A REVIEW OF LANDSCAPE INFLUENCES ON RIPARIAN ZONE PROCESSES IN MOUNTAINOUS HEADWATER CATCHMENTS

by

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ABSTRACT

Understanding the drivers of riparian zone hydrology is crucial for informed management of water quality, especially in headwater catchments. This study reviews landscape influences on riparian zone processes in mountainous headwater catchments, and combines recent findings and management techniques into a conceptual analysis of riparian zone hydrology and nutrient export. A case study synthesizing recently published work in Tenderfoot Creek Experimental Forest (TCEF) is developed outlining riparian zone hydrology, riparian buffering, and nutrient export. We demonstrate that a major influence on the hydrology and nutrient export in mountainous catchments can be landscape structure, and use this finding as a framework to develop a conceptual approach to riparian zones in mountainous areas. The conceptual analysis is intended to inform management through the identification of riparian areas that are important for stream water quality depending on hydrologic drivers in the catchment. Understanding the variability of riparian zone hydrology and subsequent water quality impacts will allow for more focused and informed management decisions for riparian areas.

INTRODUCTION

What Are Riparian Zones?

Riparian zones are the physical landform between a body of water and the uplands. Riparian zones can provide connections between terrestrial communities and aquatic communities as well as define the boundaries of each, and as such they are at a crucial interface between the two. Landscape boundaries and transition zones between ecosystems, commonly referred to as ecotones, play an integral role in ecological diversity and the flow of energy and materials (Holland, 1988). As an intermediary, riparian zones have a great potential to impact the magnitude and chemical composition of water and nutrients delivered to a stream.

Riparian zones differ, and are delineated, from uplands through changes in topography, vegetation community structure, water table depth, soil type, and microbial communities (Gregory et al., 1991).Riparian areas are traditionally delineated by vegetation, but abiotic factors such as slope break and water table depth can often be more accurate and useful for delineation(Verry et al., 2004, Polvi et al., 2010). The use of abiotic factors may be better at finding the inflection point between riparian and upland areas than vegetative analysis due to the successional nature of biotic systems. Consequently, abiotic factors could make riparian delineation more consistent across landscapes and over time.

Riparian systems provide similar functions across ecosystems, but their form, demarcation from upland and stream areas, and even terminology is not well agreed upon and usually depend on the objectives of the study being undertaken (Fischer et al., 1998).

Objectives

This paper surveys the current state of knowledge regarding water table dynamics in riparian zones, riparian buffering, and nutrient export from watersheds, focusing specifically on riparian areas in mountainous headwater catchments. This summary will be supplemented by a case study of past work from the Tenderfoot Creek Experimental Forest (TCEF) that highlights recent research and field observations in a well-studied, localized area. Current riparian management practices will be discussed, both agricultural and forestry, and put in the context of current hydrology research. The study concludes with recommendations for management of riparian zones along mountain streams in snow dominated systems and a framework for a conceptual approach to modeling riparian zone hydrology that will have wide applicability.

Riparian Functioning and Management

What Important Functions Are Performed by Riparian Zones?

Riparian areas provide many ecological services to their watershed through their unique landscape position, often high nutrient concentration, and water availability. Riparian zones provide and enhance watershed services and processes including: dissipating stream energy, entrapping sediment, enhancing nutrient cycling, controlling erosion and deposition, and providing habitat (Gregory et al., 1991). These services will vary in the degree to which they are expressed in each particular riparian zone or transect of a riparian zone due to the location of the riparian zone in the watershed, varying inputs of water and nutrients, and climate (Sabater et al., 2003).

Riparian areas can help maintain baseflow levels in their adjacent streams. In humid areas baseflow is influenced by riparian zone contributions, basin physiographic characteristics, landscape geomorphology, evapotranspiration, and storage in the watershed (Baldwin et al., 2012).Riparian zones are also thought to help sustain baseflow in arid and semi-arid areas by acting as a storage zone from high flow to low flow periods (Ponce & Lindquist, 1990). By maintaining a hydrologic connection to the stream, riparian zones provide the physical substrate in which biogeochemical transformations occur, as well as maintain flow during low streamflow periods.

Riparian zones can also attenuate the destructive power of stream flooding. The aboveground vegetation in riparian zones can increase channel roughness during flood events which in turn decreases the erosive capabilities of the flood as well as retaining sediment and nutrients (Gregory et al., 1991). Overbank flooding can also be partially mitigated through hydrologic exchange with the riparian zone. Flood attenuation can also be achieved through the interception of water from the uplands before it reaches the stream, a buffering effect.

Another ecological service often provided by riparian zones is the maintenance and creation of habitat for multitudes of organisms, as well as maintenance of the biodiversity of stream systems. Dynamic biogeochemical processes, converging nutrients, and a partially saturated soil create a diverse environment in which there is large variation in habitats; ultimately providing many ecological niches (Schiemer & Zalewski, 1991). Riparian zones are dynamic systems that are frequently disturbed by changing flow regimes, soil saturation status, and nutrient availability(Naiman et al., 1993). Dynamic environments provide an organized heterogeneity that many species are able to thrive in by incorporating differing life cycle strategies and a diversity of essential nutrients(Shmida & Wilson, 1985, Roland, 1976).

Riparian zones, due to their location in the landscape, can play a vital role in nitrogen cycling and transport to streams (Lowrance et al., 1984). Hydrologic and biogeochemical factors varying across space and time influence the nitrogen transport in near-stream zones. The nitrogen pool in near-stream zones can be lost to the atmosphere through denitrification, assimilation of nitrates by vegetation, and export to the stream(Hedin et al., 1998). Saturated soils often lead to anoxic conditions in riparian zones, a necessary environmental condition for denitrification(Hill, 1996). Nitrogen can be gained through groundwater inputs, atmospheric deposition, and delivery from upslope areas. The convergence of nutrients in the riparian zone contributes to the high biogeochemical activity in riparian areas. There is evidence that nitrogen removal effectiveness varies widely among riparian zones (Mayer et al., 2006).Width of the riparian zone is not the only determining factor that affects nitrogen loading to streams, although it should be noted that Mayer et al (2006) found that small riparian zone buffers contribute to nitrogen loading in streams in excess of nitrogen provided to it from the uplands. Width of the riparian zone is not a first order predictor, but soil type, subsurface flow paths, saturation depth, surface saturated areas, and subsurface biogeochemistry have been shown to be more important for dictating nitrogen removal efficiency (Gold, 2001).Organic matter decomposition rates are often high in riparian soils and they help increase carbon accumulation in the soil. Increased carbon concentration can lead to a greater denitrification capacity for the soil and carbon accumulation in the soil can be a significant predictor of denitrification when comparing across different classes and structures of soils(Burford & Bremner, 1975). Riparian zones are important areas for many other nutrient transformations whose efficiency can be a function of landscape factors, nutrient loading, and wetness states.

Forest wetlands and riparian zones have also been shown to be an important global carbon reservoir as well as relatively quick nitrogen cyclers. Their nutrient budgets are strongly impacted by timing of precipitation and water inputs, evapotranspiration losses, vegetation cover related to evapotranspiration, and hydrologic connectivity (Pelster et al., 2008). Riparian zones provide a more dynamic relationship with carbon and nitrogen due to their fluctuating water table. The landscape setting of a riparian zone also influences the efflux magnitude of carbon dioxide from riparian zones (Riveros-Iregui & McGlynn, 2009, Pacific et al., 2008).

Vegetation in riparian areas has a significant impact on the hydrological and biogeochemical processes. Riparian vegetation can influence runoff through physical barriers to flow, increased interception, and evapotranspiration. The water uptake by plants can lower the subsurface water table in the riparian area as well(Tabacchi et al., 2000). Water quality is impacted through assimilation by riparian plants, input of nutrients when riparian vegetation is decomposed, as well as by creating areas with redox potential for nutrient transformations.

Soil depth and structure alters riparian zone function by providing a connection to the upslope as well as the variability of water table fluctuations. Vidon and Hill (2004) reported that in areas of deeper permeable sediments in the riparian zone there can be a more permanent hydrologic connection to the upslope, while in areas of thinner permeable sediments overlying an aquitard there was an intermittent hydrologic connection. These areas of deeper permanent sediment also provided a surface such that when the slope is greater than 5% the subsurface water tends to flow down slope(Vidon & Hill, 2004).Understanding the importance of slope or other factors impacting subsurface flow can be used to identify different drivers or controllers of the hydrology of riparian zones across landscapes (Ocampo et al., 2006).

Landscape control of runoff generation, though first proposed in the early 20th century (Horton, 1933), has been shown in recent research to link nutrient transformations and transport based on runoff generation (Detty & McGuire, 2011, Burt, 2005).How a parcel of water arrives at the stream whether through overland flow, macropore flow, or another way will determine the biogeochemical processes experienced, the nutrient concentrations in the water and thus its impact on water quality.

