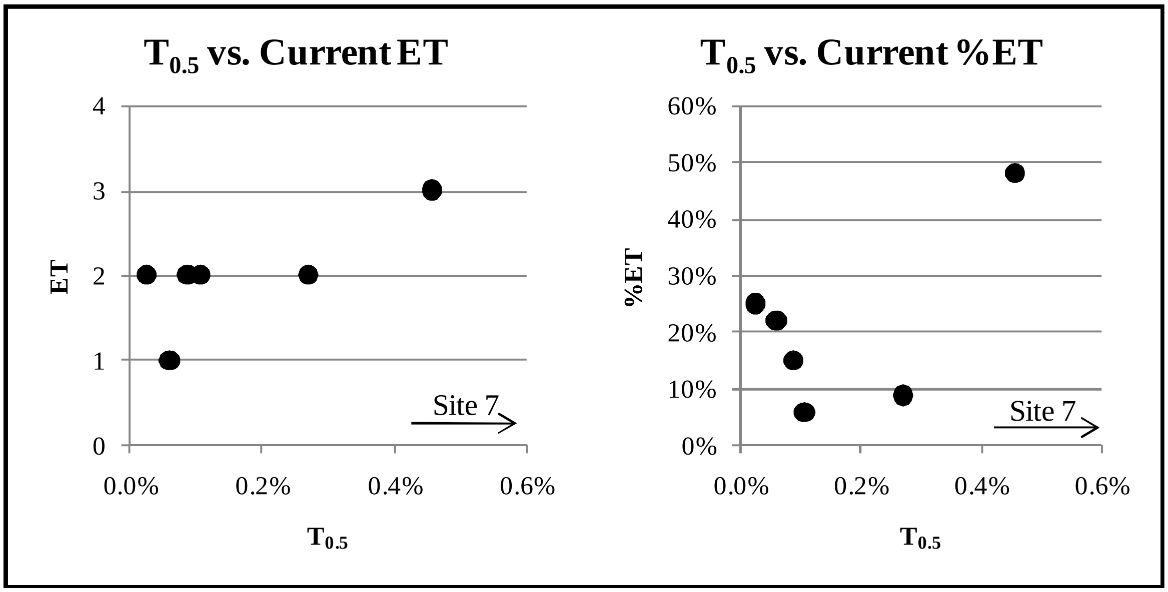

Figure 4-4: 2010 benthic macroinvertebrate data (ET richness and %ET) compared to the $T_{0.5}$ calculated using a 48 hour inter-event time and the entire set of available gage data.

It should be noted that Site #7 is excluded from this comparison in Figure 4-4. This site, located on Boxelder Creek, is in a largely agricultural region. Irrigation flows caused high values of the $T_{0.5}$ however, these flows created average boundary shear stress at this location to be nearly double that of any of the other sites (see Table 3-3). The sediment transport parameter ($\tau_0^{1.5}$) was also nearly double that of all other sites as shown in Table 3-4.

As was done with the historic benthic macroinvertebrate data, values of the $T_{0.5}$ were calculated using only the most closely matching years of record. For the current data, $T_{0.5}$ was calculated based on 2007 to 2009 flow data. Values of the $T_{0.5}$ for this period are shown below in Table 4-3. As before, a 48 hour inter-event time was used for this calculation.

Table 4-3: $T_{0.5}$ hydrologic metric calculated from 2007-2009 gage data using a 48 hour inter-event time.

Gage	1	2	3	4	5	6	7
$T_{0.5}$	0.04%	0.08%	0.17%	0.06%	0.30%	0.19%	3.10%

$T_{0.5}$ values obtained from 2007 to 2009 data were plotted against the 2010 benthic data. Again, Site #7 was eliminated from this analysis for the reasons mentioned above. Despite this, virtually no correlation can be seen between $T_{0.5}$ and benthic health. The comparison between current $T_{0.5}$ and benthic data is shown below in Figure 4-5.

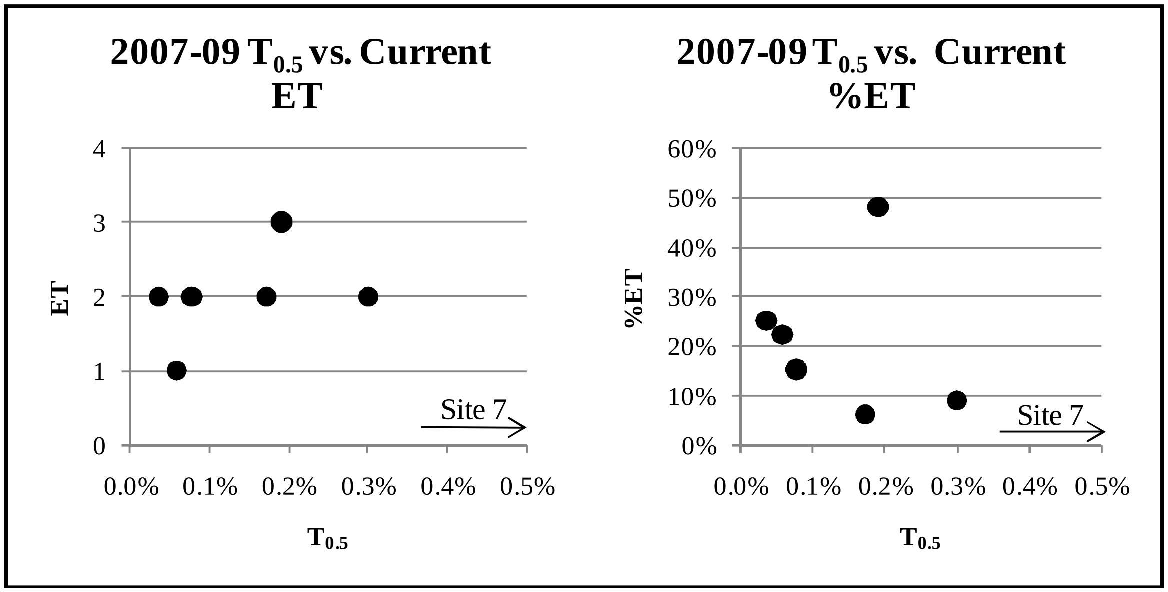

Figure 4-5: 2010 benthic macroinvertebrate data (ET richness and %ET) collected in 2010 compared to the $T_{0.5}$ calculated from 2007-2009 stream gage data.

4.2 Urban Intensity Index

Values of the $T_{0.5}$ were related to the Urban Intensity Index (McMahon & Cuffney, 2000). The final values of the UII from Table 3-7 were compared to values of the computed $T_{0.5}$ from Table 3-2. In Figure 4-6, the UII is plotted against the $T_{0.5}$ with Site #7 again removed for the reasons explained above. Pomeroy (2007) showed a negative logarithmic correlation indicating that the $T_{0.5}$ decreased with increasing levels of urbanization. Such a trend can be drawn through the Fort Collins data however the relationship is much weaker than that calculated by Pomeroy (2007) as shown in Figure 4-6. The poor correlation may be partially attributable to the data used to calculate the UII. As described in Section 3.7, census data used in the UII calculation was from 1990 and 2000 and land use data sets were developed in 2001. Therefore, data used for the UII are from a different time period than that used in the calculation of the $T_{0.5}$ (2001 to 2009).