Nutrient export from a riparian zone often occurs through flushing and draining mechanisms that are controlled by nutrient supply, demand, and hydrology. Flushing refers to snowmelt or stormflow moving solute to the stream. Nitrogen built up in the top layer of soil during times of low demand, such as winter, can be flushed during snowmelt or stormflow. The draining mechanism is a more consistent discharge from the riparian zone to the stream that occurs because of snowmelt or stormflow recharge that moves into deeper flow pathways and then slowly released over the year (Creed et al., 1996).The flushing mechanism will not deliver nutrients to the stream if there is no accumulation period (Burns, 2005).In order for there to be solute to move to the stream, a period of solute accumulation is necessary. If there are two large storm events in a short period of time, the second storm will deliver much less solute to the stream than the first simply because the first storm had more potential solute to flush than the second storm.

Flushing and nutrient release are not just influenced by saturated area extent. Factors such as transmissivity, soil depth, and mass exchange between saturated and unsaturated zones can also influence nutrient release (Weiler & McDonnell, 2006).Transmissivity controls how fast water moves through the soil in a particular area, which would thus influence the time for potential reactions to occur. Saturated soils have a higher transmissivity than unsaturated soils, so water and nutrients would be expected to move faster through saturated soils. Soil depth will determine potential rooting depths for vegetation and the probability of intersection of the subsurface water table and nutrient extraction by plants in the upper soil layers.

Riparian zones can thus provide ecological services like maintenance of baseflow, attenuation of flooding, creation of habitat, as well as storage and cycling of nutrients. These services help maintain water quality in streams as well provide inputs to areas downstream of the riparian zone in question. Riparian zones can provide the aforementioned ecological services due to their vegetation, nutrient load, water table fluctuations, soil structure and composition, and chemical processes. These factors introduce a variability in riparian zones that affects their ability to function and their relative importance to the water quality and ecological health of the watershed compared to other areas.

What Causes Heterogeneity in Riparian Zone Form and Function?

As discussed previously, riparian zones are heterogeneous in both their spatial configuration and ecological services. Many drivers of the heterogeneity in riparian zones are known, but these drivers are diverse and their interactions with other contributors are not fully understood (Naiman et al., 2005).Identification of contributors to the heterogeneity of form and function of riparian zones has progressed significantly in recent years, but more progress is needed for better understanding of factors that affect riparian zones.

Understanding the variability in nutrient transformation efficiency in riparian areas is important for further advancement of riparian management. Areas of the riparian zone that are an interface between coarse, permeable material and fine, organic materials provide a denitrifying environment because they combine areas with potential for a large volume of nitrate rich water with plenty of organic carbon to serve as the final electron acceptor for denitrification reactions (Vidon et al., 2010). The timing of nutrient delivery and wetness state is also important because denitrification in particular requires the intersection of nitrate, a carbon source, and reducing environments. Nutrient solute inputs to riparian areas can be quickly transformed upon entry, often within the first few meters

(Peterjohn & Correll, 1984).This early transformation upon reaching the riparian zone makes the edges of riparian zones very important in terms of stream water quality and overall watershed health, which are dependent on connections to the uplands and the delivery of water and solutes to the riparian zone.

Hillslope delivery of water to riparian zones is highly impacted by antecedent conditions (McGuire & Detty, 2010).Consequently, seasonal and storm effects drive hillslope-riparian-stream (HRS) connectivity. If the hillslope in question is dry before the hydrologic event, it will be less likely to develop a subsurface water table and subsequently a connection to its riparian area (Hopp & McDonnell, 2009). If wet antecedent conditions exist, such as a recent storm or snowmelt, it is more likely that HRS connectivity will occur due to the establishment of a subsurface water table in the hillslope. The delivery of water from upslope starts a pressure wave which dictates the response of the riparian zone water table (Vidon, 2011).The water table rise in riparian soils is not solely due to infiltration in riparian soils, but instead inputs from infiltration in the uplands. The development of a hydrologic connection will impact the amount and timing of water delivered to the riparian zone(Ocampo et al., 2006).Knowing the antecedent conditions of a hillslope will confer a much greater ability to predict quantity and timing of water delivery to riparian zones.

If there is HRS connectivity, water will flow from the hillslope to the riparian area, but its path to the stream is determined by the height of the subsurface water table. Water will always follow the path of high to low potential and that gradient is set by the height of the water table in the stream, riparian area, and uplands. If the subsurface water table is high in the soil profile, water often flows perpendicular to the stream (Rodhe & Seibert, 2011). Meaning that water oftentimes flows through the riparian area to the stream but if the subsurface water table is lower in the soil profile, the flow direction can become parallel to the stream. This means that when the subsurface water table is low, water may not flow directly into the stream from the riparian zone, but instead may traverse down valley or down gradient before entering the stream. Longer time spent in the riparian zone gives nutrient laden water more time to undergo redox reactions and thus have a greater effect on water quality.

The source of nutrients delivered to the riparian zone will help determine the concentrations and quantities of nutrients entering the riparian zone. Changing runoff source areas within a catchment can affect nutrient transport(Stieglitz et al., 2003).Discharge is a very strong predictor of nitrogen export, but catchments with less variable runoff source areas show less nitrogen export than catchments with more variable runoff source areas(Creed & Band, 1998). If a catchment readily saturates, creates hydrologic connectivity, and generates runoff from the same areas, it will provide most of the nutrients to the stream, whereas if there is high variability in saturation zones during a hydrologic event there is a larger potential for areas that have accumulated nutrients for longer periods of time to contribute nutrients to the stream. The saturation of different source areas in a catchment is based on catchment structure as well as storm frequency and intensity (Anderson & Burt, 1978).

Precipitation patterns add to the complexity of nutrient delivery caused by variable source areas. The nitrogen pool in near-stream zones responds to the biogeochemistry of hydrologic events each with different timing and magnitude (Cirmo & McDonnell, 1997).The environmental conditions necessary for specific biogeochemical reactions, such as denitrification, are highly dependent on the hydrology of the riparian area. The timing between storms will determine the length of time riparian areas have to dry. The intensity of storms will determine the magnitude of water and nutrients stored and thus potential substrates for nutrient transformation.

The variability of riparian zone storage and transport of nutrients is largely controlled by the depth of permeable sediments, hydrologic regime, antecedent conditions, and source areas. Knowledge of these drivers can help us predict areas of high potential for positive ecological services as well as understand why some areas are less efficient in providing those ecological services.

How Are Riparian Zones in Mountain LandscapesDifferent fromOther Riparian Zones?

Riparian zones in mountain landscapes have different primary controls than riparian zones in lowland areas. The hydrograph of mountainous catchments is oftentimes dominated by snowmelt. The peak flows created by snowmelt and the ensuing runoff is often the major hydrologic event for the year, with the ability to determine whether the year will be above or below average in terms of precipitation and streamflow in a relatively short period(Rodhe, 1998). Snowmelt sets the hydrologic regime for the entire catchment, including the riparian zone. Riparian zones' water table rise is then controlled in large part by the snowpack and the ensuing snowmelt runoff and infiltration.

Undisturbed headwater streams and their watersheds are typically very retentive of nitrogen, but the processes in the riparian zones of these watersheds are not as well understood as those for agricultural riparian zones (Ranalli & Macalady, 2010).Catchments with physical similarities are frequently hydrologically similar, especially in the case of headwater streams (Oudin et al., 2010). Topography and surface characteristics that drive headwater streams, often 1st or 2nd order, can often be more easily modeled than higher order streams whose hydrology is less driven by topography and more driven by soil structure and groundwater flowpaths. Riparian zones in headwater streams and their inherent heterogeneity can then potentially be understood through observable terrain structure. Topography can also influence the chemical and nutrient load delivered to 1st and 2nd order streams.

Headwater streams and their surrounding landscapes are more able to influence stream chemistry than higher order streams (Cirmo & McDonnell, 1997).This ability is due to the relative volume of water in the headwater stream compared to the volume of water inputted from the surrounding landscape. Therefore, first order streams have the greatest potential to improve water quality because they have a smaller volume, meaning that inputs will compose a greater percentage of the total flow. In comparing soil type and a topographic wetness index, it has been suggested that the best place to put riparian buffers is in first order streams (Helmers et al., 2009).Furthermore, smaller cross-sectional stream channel areas can also allow for more interaction with riparian and hyporheic zones, allowing nutrients to be in contact with reactive substrates more frequently and for longer periods. Increased interaction with riparian zones in low-order streams points to an increased importance of riparian zones in low order streams.

In summary, riparian zones in mountain landscapes and headwater streams differ due in part to stream size, hydrologic controls, and level of understanding. The dominance of surface processes and the degree to which headwater streams influence the water quality for their downstream areas makes headwater streams in mountain landscapes potentially an easier area to predict riparian zone function as well as an area that understanding the function of the riparian zone could make a large difference in the management and subsequent water quality of the stream.

How Do We Care for Riparian Zones?

Management of riparian zones has been primarily to improve water quality of the stream in question (Osborne & Kovacic, 1993). Riparian zones, with their role as nutrient filter and volumetric hydrologic buffer, are an important portion of the landscape if one desires to impact water quality. Ensuring the functionality and protection of a riparian zone influences stream output more than protection of the same sized piece of uplands. This has traditionally been accomplished through in-stream management and buffer zones(Lowrance et al., 2000). An example of in-stream enhancement of riparian zones or creation of hyporheic flow in forested areas involves placing woody debris and large rocks in the river channel that would force water to flow around it (Fetherston et al., 1995).This obstruction in the channel is intended to force water down into the hyporheic zone below the stream as well as into the riparian areas adjacent to the stream. This creation of lateral and vertical flow into the soil helps develop the requisite exchange between the stream and riparian zone, necessary to produce a more connected system. Buffer zone management refers to a specific width of land that will be maintained between the stream and any development, logging, grazing, or agriculture. This approach was originally based on the concept that the larger a riparian zone is, the better it is able to attenuate nutrient and water inflows as well as contribute to streamflow by virtue of having a larger volume of subsurface water (Lowrance, 1985).

When examining riparian buffer guidelines and regulations, a recent study undertaken by Lee et al. (2004) found that just under half of guidelines imposed by state and local authorities in North America have at least 3 modifying factors instead of having a standard riparian buffer width. The most common modifying factors are type of body of water, shoreline slope, size of body of water, and presence of fish. Other modifiers used are basin size, shoreline forest management, saltwater flow, shoreline vegetation, whether the reach is upstream of fish bearing areas, the threat of sediment to downstream areas, flow rates, and drinking water or aesthetics concerns(Lee et al., 2004).None of these guidelines take into account the position of the riparian zone in the landscape in the fullest extent, but they do provide modifications to recognize the inherent complexity of riparian zone functions and their management. Taking into account the characteristics of the surrounding landscape and water body when determining riparian zone buffer guidelines allows for a greater flexibility and adaptation to management needs; meaning a greater potential to balance development and conservation interests.

Our understanding of the inherent variability in riparian zones in terms of nitrogen removal points to the necessity of varying width of riparian zone buffers to provide a consistent buffering pattern. It has been found that GIS-based riparian zone buffer placement that takes into account topography and spatial location of development in a watershed is more cost-effective than conventional fixed-width scenarios (Qiu, 2009). By recognizing the importance of spatial location of source areas and hydrologic contributing area, GIS-based riparian zone buffer placement affords for development in a larger portion of the catchment with the riparian zone still providing the same ecological services.

Management of riparian zones has evolved considerably in the past few decades, but there are still advances to be made in recognizing the heterogeneity of riparian zones and drivers of this heterogeneity. One of these drivers appears to be the position of the riparian area within the broader landscape. The location of a riparian zone can make a significant impact on the efficiency and functionality of that riparian zone. The following case study will be used to demonstrate the influence the surrounding landscape has on the hydrology and biogeochemical activity of the riparian zone.

CASE STUDY

The case study that follows will be a synthesis of recently published studies in the Tenderfoot Creek Experimental Forest (TCEF). A framework for a modeling approach to riparian zone hydrology will be organized from the salient features of each of the published studies. This modeling approach will synthesize the recently published work in an effort to understand processes at a single locality, apply that knowledge to areas with similar characteristics and landscape setting, and postulate the utility of the modeling approach's framework to predict riparian zone hydrology in various ecosystems.

The Tenderfoot Creek Experimental Forest (TCEF) is situated in the Little Belt Mountains of central Montana. TCEF consists of 11 nested gauged watersheds of varying size and shapes, each recording stage runoff and water quality parameters at the catchment outlet (Figure 1). Instrumentation for shallow groundwater monitoring consists of more than 150 recording groundwater wells and piezometers across 25 transects, as well as multiple transects recording specific conductance of riparian and hillslope well positions. Also available is 1m ALSM topography and vegetation structure data, QUICKBIRD remote sensing data, and two SNOTEL sites near the high and low elevations of the catchments (See Appendix A for a more detailed site description). This extensive instrumentation makes TCEF an ideal location for focused riparian research within a wider landscape context.

Previous studies used topographic analysis of the study area based on high-resolution digital elevation maps (1m DEMs) to calculate terrain indices including UAA, buffer ratios, and areas of topographic convergence and divergence (Jencso et al., 2010, Jencso et al., 2009, Pacific et al., 2010). These analyses were used to scale landscape riparian buffering observations across larger portions of the catchment. In combination with landscape analysis, hydrometric monitoring of shallow groundwater levels allowed for determination of duration of hydrologic connectivity for transects of varying landscape attributes. The combination of landscape analysis and hydrometric monitoring allowed for a modeling of riparian turnover times using a mixing model and the declining specific conductance of the riparian zone water upon hydrologic connection. Nutrient grab samples were also collected across multiple transects and watershed outlets in order to determine how landscape organization affected nutrient export (See Appendix B for a more thorough description of previous studies' methods).

Landscape analysis, hydrometric monitoring, riparian zone turnover modeling, and nutrient monitoring were combined to develop a conceptual approach for hydrology in headwater systems. Through understanding differing landscapes across watersheds and how that affected hydrologic connectivity, riparian turnover, and nutrient export, we could show that landscape position is a primary driver on hydrologic connectivity, riparian turnover and nutrient export and encourage its use in hydrologic models.

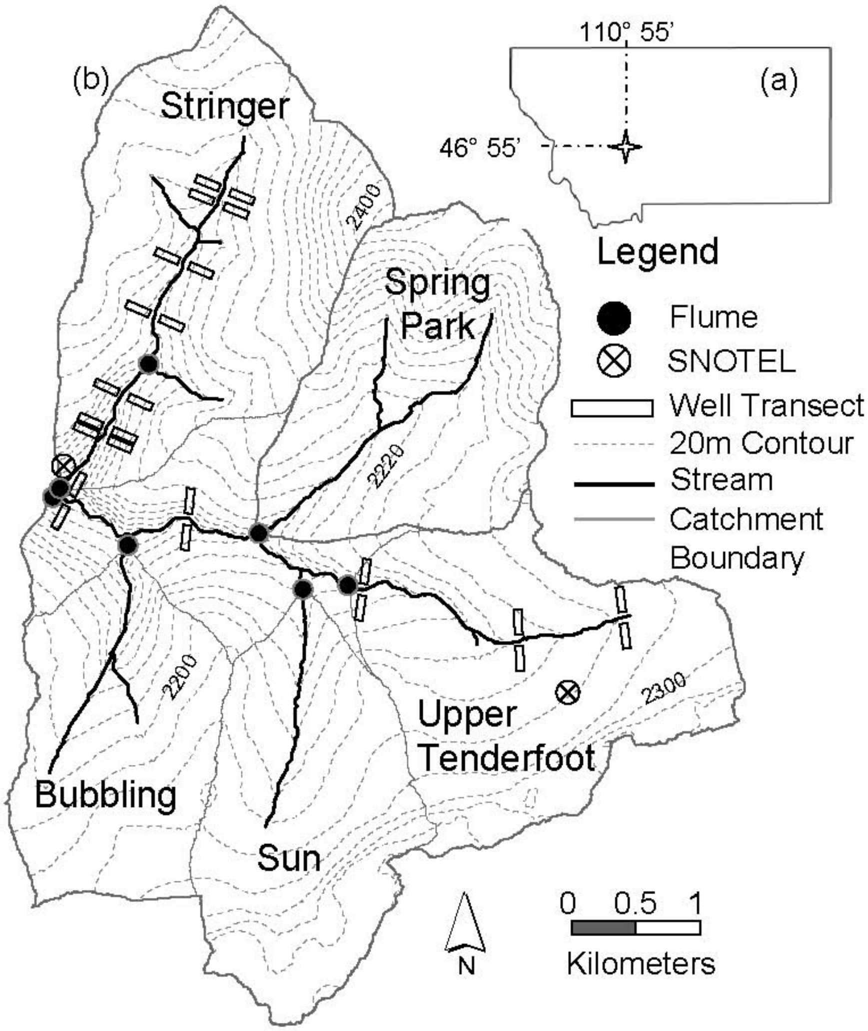

Figure 1.Location of instrumentation in TCEF and its spatial location in Montana. Well transects, catchment flumes, and SNOTEL locations. Extent of instrumentation is not drawn to scale.

RESULTS

Riparian Zone Hydrology

Jencso et al (2009) studied 24 transects in the Tenderfoot Creek Experimental in order to determine the relationship between the topography of the transect and its connectivity. The transects had upslope accumulated areas (UAAs) between 0.06 and 4.61 ha. Transects displayed connectivity durations of between 0 and 100% of the year. The connectivity duration of a transect was directly related to its UAA (r^2=0.91, n=24), with transects having a larger contributing area being connected to their uplands for a larger portion of the year.