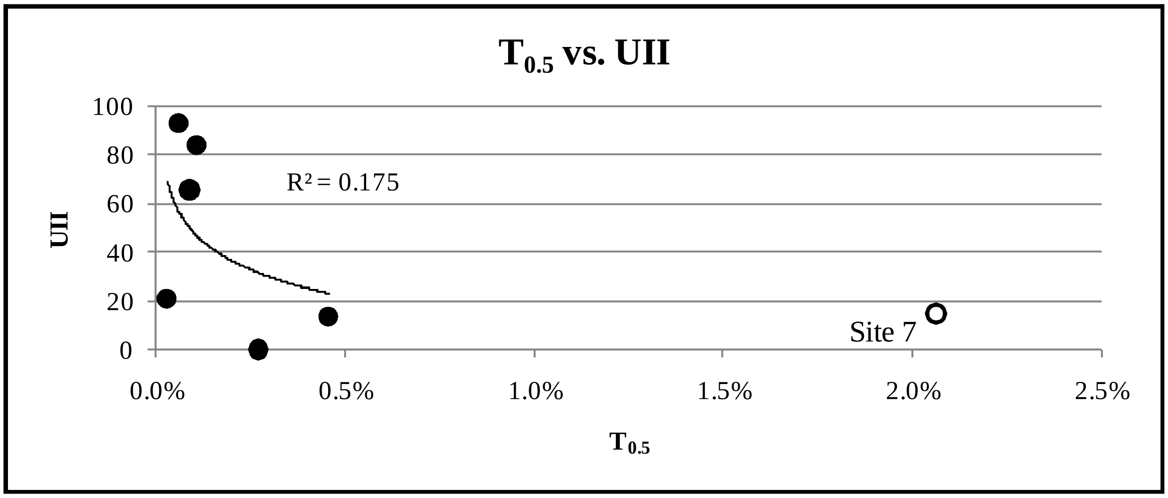

Figure 4-6: Urban Intensity Index plotted against the $T_{0.5}$ calculated from the entire set of available stream gage data.

The UII was also compared directly to indicators of benthic community health. Figure 4-7 shows a slight inverse trend between the UII and both the historic and current benthic studies. Site #7 was excluded due to the degraded channel conditions previously attributed to irrigation flows and high shear stress. Since no data were available at Site #7 from the historic benthic assessments, it was only excluded from the 2010 assessment data. It should be noted that a stronger correlation between UII and benthic indices existed with the historic benthic data. As was previously mentioned, the UII was calculated from population and land use data from 2000 and 2001 respectively. Therefore, it is logical that the historic benthic assessments by Hoffman (1998) and Zuellig (2001) would better reflect conditions represented by the UII than would more current benthic data.

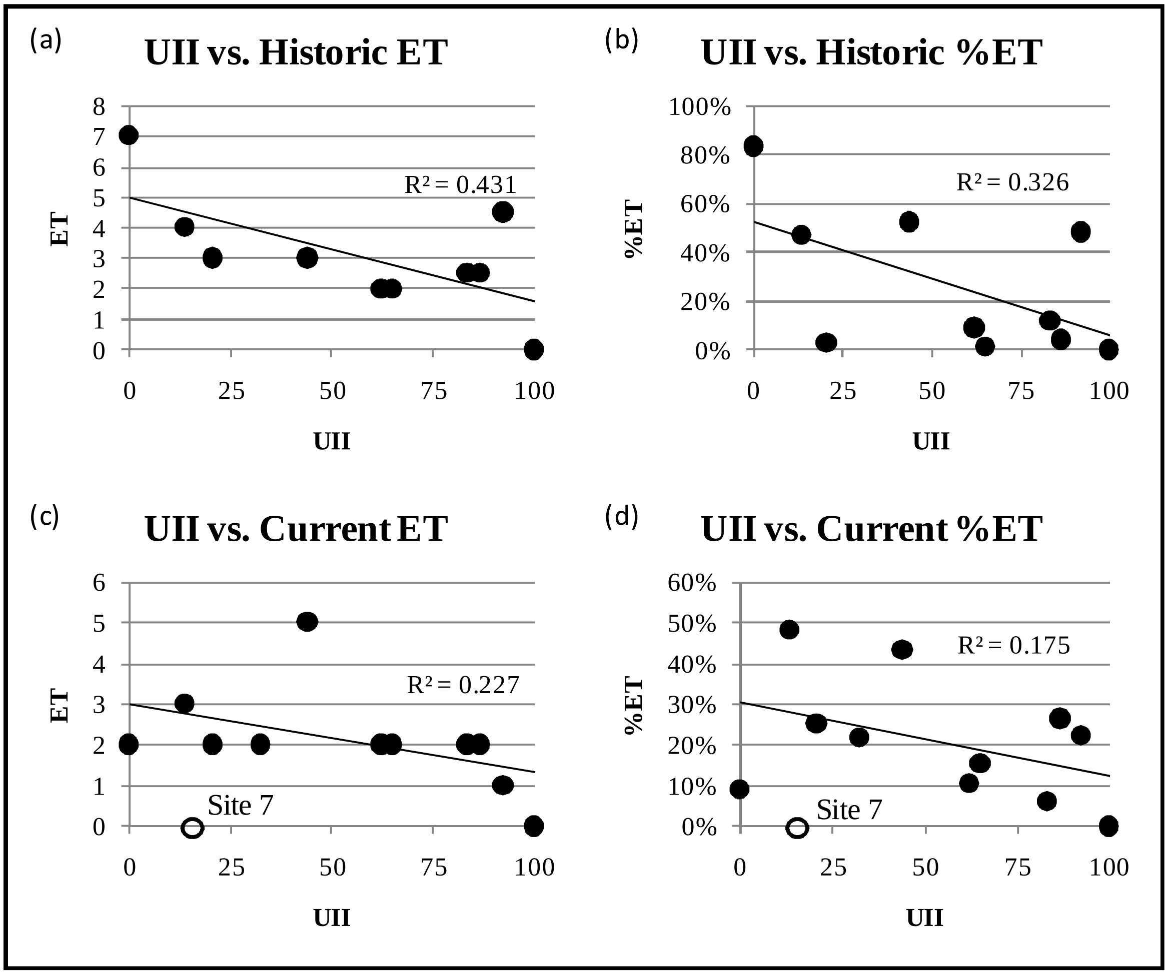

Figure 4-7: Relationship between Urban Intensity Index and (a) historic ET from Hoffman (1998) and Zuellig (2001), (b) historic %ET from Hoffman (1998) and Zuellig (2001), (c) current ET values from 2010 study, and (d) current %ET from 2010 study.

4.3 BMP Performance

In addition to the UII, BMP performance was used to characterize the watershed area contributing to each site. It should be noted that the BMPs shown in the Fort Collins GIS layer were mapped for conditions current as of 2009. Therefore, various measures of BMP coverage were compared to both the composite $T_{0.5}$ from Table 3-2 (48 hour inter-event time) and the $T_{0.5}$ from Table 4-3 which used only 2007-2009 data. This comparison of $T_{0.5}$ to BMP coverage is shown below in Figure 4-8.

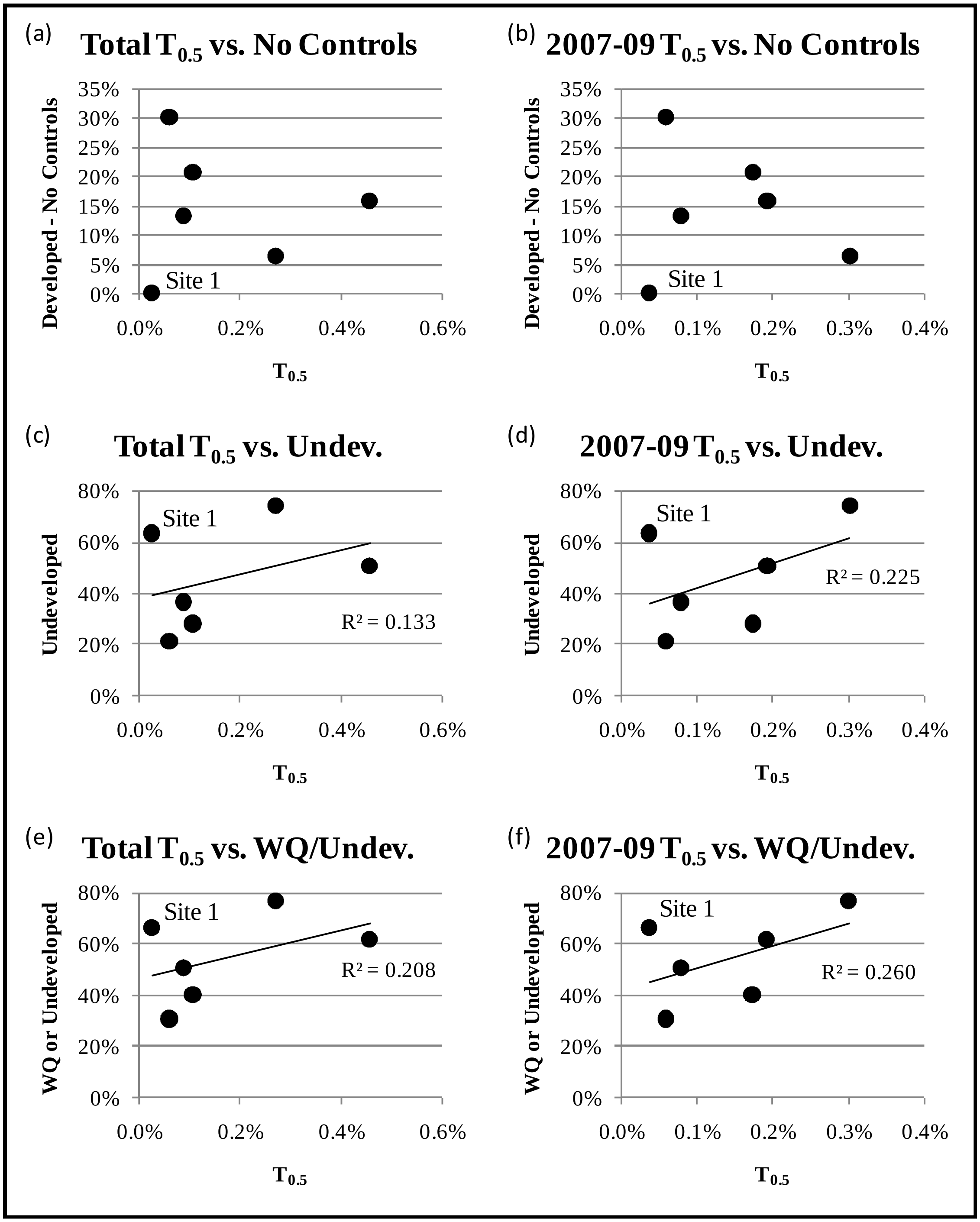

Figure 4-8: Comparison of developed area without stormwater controls to $T_{0.5}$ hydrologic metric calculated from (a) entire period of gage record and (b) 2007-2009 gage data; undeveloped area to $T_{0.5}$ calculated from (c) entire period of gage record and (d) 2007-2009 gage data; sum of undeveloped and water quality controlled areas to $T_{0.5}$ calculated from (e) entire period of gage record and (f) 2007-2009 gage data.

Note that data from Site #1 appears to dominate several of the trends in Figure 4-8. This site was relatively undeveloped however the gage indicated low values of the $T_{0.5}$. There were several possible explanations for this discrepancy. First, since this was the most upstream site on Spring Creek, storm flow came from the steep slopes adjacent to Horsetooth Reservoir. Though the area was undeveloped, the steep slopes may have created flashy flows similar to those experienced by urban areas. Secondly, as noted previously, gage data at this point was inconsistent. No data from 2002 was available and the data from 2004 was removed due to large data gaps. Finally, downstream of this point, flow was intercepted by the New Mercer irrigation canal. At the confluence, Spring Creek flowed directly into the canal and flow was released on the other side via a sluice gate. Though flow was not intentionally diverted to or from Spring Creek, it was not likely that the flow entering the canal exactly equaled the flow leaving. Therefore, there may have been a discontinuity of flow when Site #1 was related to the downstream sites on Spring Creek.

From Figure 4-8, BMP coverage most closely predicted the $T_{0.5}$ calculated from 2007-2009 data. Both the proportion of contributing area that was undeveloped and the area that was undeveloped or controlled by BMPs showed some relationship to the $T_{0.5}$ hydrologic metric, however the trend was lessened by Site #1 for the reasons described above. Considering the relationship seen between the $T_{0.5}$ and both benthic stream health and BMP coverage, there could possibly be a direct link between BMP coverage and the health of receiving streams. As stated previously, BMPs have only recently become widespread in the City. Furthermore, the BMP data available was current as of 2009. Therefore, BMP coverage was only compared to the most recent benthic data as shown in

Figure 4-9. BMP data at Site #7 was unavailable and was therefore not included as part of this comparison.

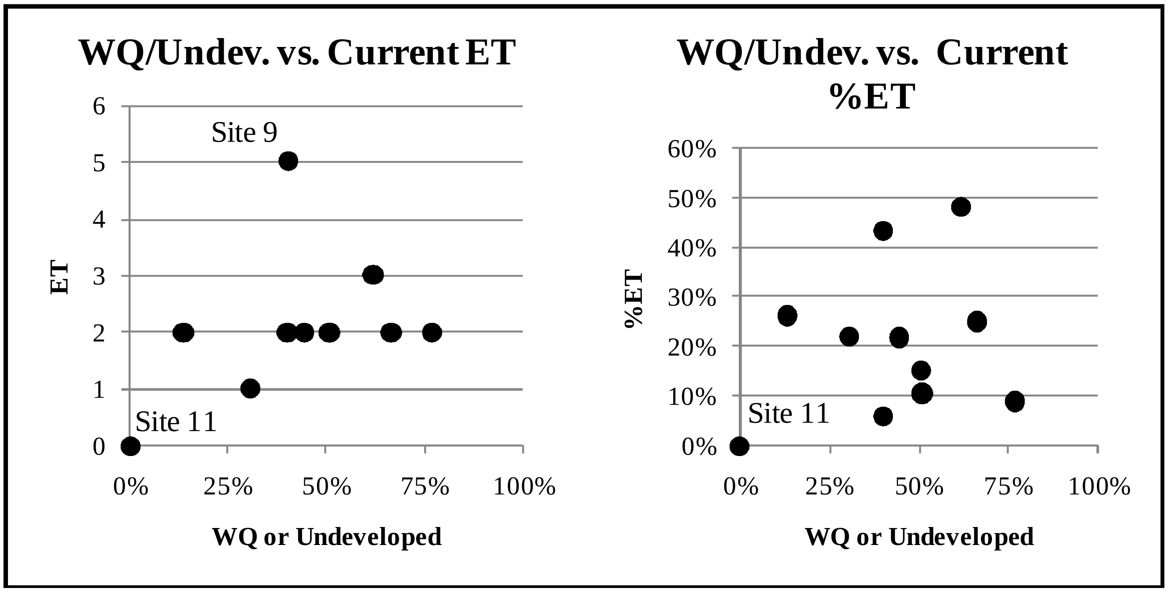

Figure 4-9: Watershed coverage of water quality best management practices and undeveloped area related to ET and %ET from the study conducted in 2010.