Transects with a small contributing area, below 0.4 ha, exhibited no connection during the year or a rapid connection after peak snowmelt or large hydrologic events (Figure 2).Overall the transects' connection to the uplands was less than 4% of the year(Jencso et al., 2009).Large contributing areas, UAA above 4.44 ha, were connected for the duration of the year, 100% connectivity. These transects were at the base of convergent hillslopes. The UAAs lying between these two extremes exhibited a transient connection to their uplands. Their connection ranged from 3% to 61% of the year. These transects were connected largely during snowmelt as well as transiently during large rainfall events during the hydrograph recession.

In order for the connectivity correlation to be more continuous, the percent of the year HRS connectivity occurred was regressed against the UAA of the transects (Figure 3).The 24 transects exhibited a pattern showing that larger UAAs are positively linearly correlated with a longer connection time (%) throughout the year (r^2=0.91, n=24)(Jencso et al., 2009).

Areas of higher convergence or higher UAA exhibited a longer duration of HRS connection than areas of lower UAA. No connection was observed in transects with UAA lower than 0.4 ha, while there were transects with UAA above 4.44 that were connected 100% of the year. UAA is linearly correlated with HRS connectivity; areas with higher UAA had higher HRS connectivity.

Riparian Buffering

Jencso et al (2010) focused on riparian zone buffering capacity and its relation to inputs from upslope and landscape structure. They found that hillslope, riparian, and groundwater have different specific conductance. Hillslope water has the lowest SC, always ~27 µs cm^{-1}, with riparian water usually ~127 µs cm^{-1} during baseflow in transects with transient HRS connectivity. Using this relationship they were able to describe the riparian buffering capacity of different transects.

The four transects that were monitored had riparian buffer ratios ranging from 0.01 to 0.45, with lower numbers indicating a smaller ratio of riparian area to upland draining area. Each transect had a distinct decline in riparian zone specific conductance from high riparian values toward lower hillslope values. The slope of the decline in each riparian zone was determined to be the rate of turnover of the riparian zone (Figure 4). The rates of turnover ranged from a half-life of 3 days to a half-life of 27 days, with half-life being the time needed for half of the volume in the riparian zone to be replaced with water from upslope(Jencso et al., 2010).

The turnover half-life was positively correlated with the riparian buffer ratio (riparian:upland).Areas with a higher riparian buffer ratio took longer to turnover, while areas with a smaller riparian buffer ratio had a shorter turnover half-life (Figure 5).If the transect had a larger riparian area or a smaller upslope area it could be expected to take longer to turnover than a transect with a small riparian area or large upslope area.

After the turnover half-life was calculated, the number of turnovers that occurred during the time of connection was calculated. Transects with a short turnover half-life had their volumes turned over up to 27 times, while the transects with larger turnover times turned over less than half of their volume (Figure 6) (Jencso et al., 2010).

Volumetric riparian buffering is controlled by the ratio of uplands draining to the riparian area and the area of the riparian area. A larger ratio (riparian:upland) indicates a riparian zone that isn't flushed very often and doesn't contribute to the stream as much, while a smaller ratio indicates a riparian zone that is constantly being flushed and contributing to stream flow and water quality. The longer it takes for a riparian zone to turnover, the greater potential that redox reactions will be taking place and transforming the nutrients in the riparian zone.

Nutrient Export

Carbon

Pacific et al (2010) elucidated the primary controls of DOC export in mountainous, snowmelt dominated catchments based on their analysis at TCEF. They posited a combined source area and water table dynamic convergence that leads to DOC export. Three mechanisms combine to create the DOC export measured in the TCEF. During low flow and drier times, water connected to the stream is flowing through mineral soil with little DOC. This leads to low DOC concentrations in the stream due to a DOC poor source area. On the rising limb of the hydrograph during snowmelt the water table in the riparian zone rises into the organic layer of the soil. This organic soil is DOC rich and the water coming into contact with it increases its DOC concentrations, ultimately resulting in a high DOC concentration in the stream. At peak flow a connection develops with the uplands, creating a pathway for the DOC stored there to be delivered to the stream, again creating a high DOC concentration in the stream. The initial pulse of high DOC concentrated water from the uplands is sub sequentially diluted by low DOC water traveling through mineral soils, leading to a lower stream DOC concentration (Figure 7) (Pacific et al., 2010).

This mechanistic view of DOC export was supported by the relationship between DOC mass export of different watersheds during snowmelt and their terrain profile. Cumulative DOC export from a watershed during snowmelt in the TCEF increases as the riparian to upland ratio increases (r^2=0.67, p=<0.001) (Figure 8) (Pacific et al., 2010). Therefore with an increase in riparian area or a decrease in upland area, we would predict the catchment to export more DOC. Riparian areas can be a significant source area for DOC during snowmelt, suggesting that as the water table rises into the organic layer of soil in the riparian zone DOC is being exported.

DOC export was also negatively related to percentage of the watershed connected (HRS connectivity) at peak runoff (r^2=0.28, p=0.11)(Pacific et al., 2010).This suggests that if more of a catchment is hydrologically connected to the stream at peak runoff, then we can expect decreased cumulative DOC export during the snowmelt period.

Nitrogen

Most nutrients sampled in TCEF(DOC, DON, phosphate and ammonium)had>75% of their total mass exported during the snowmelt portion of the hydrograph, meaning the hydrologic dynamics of a catchment could play a large role in determining the nutrient export from the catchment (Figures 9-10). At TCEF, the hydrologic dynamics are primarily influenced by the topography of the catchment. Nitrate is different from the other nutrients and N species in that it experiences a large spike in export during snowmelt but it also has upwards of 60% of its mass exported during baseflow, depending on the catchment (Figure 11).

Nitrate and ammonium exhibited a distinct seasonality in their export. Ammonium was similar to DOC in that most of its mass comes out during snowmelt. Nitrate showed increased export during snowmelt, but it also had a large export during baseflow times after the hydrograph recession. The ratio of nutrient export during snowmelt:baseflow (kg N/hectare) for ammonium was above 2.1 for all subcatchments, while for nitrate the highest ratio was 1.5 with most subcatchments being below 1.0 (Figure 12).

Different nutrients have different export mechanisms, and these different mechanisms result in varied timing and seasonality in the export of nutrients from watersheds. The mobilization of source areas by hydrologic connectivity helps determine nutrient export as well, along with nutrient concentrations in source areas that are mobilized at different times (Pacific et al., 2010). The concentration of a source area combined with the mobilization mechanism results in the spatial and temporal variation of nutrient export.

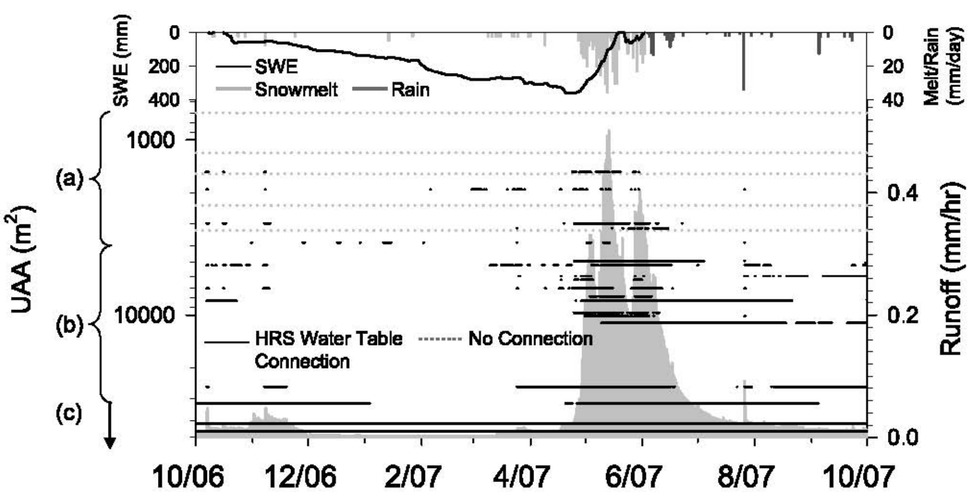

Figure 2. Summary of water table connectivity of 24 hillslope-riparian-stream transects for water year 2007. Small UAA transects have minimal or no connection, midrange UAA transects sustain a connection during snowmelt and large rainfall events, large UAA transects are continuously connected (from Jencso 2009).