Any possible trend in Figure 4-9 would be dominated by the improved conditions at Site #9 and the degraded conditions at Site #11. The remaining data show no discernable relationship. The lack of direct correlation between $T_{0.5}$ or BMP coverage to benthic stream health indicates that another factor is affecting the health of ET benthic macroinvertebrate communities. Since ET taxa originate in the stream bed substrate, the stream bed material and transport may have a more direct relationship to these species.

4.4 Bed Material and Sediment Transport

As stated in Section 3.5.1, sediment transport can only be readily determined for non-cohesive soils. Therefore, values of τ_0 can only be compared if resistance to shear at each of the six surveyed sites is similar. Figure 4-10 shows how τ_0 and $\tau_0^{1.5}$ compare to current benthic macroinvertebrate health. Note that in this figure, Site #7 is included to emphasize the impact of irrigation flows on Boxelder Creek.

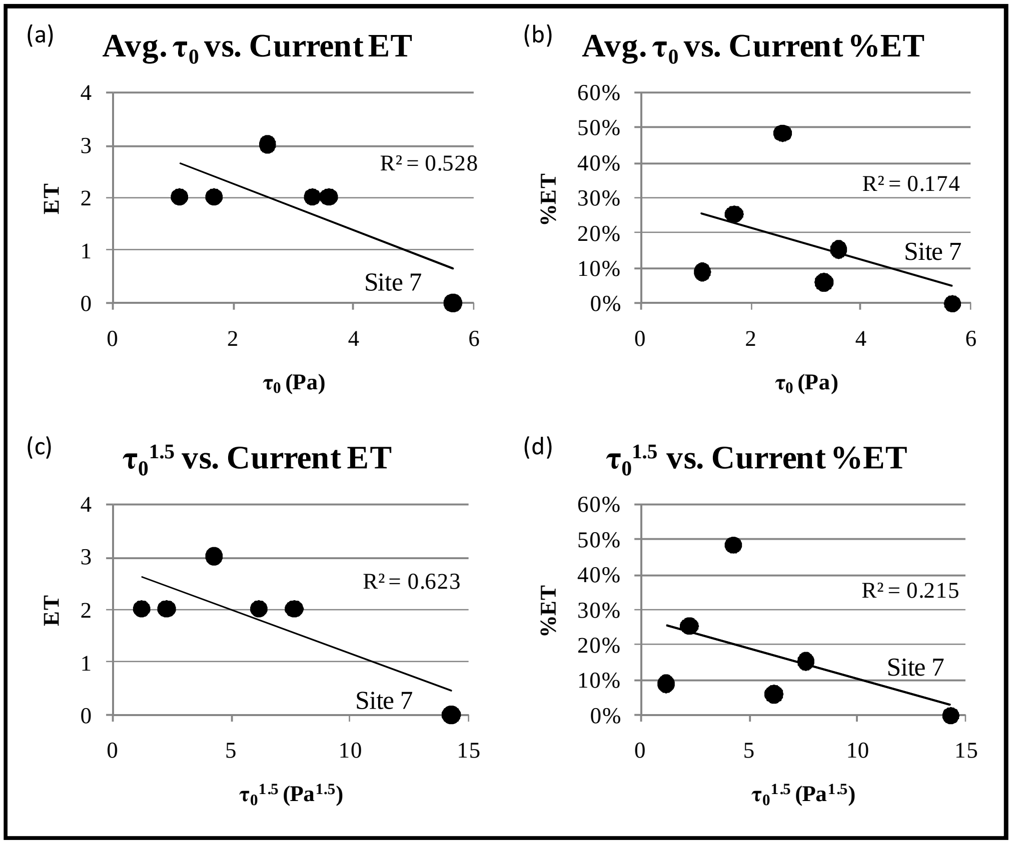

Figure 4-10: Average boundary shear stress versus (a) ET richness from 2010 study and (b) %ET from 2010 study; transport parameter $\tau_0^{1.5}$ plotted against (c) ET richness from 2010 study and (d) %ET from 2010 study.

From the above figure, the sediment transport parameter, $\tau_0^{1.5}$, shows a better relationship with both ET richness and %ET than does average boundary shear. As mentioned previously, Site #7 on Boxelder Creek showed the largest values of shear stress which coincided with the lowest values of benthic health. The correlation observed in Figure 4-10 for ET richness is dictated by this point on Boxelder Creek. With such a narrow range of ET values, there can be little distinction made between the ET values of the other five sites. In assessing the relation of shear to %ET, there appears to be a weak negative correlation. However, without accurate values of resistance to shear, the trend cannot be presumed to accurately depict the impact of sediment transport on stream health. Despite this limitation, the excessively high value of shear at Site #7 most likely does have an impact on the health of benthic macroinvertebrates.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to recommend courses of action to enhance and protect benthic macroinvertebrate communities in Fort Collins streams. Using the correlations and results discussed previously, impacts of urban development can be observed on the health of receiving streams. Appropriate methods for mitigation of the adverse effects of urbanization must be identified to protect aquatic ecosystems.

5.1 Stormwater BMPs

Stormwater BMPs have been introduced to large portions of the City of Fort Collins in recent years. Stormwater BMPs that have been designed with water quality controls have been shown to create hydrologic conditions that closely match those present prior to development (Rohrer, 2004). Therefore, the coverage of BMPs was defined in this study as the percentage of upland area protected by water quality features or left undeveloped. It was decided to use water quality BMP coverage rather than simply quantifying urbanization with an index such as the UII because measures of urbanization alone cannot represent the hydrologic impacts of development on receiving streams. BMPs are intended to mitigate the effects of urbanization and therefore, all urban development is not equal from a stormwater perspective. It can be reasonably concluded that land treated by a water quality BMP does not release runoff as quickly as the same land left uncontrolled.

The potential for positive impacts of water quality BMPs was demonstrated on Foothills Creek. Along this creek, irrigation has less of an impact on flow than in Spring Creek and Fossil Creek. At Site #11, the watershed was nearly completely regulated by flood control however; water quality control was not present. This lack of water quality control likely contributed to the degraded conditions at this site (ET richness and %ET of zero). Farther downstream, at Site #12, ET richness had improved to two and %ET had reached 26%. The area between Sites #11 and 12 was developed with nearly 45% water quality BMP coverage bringing the total level of water quality control for the watershed contributing to Site #12 up to 13%. This modest increase in BMP coverage may have aided in protecting downstream benthic communities at Site #12 whereas flood control alone was unable to preserve ET richness and %ET at Site #11.

5.1.1 Impacts on Hydrology and Benthos

Figure 4-8 showed that for the six sites having both BMP coverage and stream gage data available, there was a slight positive relationship between hydrologic quality indicated by the $T_{0.5}$ metric and the percent of the watershed classified as either undeveloped or developed with water quality BMPs. This relationship showed that water quality BMPs can have a positive impact on stream hydrology. However, there is not a specific limit of BMP coverage that can be ascertained from the available data. Though the premise for such a relationship between $T_{0.5}$ and benthic health was shown by the historical results in Figure 4-3, Figure 4-5 indicated that the most recent benthic macroinvertebrate data did not correlate well with the $T_{0.5}$. Similarly, Figure 4-9 showed that the benthic data did not relate well to the BMP coverage data.

This lack of correlation may be attributed to several key factors. First, the relatively low benthic diversity in the Colorado Front Range, primarily ET richness, made definitive trends difficult to establish. Also, the level of water quality BMP coverage in Fort Collins may not have been high enough to prevent degradation of aquatic habitat. Booth & Jackson (1997) indicated that urban channels may become unstable with as little as 8-10% uncontrolled effective impervious area. The maximum level of water quality BMP or undeveloped coverage in Fort Collins was 77% at Site #5 on Fossil Creek which still showed that benthic communities had deteriorated. Though this watershed was likely near the effective imperviousness threshold set by Booth & Jackson (1997), another factor may have been affecting the relationship between watershed characteristics and benthic health. The network of irrigation canals in Fort Collins adds flow and sediment to the creeks. Since the irrigation canals are fed primarily by diverted flow from the Cache La Poudre River rather than by runoff, watershed alteration can have little effect on irrigation flow contributions. This is especially true of Boxelder Creek, Fossil Creek, and the downstream reaches of Spring Creek where irrigation canals comingle with stream flow. Therefore, even if urban areas are completely controlled by stormwater BMPs, these streams would be unlikely to return to natural conditions. Though BMPs can have a positive impact on stream habitat quality, the effects of irrigation flows can limit the maximum level of their effectiveness. Despite these factors, practical limits for BMP coverage can be established based not only on hydrology but also on changes that have been observed in benthic communities over the past ten years.

5.2 In-Stream Modifications

In-stream modifications would likely only be useful in conjunction with upstream controls and would only affect the specific location where improvements were made. Without some level of watershed control, channel modifications may be damaged or rendered ineffective by high storm flows generated by urban runoff. For instance, Site #9 had 40% of its upland watershed that was either undeveloped or controlled by water quality BMPs. This site was shown to be a location where channel improvements yielded positive benthic results. Since high values of the $T_{0.5}$ metric contribute to healthy benthic communities (Booth et al., 2004; Pomeroy, 2007) and BMP coverage was observed to create favorable values of $T_{0.5}$ (see Figure 4-8), regions with better hydrology will generally require fewer in-stream improvements. However, areas with high levels of pollutants could degrade benthic communities regardless of whether or not the $T_{0.5}$ indicates appropriate hydrologic conditions. Also, shear stress must be considered in cases where large portions of the flow are not generated solely by runoff, such as stream segments that carry substantial irrigation flows. The following section uses these observations to outline recommendations for each of the creeks analyzed.

5.3 Recommendations

The watersheds analyzed in this study are not independent of one another which fundamentally differs from prior studies of the effects of urban development on stream hydrology and health (Booth et al., 2004; Pomeroy, 2007). This presents a unique opportunity for the application of stormwater controls and watershed improvements. Stormwater controls placed at an upstream location have the potential to positively impact those regions downstream. Therefore, an upstream-to-downstream approach will likely be the most cost-effective method. Furthermore, in-stream rehabilitation should be focused only on those areas with significant water quality BMP coverage. Some improvement was observed from channel modifications at Site #9 with 40% of its watershed being undeveloped or protected by water quality controls. Due to the inherently low biodiversity of streams in Fort Collins, the change in ET richness from three to five can be reasonably assumed to represent substantial improvement (Kondratieff, 2010). Based on this observation, to reasonably expect improvement in benthic macroinvertebrates from in-stream modifications, a minimum of 40% of a watershed should be undeveloped or have stormwater peak-shaving plus water quality controls on the developed areas. However, preference should be given to those regions with higher levels of control.

Due to the impact of irrigation canals, it is unlikely that a level of water quality control can be reached that will maintain strong benthic communities without channel improvements. Therefore, streams with significant contributions from irrigation waters should be carefully observed before making improvements. Large irrigation contributions such as those in Fossil Creek, Boxelder Creek, and the downstream end of Spring Creek cause high shear stresses and sediment loads which will likely counteract any improvements made in-stream or on the watershed. Specific recommendations for each creek are listed below.

5.3.1 Spring Creek

Sites #1 and 2 have relatively high levels of BMP coverage (66 and 51% respectively). Therefore, these sites may benefit from in-stream habitat improvement. Specifically, there are several horse pens located adjacent to the creek upstream of Taft Hill Road. Buffer strips and grading at these locations may prevent uncontrolled runoff and related loads of organic materials from entering the creek. The two downstream sites however, Sites #3 and 4, have lower levels of water quality BMP coverage (40 and 31% respectively). At these sites, an increase in the level of water quality control upstream should be considered before making physical improvements to the stream. It should be noted that the impact of the Arthur Canal, Pitkin Lateral, and Emigh Lateral cannot be readily determined as no flow monitoring is available for these irrigation canals. It is possible that large flows from these canals may cause degraded habitat in the downstream reaches of Spring Creek, particularly at Site #4 where benthic communities have diminished since the studies by Hoffman (1998) and Zuellig (2001). Also, when adding BMP protection, it should be noted that there is a disconnect in Spring Creek at its confluence with the New Mercer Canal (between Sites #1 and 2). Therefore, improvements in BMP coverage made upstream of the disconnect may not have as strong of an effect on downstream hydrology as water quality features added downstream of the New Mercer Canal.

5.3.2 Fossil Creek

High levels of water quality BMP coverage and undeveloped area on Fossil Creek promote good quality stream habitat however, sediment and high flows from irrigation canals have still degraded the creek. This is especially true of Site #5 where benthic communities have degraded substantially since the study by Zuellig (2001) despite the fact that this watershed has the highest level of water quality BMPs and undeveloped area of any site in Fort Collins. Siltation appears to have occurred in the channel causing degraded habitat. Therefore, improvements to this watershed cannot be recommended until irrigation flows are appropriately mitigated. If irrigation flow and sediment inflows were controlled, the high level of BMP coverage and undeveloped area in the watershed would make Fossil Creek a prime candidate for rehabilitation.

5.3.3 Boxelder Creek

Though there is little development in the Boxelder Creek watershed, irrigation flows have created a condition with exceptionally high shear stress and the potential for bed degradation. Without eliminating incoming irrigation flows, it would be difficult to improve the creek in reaches near Fort Collins. Water quality BMP coverage would be ineffectual as irrigation flows would not be lessened. In-stream modifications would also be negated by the high shear stress and bed movement caused by irrigations flows.

5.3.4 Clearview Creek

Benthic conditions in Clearview Creek have remained largely unchanged since the study by Zuellig (2001). The creek's 51% water quality BMP and undeveloped coverage makes it a candidate for in-stream rehabilitation. However, the creek is small and relatively independent of the rest of the creeks in Fort Collins. Therefore, improvements made to Clearview Creek would not have wide-reaching impacts.

5.3.5 McClellands Creek

The high values of ET richness and %ET at Site #9 on McClellands Creek were attributed to channel improvements made at that location. Since coverage of water quality BMPs and undeveloped area increases moving downstream, improvement of benthic macroinvertebrate indicators could possibly be observed if similar channel modifications were made at the downstream end of the creek.