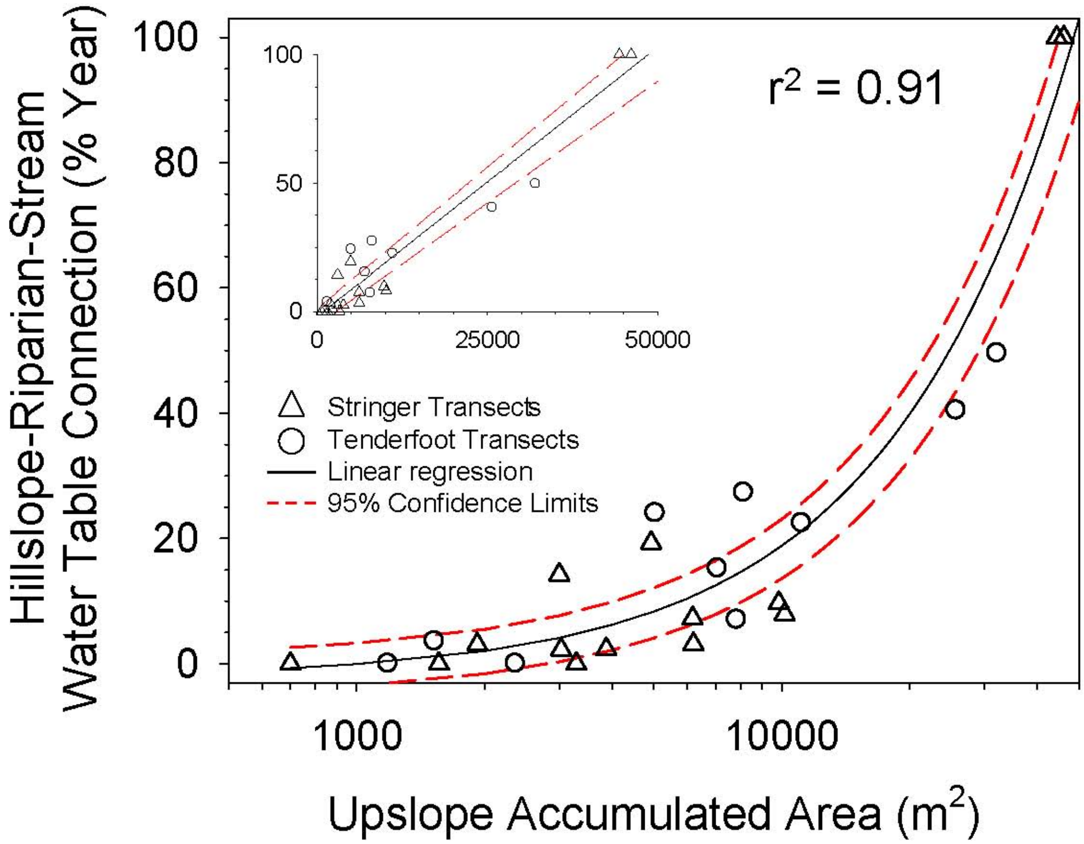

Figure 3. UAA of 24 well transects linearly regressed against the duration of hillslope-riparian-stream connection expressed as a percentage of the water year. Connections were recorded when streamflow was present as well as water present in riparian and hillslope wells (from Jencso 2009).

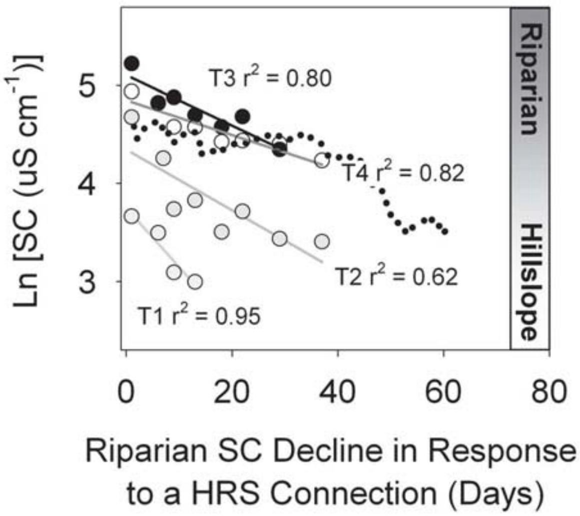

Figure 4.Exponential decline in riparian zone specific conductance towards the hillslope signature following hillslope-riparian stream connection. The dotted line represents the decline in the stream specific conductance during the same time period. The slopes indicate the rate of riparian zone turnover by hillslope water (from Jencso 2010).

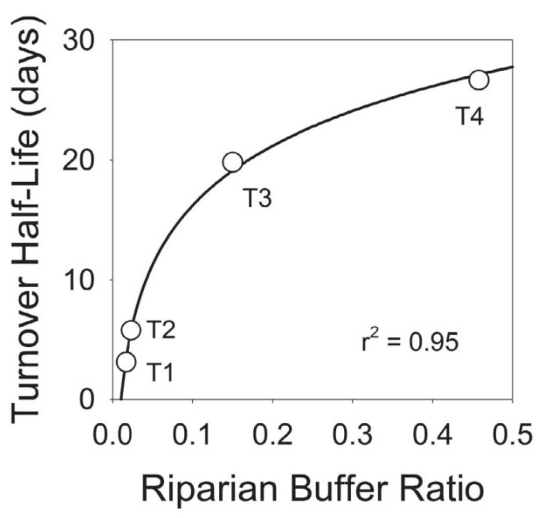

Figure 5. Relationship between riparian buffer ratio (riparian area divided by hillslope area) at each transect and the time it takes for half of the initial riparian zone concentration to be turned over by hillslope water (from Jencso 2010).

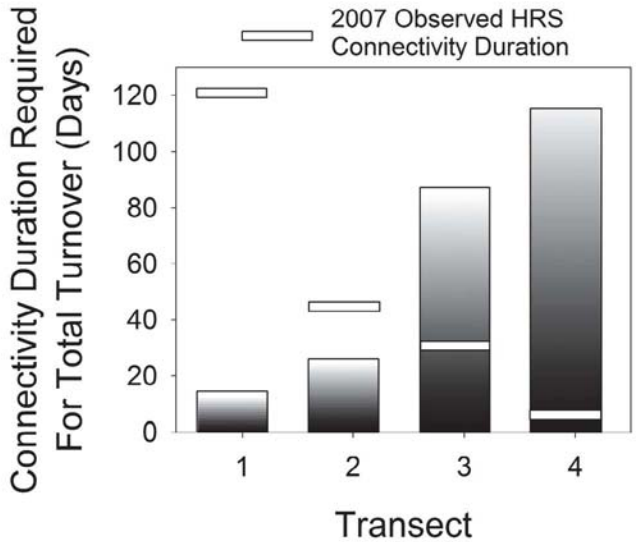

Figure 6. Estimated required duration of hillslope-riparian-stream connectivity for 95% of initial riparian water to be replaced by hillslope throughflow (shaded bars). White rectangles indicate the observed hillslope-riparian-stream connectivity for the study's duration period (from Jencso 2010).

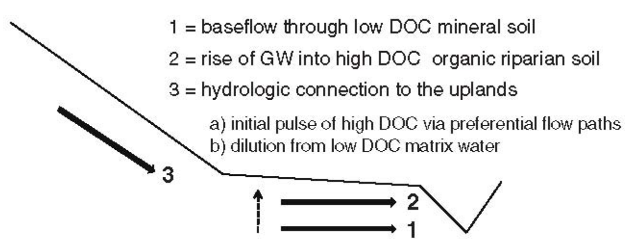

Figure 7. Conceptual diagram of flushing mechanisms for DOC. (1) Drier and low flow times has groundwater moving through mineral soil with low DOC concentrations, resulting in low stream DOC concentrations. (2) In the rising limb of the hydrograph, the groundwater rises into organic-rich soils in the riparian zone and DOC inputs to the stream increase. (3) At peak flow, HRS connectivity occurs and an initial high DOC pulse from the uplands is transmitted to the stream (3a). Water from the uplands is then diluted by low DOC matrix water traveling through mineral soil (3b) (from Pacific 2010).

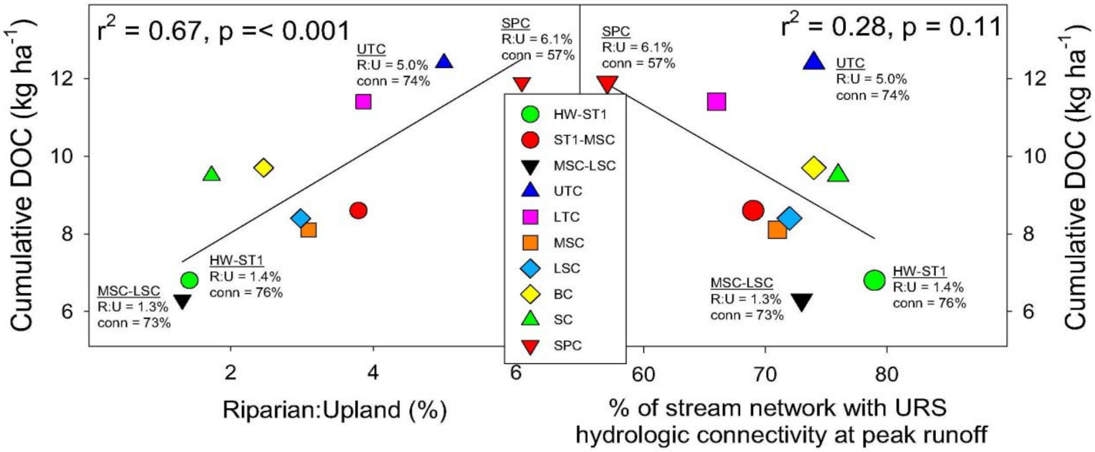

Figure 8. Cumulative DOC export during snowmelt at each of the subcatchments of the TCEF regressed against riparian:upland ratio and percent of the stream network with HRS connectivity at peak runoff. A larger riparian:upland ratio leads to increased DOC export, while a larger amount of the watershed connected at peak runoff leads to decreased cumulative DOC export (from Pacific 2010).