5.3.6 Foothills Creek

Though Foothills Creek has high levels of flood control, extremely low levels of water quality BMP coverage have allowed ET richness and %ET scores to decrease. This is especially true of Site #11 at the upstream end of the creek which has no water quality BMP control. Farther downstream at Site #12, some water quality controls have been implemented which have helped aquatic health. However, significant additions of water quality controls in the upstream reaches of the creek should be implemented before any in-stream improvements are attempted.

5.4 Prioritized Rehabilitation

Based on the recommendations made above, a minimum of 40% water quality BMP or undeveloped land should be present prior to attempting in-stream improvements. In Table 5-1, the added area of water quality BMP coverage necessary to achieve the suggested limit of 40% is given for each watershed. Note that for sites on the same creek, improvements made upstream would also benefit reaches downstream (e.g. – Since

Table 5-1: Area of watershed improvement necessary to reach 40% threshold for in-stream modification at 12 sites in Fort Collins, Colorado. "WQ/Und. Cover" represents the current portion of each watershed that is protected by water quality BMPs or left undeveloped.

Site ID	Creek Name	Area (sq. km.)	WQ/Und. Cover	Area to 40% (sq. km.)
1	Spring	7.5	66%	0.0
2	Spring	15.3	51%	0.0
3	Spring	20.1	40%	0.0
4	Spring	26.9	31%	2.5
5	Fossil	28.4	77%	0.0
6	Fossil	41.8	62%	0.0
7	Boxelder	696.3	N/A	N/A
8	Clearview	2.9	51%	0.0
9	McClellands	6.1	40%	0.0
10	McClellands	8.7	44%	0.0
11	Foothills	3.3	0%	1.3
12	Foothills	4.7	13%	1.3

the watershed of Site #11 is contained within that of Site #12, improvements to Site #11's watershed would also benefit Site #12). Therefore, if the watershed coverage of BMPs at Site #11 were increased to meet the 40% threshold, Site #12 would also meet the level of water quality control necessary for in-stream improvements.

Given a limited amount of funding available for improvement, sites requiring only in-stream improvement are prioritized ahead of those needing both in-stream and watershed improvement. Furthermore, sites with the highest levels of water quality control are better candidates for improvement than those only meeting the minimum of 40%. If a site has less than 40% water quality control or undeveloped area, it is not recommended for in-stream improvement until the necessary level of watershed improvement is implemented. Additionally, sites near the 40% threshold could likely benefit from a combination of in-stream and watershed improvement. Table 5-2 suggests relative priorities for each of the sites discussed in this report based on the findings in Section 5.3. Note that watershed and stream improvements are not recommended for Sites #4-7 due to the im-

Table 5-2: Priority and recommendations for watershed and stream improvements at each of the 12 study sites in Fort Collins, Colorado (highest priority = 1).

Priority	Site ID	Creek Name	Area (sq. km.)	WQ/Und. Cover	Area to 40% (sq. km.)	Improvements Watershed	Improvements Stream
1	1	Spring	7.5	66%	0.0	No	Yes
2	2	Spring	15.3	51%	0.0	No	Yes
3	10	McClellands	8.7	44%	0.0	Yes	Yes
4	3	Spring	20.1	40%	0.0	Yes	Yes
5	9	McClellands	6.1	40%	0.0	Yes	No
6	8	Clearview	2.9	51%	0.0	No	Yes
7	11	Foothills	3.3	0%	1.3	Yes	No
8	12	Foothills	4.7	13%	1.3	Yes	No
9	4	Spring	26.9	31%	2.5	Irrigation	
10	5	Fossil	28.4	77%	0.0	Irrigation	
11	6	Fossil	41.8	62%	0.0	Irrigation	
12	7	Boxelder	696.3	N/A	N/A	Irrigation	

pact of irrigation flows. If however, the impacts of these irrigation flows could be controlled, Sites #4-7 could become candidates for improvements. Figure 5-1 shows a map with watersheds shaded based on this relative priority.

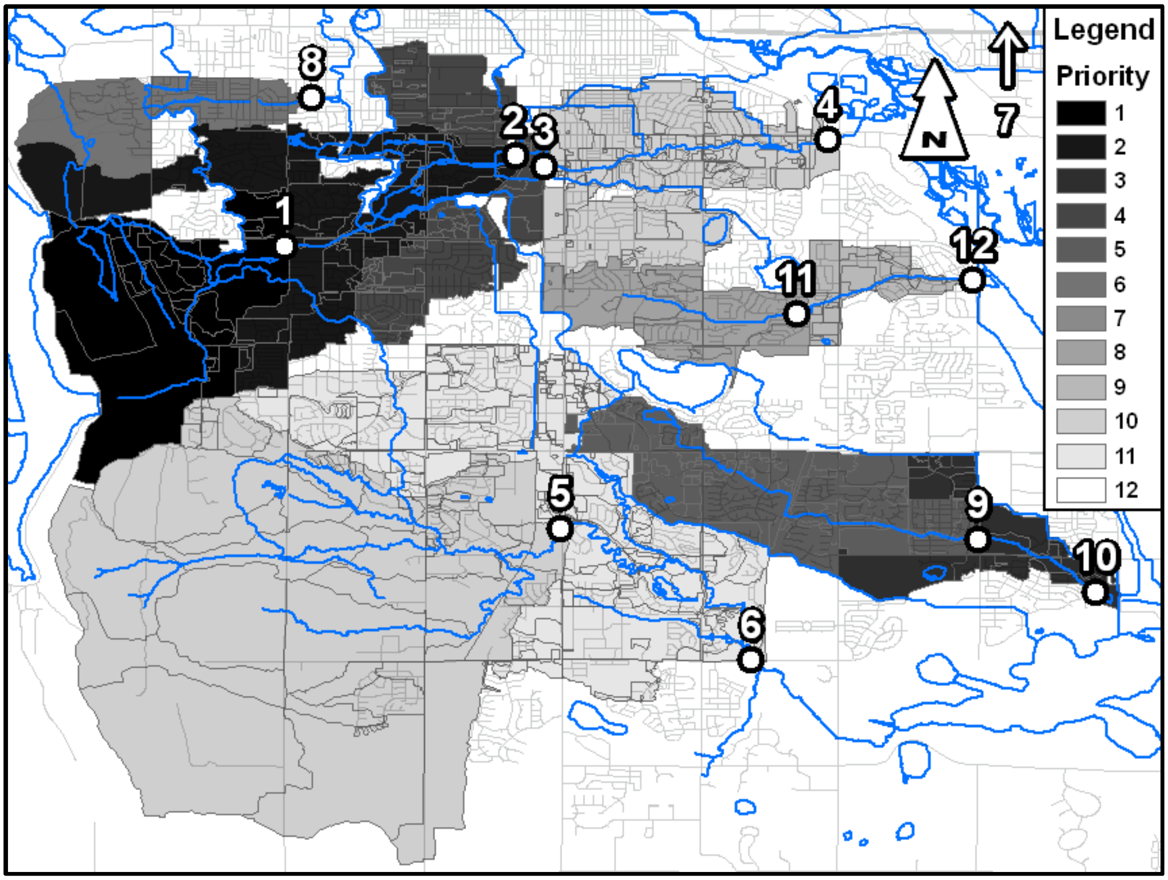

Figure 5-1: Priority of stream improvement at 12 locations in Fort Collins, Colorado. Darker areas indicate watersheds recommended for immediate improvement.