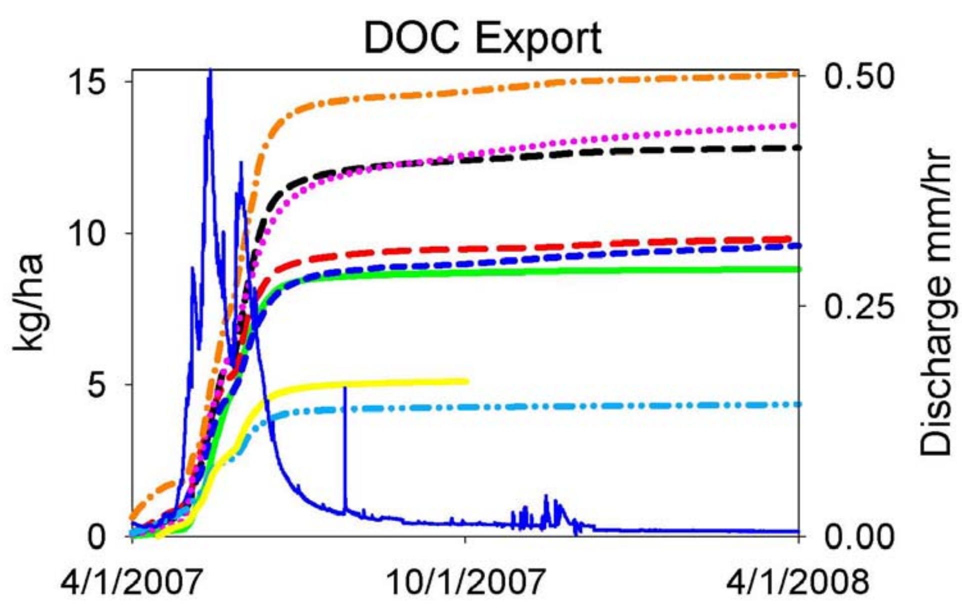

Figure 9.Cumulative DOC export from the adjacent subcatchments of the TCEF. Most of the mass exported comes out during snowmelt for all catchments.

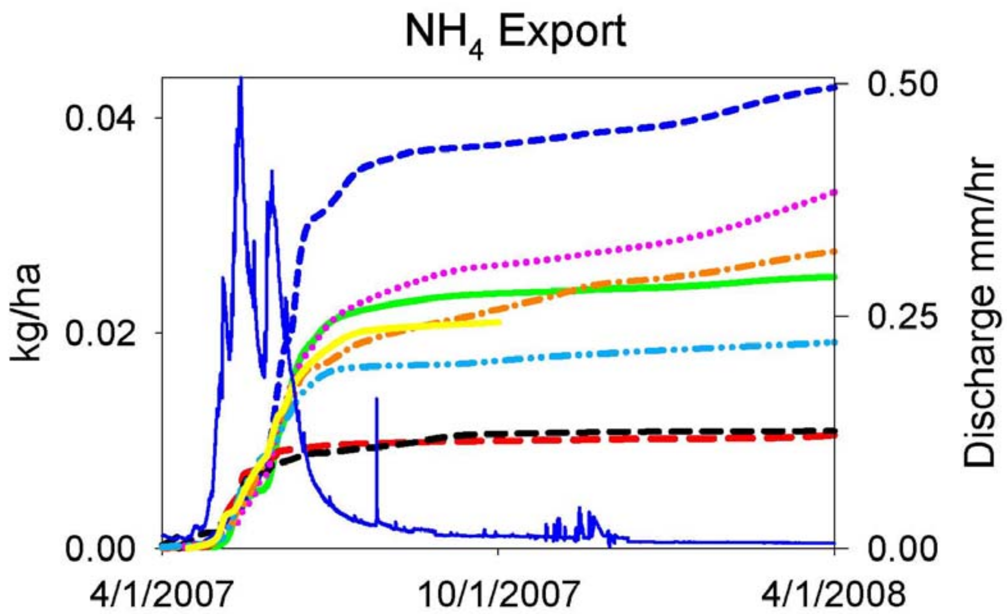

Figure 10.Cumulative ammonium export from the adjacent subcatchments of the TCEF. Snowmelt is when most of the export occurs.

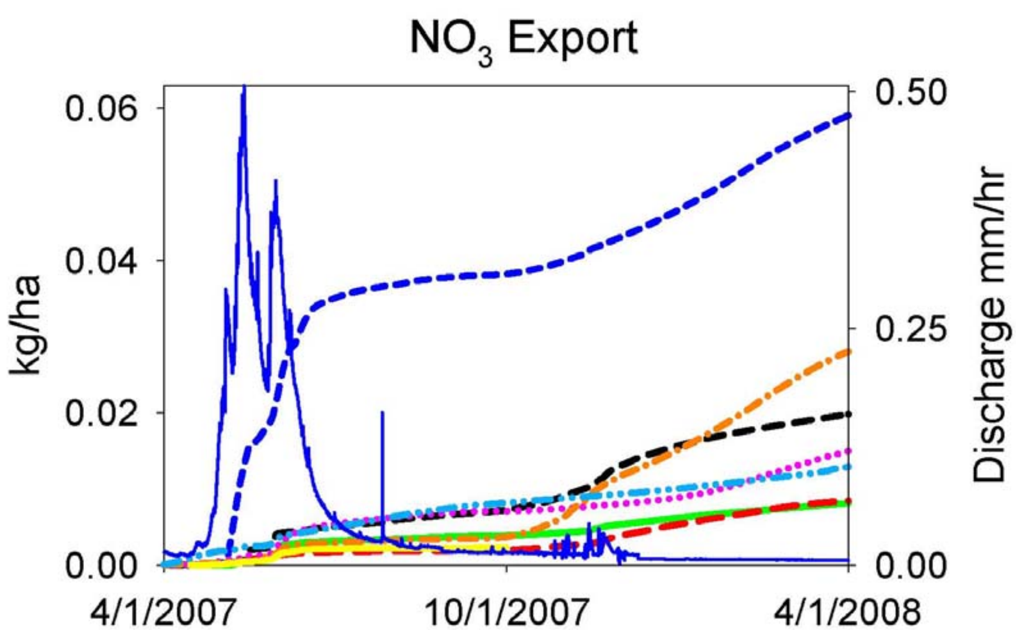

Figure 11.Cumulative nitrate export from the adjacent subcatchments of the TCEF. Nitrate export occurs during snowmelt as well as during baseflow.

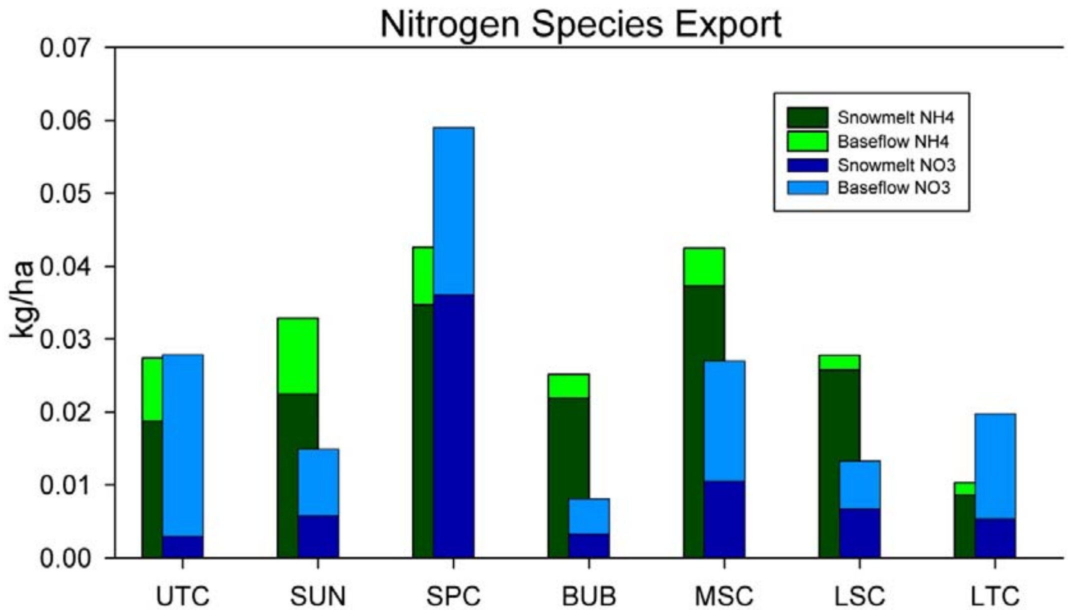

Figure 12. Cumulative export of nitrate and ammonium in subcatchments of the TCEF separated into snowmelt and baseflow time periods. Ammonium comes out mostly during the snowmelt periods in all of the watersheds, whereas nitrate has a much larger portion of cumulative export during baseflow.

DISCUSSION

The position of a riparian zone in the overall landscape of the watershed greatly impacts its function. By understanding that the landscape position of the riparian zone can greatly affect the transport of water or nutrients from the hillslopes through the riparian zone to the stream, better predictions of riparian zone function and management of riparian zones can be expected.

The landscape position of a riparian zone is largely a part of what the surrounding landscape is and how it influences the riparian zone. Because riparian zones are influenced by areas upstream as well as areas upslope, each riparian zone will be different based on how far downstream it is from the source and the area upslope that drains to that particular riparian zone, the variability of parent materials, vegetation, elevation, and climate. We focus on headwater streams with relatively shallow sloped uplands that steepen and converge on narrow near stream areas. Riparian areas in this system are found in the narrow canyon bottoms of the watershed, rather than larger alluvial fans or valley bottoms represented in larger or higher order streams. These landscape features and position have considerable influence on riparian zone processes.

The landscape position of a riparian zone partially determines its hydrologic connectivity. The establishment of a water table in the hillslope areas, and its hydrologic connection to riparian zones and streams, is driven by the area that a particular hillslope drains, also referred to as UAA. The relationship between UAA and HRS connectivity shows that areas of higher UAA are expected to have a more constant water table connection than areas of low UAA (Jencso et al., 2009).Areas of low UAA are only expected to have a HRS connection after large rainfall events or snowmelt. The transient connection of low UAA hillslopes can be predicted and therefore managed appropriately. Riparian position in the landscape influences when and where hydrologic connections to the hillslope will occur and this connection is largely determined by the UAA or contributing area of that riparian area.

Landscape position of riparian zones and the subsequent hydrologic connectivity also contribute to the control of riparian zone flushing. Riparian zone flushing is influenced by the ratio of riparian area to hillslope area. Areas of high riparian:upslope (buffer) ratio will be expected to turn over less often than areas of low riparian:upslope ratio(Jencso et al., 2010). An increase in riparian area, a decrease in upslope area, or a combination of the two will increase the riparian:upslope ratio, thereby increasing the expected turnover time. We know that the expected turnover time is inversely related to HRS connectivity duration(Jencso et al., 2010). Shorter turnover times are expected with a longer HRS connection. Understanding hydrologic connectivity based on a riparian area’s landscape position facilitates examination of how connectivity and nutrient source areas contribute to nutrient export. The intersection of a hydrologically connected hillslope and a nutrient source area drives the nutrient export of a watershed.DOC, DON, and ammonium are all primarily exported during the snowmelt portion of the hydrograph, while up to 60% of nitrate is exported during baseflow. This differing seasonality could be due to differing source areas, biogeochemical activity, mobility, or a combination of the three.

Pacific et al (2010) showed that DOC export decreased as HRS connectivity of a catchment increased, suggesting a riparian source of DOC.DOC export also increased with an increased riparian buffering ratio indicating a potential riparian source of DOC that is exported to the stream. Therefore the mechanism of DOC export appears to be a convergence of hydrologic connectivity and contributing source areas. As the water table rises in the riparian zone due to rainfall or snowmelt DOC rich soil becomes saturated and the DOC present can be transported to the stream. At peak flow HRS connectivity has been established with the hillslopes, which are a source of low DOC concentrations, leading to a low DOC concentration in the stream. A return to baseflow lowers the water table and DOC concentrations fall because the mineral soil that is connected to the stream is DOC poor. These relationships enhance our ability to understand and predict nutrient export.

The landscape position of a riparian zone thus has great influence over flow patterns, riparian turnover, and nutrient export. In mountainous headwater catchments, the dominant feature of landscape position is topographic relief and the upslope area that contributes to the riparian zone. By identifying riparian zones by their landscape position, and thus their contributing areas, we will be better able to understand areas of importance for nutrient export and riparian buffering.

How Do the Findings of the Case Study Contribute to the Understanding of Riparian Function?

Our understanding of riparian zone function as driven by landscape position can be described via a framework that may subsequently be included in quantitative models of riparian zone hydrology. We know that there is large variability in riparian zone form and function, and finding a way to explain this variation will allow for a prioritization of riparian areas for specific management purposes.

Landscape's influence on hydrologic connectivity is a primary driver of hydrologic processes in mountainous catchments. Hydrologic connectivity provides a conduit allowing for water and solutes from uplands to be transported to the riparian zone and stream more quickly. Saturated areas of the soil have a higher transmissivity than unsaturated areas, thus reducing transit time in areas that have a consistent saturated area connection. The hydrologic connectivity in a landscape determines areas of larger and smaller water contributions to streamflow, thus allowing identification of potential areas of importance in management.

Observed variability in nutrient export highlights the spatial and temporal variability of riparian zones, with their differing source areas as well as their differing periods of greatest export.DOC has source areas of high and low concentrations, and the varied connection to the stream is a large driver of export of DOC. Sources of nitrogen export are not as well understood in mountain watersheds but it is known that different nitrogen compounds have different export patterns over the course of a year(Inamdar et al., 2004, Inamdar & Mitchell, 2007).These export patterns set bounds for ecological communities based on the nutrient loading or scarcity in particular areas or time periods. Management of nutrient export can use the landscape position of the riparian zone to determine specific areas or times that it is important for the riparian zone to be functioning properly and use that information to protect the riparian zone from development or identify priority areas for restoration.

In order to compartmentalize ammonium and nitrate export for hydrologic models we can make assumptions about source areas from previous studies in combination with our knowledge of the temporal nature of export. Ammonium is found in larger quantities in poorly drained soils, where there is a decreased chance of nitrification (Groffmann et al., 1993). Ammonium export peaks during a flushing of the riparian zone through hydrologic connection to the uplands. The hydrologic connection moves ammonium from the upslope to the riparian zone. The full flushing of the riparian zone will depend on the length of the hydrologic connection and the volume of the riparian zone, and this will subsequently determine the ammonium export of the watershed.

One way nitrate can be accumulated in the uplands of a catchment is during periods of no hydrologic connection to the riparian zone or stream(Ocampo et al., 2006). When a hydrologic connection is formed the nitrate from the upslope can then be transported to the riparian zone and subsequently the stream. However, nitrate can be denitrified along this transport path and in the riparian zone when there is adequate moisture available, thus partially mitigating the potential spike in stream export (Devito et al., 2000). Once there is no hydrologic connection to the uplands, the export magnitude will taper and denitrification in the riparian zone will commence, until soils dry. After the recession of the hydrograph there is still nitrate being exported. This nitrate may represent “leakage” from deeper horizons of riparian soils, thus maintaining nitrate export. Nitrate is able to leak out of the riparian zone due to its increased mobility compared to ammonium and DOC (Inamdar et al., 2004). Nitrate uptake by plants can explain the delay of export during the summer months and its subsequent rise in the fall.

The landscape position of the riparian zone will affect nitrate and ammonium export by driving the length of hydrologic connection between the hillslope, riparian zone, and stream (HRS connectivity). Increased length of hydrologic connection could cause the connection to occur further upslope, allowing for more area to contribute to the riparian zone, leading to increased export. An increased hydrologic connection will also set the duration of the dry down period occurring in the soils of the riparian area. A faster dry down would mean less opportunity for denitrification. A slower dry, possibly due to a multiple rain events, down could allow for increased denitrification by maintaining a balance between soil moisture concentration and oxygen depletion during dry down.

There are areas of high biogeochemical activity as well as times of high biogeochemical activity (Vidon et al., 2010). These areas will show varying patterns of nutrient transformations as well as varying gas efflux. In areas of high denitrification, there can be expected to be a greater gas export of nitrogen gas and nitrous oxide than areas of lower denitrification. Carbon dioxide efflux from soils is largely influenced by soil moisture, with areas of higher soil moisture showing the highest rate of efflux (Riveros-Iregui & McGlynn, 2009, Pacific et al., 2009). By looking at the landscape position of a riparian zone, a general picture of areas of higher biogeochemical activity or ebullition can be drawn. Converging areas of the landscape would be expected to have higher biogeochemical activity than areas of diverging topography. This general picture can be expanded upon by adding in more complex factors contributing to gas efflux and biogeochemical activity, and by utilizing landscape position as an initial probe; the areas of higher yield are quickly identified.

We have shown that the spatial and temporal variability of riparian zones is an organized heterogeneity, based primarily on landscape position. Riparian hydrology is largely dominated by the contributing area, meaning that predictions can be made about areas that will be wet more often during the year and areas that would be expected to be drier during the year. Knowing the driving factor of the hydrology, in this case landscape position, allows for a greater understanding of the processes occurring in a watershed as well as allowing for predictions about internal function of specific locations.

Where Is Our Conceptual Understanding Appropriate?