5.5 Other Considerations and Further Research

Though this analysis uses benthic macroinvertebrates to indicate the quality of urban streams in Fort Collins, other measures are often used and may be relevant to stream condition, such as certain chemical water quality parameters. The City of Fort Collins currently measures baseline water quality on Spring, Fossil, and Boxelder creeks. Monitoring is done for conductivity, dissolved oxygen, nitrate, nitrite, ammonia, ***Escherichia coli***, pH, phosphorus, and selenium. In analyzing these data, there do not appear to be any obvious water quality problems that are likely to have caused substantial reductions in ET or %ET.

Benthic macroinvertebrates were selected to indicate overall stream health because they indicate more about overall stream quality than grab samples for chemical water quality. Chemical constituents may be quickly carried through a stream system and therefore point samples may not be indicative of baseline conditions. However, benthic macroinvertebrates are responsive to stream habitat changes over a longer period of time. Therefore, it is suggested that benthic macroinvertebrate community structure be used because it provides a more complete evaluation of stream health and quality than chemical parameters alone. This does not however, discount water chemistry as an important measure of BMP effectiveness. Research is currently ongoing as to the effectiveness of BMPs at not only attenuating flows, but also removing pollutants. Future studies may use this information on pollutant removal in conjunction with benthic macroinvertebrate data to assess the impacts of specific types of water quality BMPs on developing urban stream systems.

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7.0 APPENDIX A

Figure 7-1: Site #1 - Spring Creek at Taft Hill Road in Fort Collins, Colorado.

Figure 7-2: Site #2 - Spring Creek at Centre Avenue in Fort Collins, Colorado.

Figure 7-3: Site #3 - Spring Creek at Burlington Northern Railroad in Fort Collins, Colorado.

Figure 7-4: Site #4 - Spring Creek at Timberline Road in Fort Collins, Colorado.

Figure 7-5: Site #5 - Fossil Creek at College Avenue in Fort Collins, Colorado.

Figure 7-6: Site #6 - Fossil Creek at Trilby Road in Fort Collins, Colorado.

Figure 7-7: Site #7 - Boxelder Creek at County Road 56 in Fort Collins, Colorado.

Figure 7-8: Site #8 - Clearview Creek at Castlerock Drive in Fort Collins, Colorado.

Figure 7-9: Site #9 - McClellands Creek at Ziegler Road in Fort Collins, Colorado.

Figure 7-10: Site #10 - McClellands Creek upstream of Fossil Creek Reservoir Inlet in Fort Collins, Colorado.

Figure 7-11: Site #11 - Foothills Creek at Union Pacific Railroad in Fort Collins, Colorado.

Figure 7-12: Site #12 - Foothills Creek at Ziegler Road in Fort Collins, Colorado.

8.0 APPENDIX B

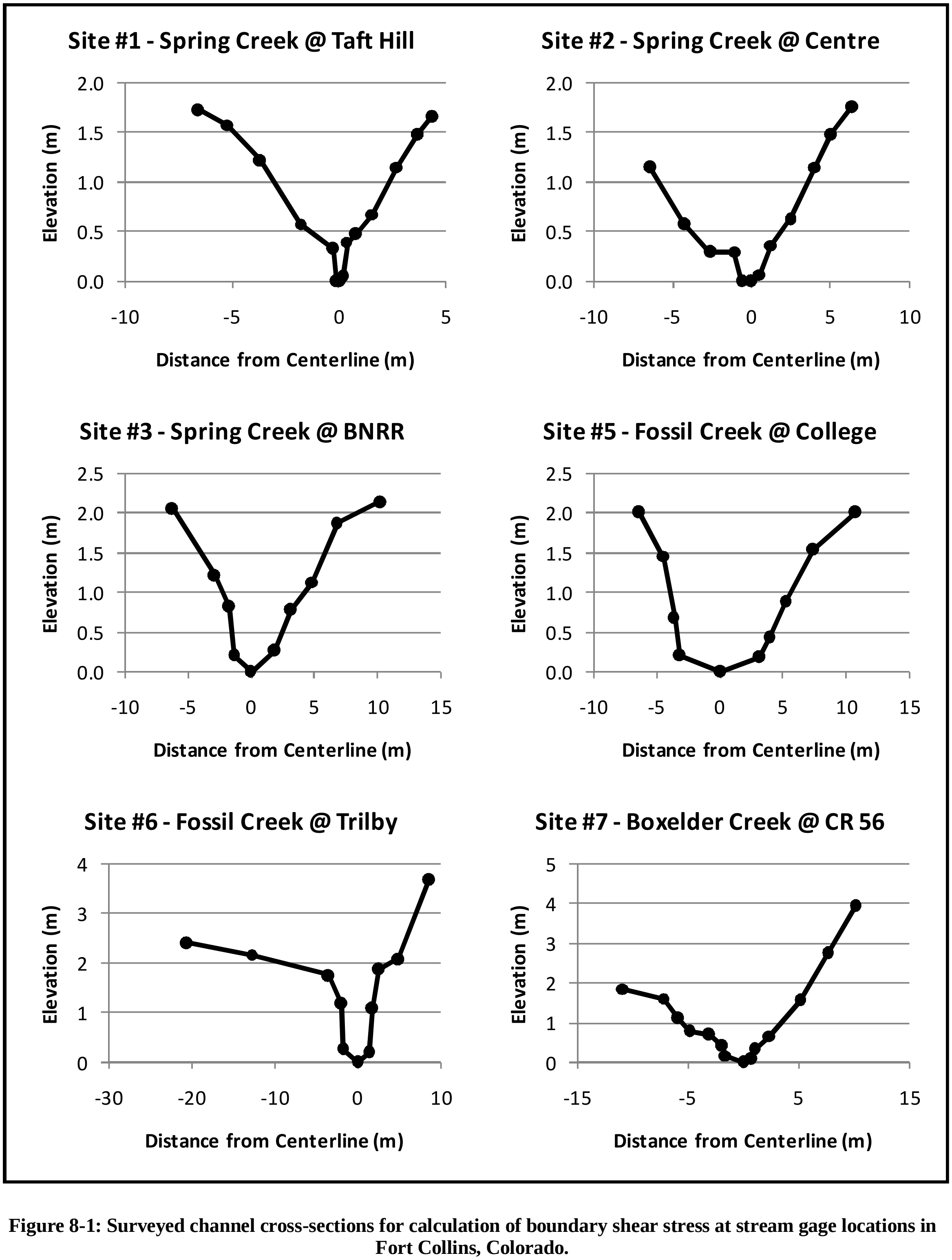

Figure 8-1: Surveyed channel cross-sections for calculation of boundary shear stress at stream gage locations in Fort Collins, Colorado.

9.0 APPENDIX C

Table 9-1: Sources of geospatial information used in the calculation of the Urban Intensity Index.

Data Type	Agency	Source
Water Bodies	City of Fort Collins Utilities Colorado Department of Transportation	Geographic Information Services <http://www.fcgov.com/gis/> Geographic Data <http://www.dot.state.co.us/App_DTD_DataAccess/GeoData/index.cfm?fuseaction=GeoDataMain>
Watershed Boundaries	City of Fort Collins Utilities	Geographic Information Services <http://www.fcgov.com/gis/>
Level IV Ecoregions	U. S. Environmental Protection Agency	Western Ecology Division <http://www.epa.gov/wed/pages/ecoregions/level_iv.htm>
Soils	U. S. Department of Agriculture	Natural Resources Conservation Service <http://soildatamart.nrcs.usda.gov/>
Land Use	U. S. Geological Survey	Multi-Resolution Land Characteristic Consortium National Land Cover Database (2001) <http://www.mrlc.gov/nlcd.php>
Impervious Area	U. S. Geological Survey	Multi-Resolution Land Characteristic Consortium National Land Cover Database (2001) <http://www.mrlc.gov/nlcd.php>
Roads	City of Fort Collins Utilities Colorado Department of Transportation	Geographic Information Services <http://www.fcgov.com/gis/> Geographic Data <http://www.dot.state.co.us/App_DTD_DataAccess/GeoData/index.cfm?fuseaction=GeoDataMain>
Dams	U. S. Army Corps of Engineers	National Inventory of Dams <https://nid.usace.army.mil>
Point Source Discharges	U. S. Environmental Protection Agency	Envirofacts Data Warehouse: National Pollutant Discharge Elimination System <http://www.epa.gov/enviro/index_java.html>
Toxic Releases	U. S. Environmental Protection Agency	Envirofacts Data Warehouse: Toxic Release Inventory <http://www.epa.gov/enviro/index_java.html>
Population and Economic Data	U. S. Census Bureau	American FactFinder <http://factfinder.census.gov/> TIGER/Line shapefiles <http://www.census.gov/geo/www/tiger/>

Table 9-2: Urban Intensity Index variables. Those with a "+" or "-" annotation to the right are positively or negatively related to the UII respectively.

Environmental Framework Characteristics		
SHED_MI2	Watershed area (square miles)	
WELLPCT	Proportion of watershed with well-drained soils	
POORPCT	Proportion of watershed with poor-drained soils	
EC_21c	Subregion 21c - Mid-elevation Forests and Shrublands (square miles)	
EC_21d	Subregion 21d - Foothils and Shrublands (square miles)	
EC_25c	Subregion 25c - Moderate Relief Plains (square miles)	
EC_25d	Subregion 25d - Flat to Rolling Plains (square miles)	
EC_25l	Subregion 25l - Front Range Fans (square miles)	
Landuse Characteristics		
LU21_AB	Proportion of watershed with developed open space on well-drained soils	+
LU21_CD	Proportion of watershed with developed open space on poor-drained soils	+
LU22_AB	Proportion of watershed with low intensity development on well-drained soils	+
LU22_CD	Proportion of watershed with low intensity development on poor-drained soils	
LU23_AB	Proportion of watershed with medium intensity development on well-drained soils	+
LU23_CD	Proportion of watershed with medium intensity development on poor-drained soils	+
LU24_AB	Proportion of watershed with high intensity development on well-drained soils	
LU24_CD	Proportion of watershed with high intensity development on poor-drained soils	+
IMPERV	Proportion of watershed with impervious land surface (not used in index calculation)	
URBAN_MI	Total urban land area in watershed (square miles)	
FOR_MI	Total forested land area in watershed (square miles)	
WET_MI	Total wetland area in watershed (square miles)	
MRLC_11	Watershed area in open water (square miles)	
MRLC_12	Watershed area in Perennial Ice/Snow (square miles)	
MRLC_21	Watershed area in Developed, Open Space(square miles)	+
MRLC_22	Watershed area in Developed, Low Intensity (square miles)	
MRLC_23	Watershed area in Developed, Medium Intensity (square miles)	
MRLC_24	Watershed area in Developed, High Intensity (square miles)	+
MRLC_31	Watershed area in Bare Rock/Sand/Clay (square miles)	
MRLC_32	Watershed area in Unconsolidated shore (square miles)	
MRLC_41	Watershed area in Deciduous Forest (square miles)	-
MRLC_42	Watershed area in Evergreen Forest (square miles)	
MRLC_43	Watershed area in Mixed Forest (square miles)	
MRLC_51	Watershed area in Dwarf Scrub (square miles)	
MRLC_52	Watershed area in Shrub/Scrub (square miles)	
MRLC_71	Watershed area in Grasslands/Herbaceous (square miles)	
MRLC_81	Watershed area in Pasture/Hay (square miles)	-
MRLC_82	Watershed area in Row Crops (square miles)	-
MRLC_90	Watershed area in Woody Wetlands (square miles)	
MRLC_91	Watershed area in Palustrine Forested Wetlands (square miles)	
MRLC_92	Watershed area in Palustrine Scrub/Shrub Wetlands (square miles)	
MRLC_95	Watershed area in Emergent Herbaceous Wetlands (square miles)	-

Landuse Characteristics Continued…		
BUF_AREA	Total area (square miles) within 240 meter wide buffer (120 m. on each side of stream)	
BUF_11	Total area (square miles) of MRLC 11 within buffer	-
BUF_12	Total area (square miles) of MRLC 12 within buffer	
BUF_21	Total area (square miles) of MRLC 21 within buffer	
BUF_22	Total area (square miles) of MRLC 22 within buffer	
BUF_23	Total area (square miles) of MRLC 23 within buffer	
BUF_24	Total area (square miles) of MRLC 24 within buffer	
BUF_31	Total area (square miles) of MRLC 31 within buffer	
BUF_32	Total area (square miles) of MRLC 32 within buffer	
BUF_41	Total area (square miles) of MRLC 41 within buffer	
BUF_42	Total area (square miles) of MRLC 42 within buffer	
BUF_43	Total area (square miles) of MRLC 43 within buffer	
BUF_51	Total area (square miles) of MRLC 51 within buffer	
BUF_52	Total area (square miles) of MRLC 52 within buffer	
BUF_71	Total area (square miles) of MRLC 71 within buffer	
BUF_81	Total area (square miles) of MRLC 81 within buffer	-
BUF_82	Total area (square miles) of MRLC 82 within buffer	
BUF_90	Total area (square miles) of MRLC 90 within buffer	
BUF_91	Total area (square miles) of MRLC 91 within buffer	
BUF_92	Total area (square miles) of MRLC 92 within buffer	
BUF_95	Total area (square miles) of MRLC 95 within buffer	
URB_BUF	Percent of watershed buffer area in urban land cover	
FOR_BUF	Percent of watershed buffer area in forested land cover	
WET_BUF	Percent of watershed buffer area in wetland land cover	

Infrastructure Characteristics		
ROAD_KM	Road length in watershed (kilometers) (ROAD_DEN)	
ROAD_DEN	Road density in watershed [road length (km)/watershed area (km2)]	
PSCOUNT	Number of points source dischargers in watershed (EPA NPDES database)	
DAMCOUNT	Number of Dams in Watershed	
TRICOUNT	Number of Toxics Release Inventory sites in watershed	

Population Characteristics		
AGESTR2000	Age structure of population (population under 18/population over 18)	-
POP1990	1990 population (P97DENM)	
POP2000	2000 population (P97DENMI)	
P1990DEN	1990 population density (people/square mile of watershed area) (P97DEN)	
P2000DEN	2000 population density (people/square mile of watershed area)	
POP90_2000	Population change 1990-2000 (proportion) (P2000DEN)	-
URBSPRWL	Urban sprawl index [(urban land area/2000 population)*10,000]	-

Socioeconomic Characteristics		
PCINC2000	2000 per capita income (dollars)	
PPLFAM	Average Family Size: 2000	-
PPLHSE	Average Household Size: 2000	-
MEDAGE	Average of Median Ages: 2000	
HSE95_2000	Percent of Housing Units Built 1995 to March 2000: 2000	-
HSEPRE40	Percent of Housing Units Built Before 1940: 2000	
URBNPPL	Percent of Persons Who Live in Urban Areas: 2000	+