Our conceptualization of a watershed's riparian zone and the importance of landscape and topography are most appropriate in mountainous areas with shallow soil, an impermeable layer near the surface, and a snow-dominated hydrograph. In other riparian zones similar conceptualizations may apply but we must take into account changing mechanisms or the relative strengths of varying mechanisms. For example, in areas of low slope or deeper soils, it could be assumed that groundwater flow patterns or flood duration could override topography as a major factor in the hydrology of the riparian zone. If the dominant hydrologic, buffering, and nutrient export mechanisms can be inferred for these low elevation sites, a useful conceptual approach can be identified. By using a similar approach of breaking down the riparian zone into the various mechanisms controlling nutrient export processes, each mechanism can be understood as well as the expected interactions between the mechanisms. The resulting conceptual frameworks of areas with different dominant drivers or mechanisms will be a building block on which research and management can be based. Understanding or predicting dominant mechanisms or drivers in watersheds and riparian zones potentially narrows the scope of research needed and the management activities useful for maintaining the watershed condition.

How Does Our Conceptual Approach Change Management Strategies?

Current management techniques typically do not adequately take into account spatial and temporal variability in riparian functioning. For example, using standard or fixed width management zones for riparian areas is too simplistic to incorporate all the variation in processes and mechanisms occurring in riparian zones. The concept of riparian buffering is integral for management activities. The traditional view of riparian width as the most important metric is only partially correct. By recognizing the importance of upslope area draining to a particular riparian area, managers can better understand areas of potentially higher impact on water quality in the watershed. The recognition and protection of these riparian extents with greater ability to impact water quality in a catchment allows managers to better tailor their management efforts to specific catchments and specific areas.

Management trends are progressing away from fixed width riparian zones and this progression should continue to take into account current knowledge of riparian zones (Inamdar et al., 2004, Richardson et al., 2012). Past research has indicated the spatial and temporal variability of nutrient source areas [*Jencso et al.*, 2009, *Jencso et al.*, 2010, *Pacific et al.*, 2010]. Using this information to protect specific riparian or upland areas will potentially allow for development or resource extraction from areas of the catchment less involved in nutrient export. By stringently protecting the areas of largest contribution to nutrient export, we can impact water quality to a greater extent than by giving equal protection to all areas. Focused and specific protection of riparian areas with the highest influence could allow for a greater impact on water quality as well as fostering development in specific catchment areas and times correctly identified as having minimal influence on nutrient export.

Nutrients also have different timing of their export, with most nutrient transport occurring primarily during snowmelt (with the exception of nitrate). Managers can use this information to decide on timing of activities in the watershed as well as sample routines and timing. Identifying the temporal variation of nutrient export can direct management actions to restrict use in “high export” areas to potentially decrease nutrients exported. A seasonal management plan would specify times when high use is allowed as well as times when low or no use is allowed, in order to maintain more natural nutrient export levels. Redirection of specific activities during their times of highest impact can also be used by managers to achieve their desired results. To see the results of these management activities, a synchronization of sampling efforts with maximum export could be planned. Sampling during periods of maximum export could allow for easier detection of the effectiveness of management activities.

Most riparian zone knowledge has been focused at the point scale and occasionally the watershed scale, but understanding and monitoring internal processes is not feasible at either of these two scales. Being able to understand the internal dynamics of watersheds spatially and temporally would increase management effectiveness and efficiency by leaps and bounds. Understanding the internal dynamics of a watershed can be accomplished through developing a conceptual understanding of processes controlling hydrology that remains true across multiple scales. Knowledge of areas and times to focus efforts on would remove many frustrations for managers, land owners, as well as the general public. Less guess work would lead to a greater understanding of closures to development or use and a greater acceptance of the need for such closures or protections.

Having a conceptual approach that works well across multiple watersheds allows for an *a priori* understanding of the watershed and its processes and mechanisms driving hydrology and nutrient flow. An *a priori* understanding significantly decreases time needed for background measurements and their interpretation. The ability to understand processes and mechanisms before measuring them could allow for process attribution to various portions and times in the catchment. Quickly and correctly identifying places and time steps of great importance to riparian function will be a great tool in constructing management guidelines for all portions of watersheds, especially the riparian zone.

By using our understanding of the importance of the place of the riparian zone in the landscape as well as the upland impacts, we can better plan development in watersheds to mitigate impacts on processes. Some riparian zones are more important to water quality in a watershed than others. The recognition of this will allow for a more nuanced development plan that indicates area of high impact on the watershed and areas that have a lower impact on the overall condition of the watershed.

An example of the utility of this approach is designing where a septic system could be placed in a watershed. If the system is placed in a hillslope area of high potential hydrologic connectivity with the riparian zone and the stream, it is likely that the increased water moving through the area could bring waste to the riparian zone and stream. By placing the septic system in an area of lower probable hydrologic connectivity, the waste will not move as freely and will have more time to be transformed through natural processes.

Planning for development or resource extraction can be done to minimize impacts on natural systems by taking into account landscape variability and its impact on hydrology. Areas of high impact on water quality, based on their landscape setting, will be more likely to be protected in order to minimize the impact of development on the watershed. Development of areas that have relatively less impact on water quality and hydrologic processes will be encouraged. This approach could potentially increase the areas of the watershed allowed to be developed than a standard riparian buffer width. Areas of high sensitivity will be given a larger buffer, but areas of low sensitivity due to topography, or other factors controlling hydrology, will have smaller buffers and development will be allowed to happen closer to the stream.

How Does Changing Climate Affect Our Conceptual Framework?

The current understanding of riparian zones is useful for current conditions, but climate variability needs to be accounted for as well. Seasonal, annual, and interannual changes in climatic inputs can change the processes that dominate a particular catchment at the most dramatic, but the simplest change to understand could be the timing of the watersheds internal dynamics. The Intermountain West is expected to experience earlier snowmelt as we move further into the 21st century (Gillan et al., 2009).How this earlier snowmelt will impact the dominant hydrological processes in a catchment is hard to predict. The rate of snowmelt could increase, causing a sharper peak in the hydrograph. This could cause more overland flow and less storage in groundwater and soil layers, resulting in lower baseflow in the late summer as well as possibly making some streams ephemeral. The earlier melt could also cause a decreased accumulation period for nutrients by decreasing the time between periods of hydrologic connectivity. The shorter accumulation periods would result in lower peak nutrient loads in source areas. Export from these source areas could be expected to decrease causing decreased availability of essential nutrients for vegetation and organisms. Climatic variability introduces many confounding factors into our understanding of riparian zones and thus makes it harder to accurately predict a system’s response. By using an understanding of processes we will be able to better predict effects of climatic variability on riparian zones.

CONCLUSION

Riparian zones are an integral part of the watershed as they transform and contribute to hydrologic and chemical inputs from the watershed to the stream. It has been argued that the position of a riparian zone in the landscape can greatly influence the function and efficiency of that riparian zone. Landscape structure can dictate the hydrological conditions of the hillslopes and their connection to the riparian zone and stream. The relative size of the hillslopes and their connection to the riparian area dictates the level of buffering and turnover of the riparian zone.As established in this paper nutrient export from the watershed is influenced by riparian processing, nutrient source areas, and the interaction of the two by way of hydrologic and biogeochemical dynamics in the riparian soil.

Understanding the landscape surrounding a riparian zone could allow for greater process attribution in ungauged watersheds, changes in riparian zones expected from land use or land change, more effective and targeted management strategies, and an ability to better understand changes to riparian zones due to climatic variability. Due to both their complexity and their importance, a continued improvement of our understanding of the function of riparian zones and how they vary both spatially and temporally in connection with their position in the landscape is requisite to advancing our understanding and management of these crucial landscape features.

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APPENDICES

APPENDIX A

SITE DECSRIPTION

In this case study we summarize recent research conducted in the Tenderfoot Creek Experimental Forest (TCEF), situated in the Little Belt Mountains of Central Montana (Figure 1).TCEF is comprised of 2,200 ha lodgepole pine forest in the Little Belt Mountains. In TCEF there is a chance for freezing temperatures and snow during every month of the year. The mean annual temperature is 0ºC.The average annual precipitation is 880 mm, with most of the precipitation falling as snow. The elevation of TCEF spans 1840 m to 2421 m and represents the full range of slope, aspect, and topographic convergence and divergence.

The parent material of TCEF is igneous intrusive sills of quartz porphyry, Wolsey shale, Flathead quartzite and granite gneiss (Farnes, 1995). Granite gneiss occurs at lower elevations and is frequently seen as exposed, steep cliffs and talus slopes according to landscape position. Flathead sandstone overlies the granite gneiss, followed by Wolsey shale in the headwaters areas.

TCEF is dominated by loamy TypicCryochrepts soils in hillslope positions and clayey AquicCryoboralfs in riparian zones and wetland complexes (Holdorf, 1981).Soils in the riparian area are 0.5-2.0 m deep, dark colored clay loams and gravelly loams high in organic matter.

The lodgepole pine forests of TCEF are characteristic of the patchwork of forests across many areas in the Northern Rocky Mountains. TCEF includes Engelmann Spruce community types in the wetlands as well as whitebark pine and subalpine fir complexes along ridges and hilltops. Riparian vegetation is predominantly sedges and rushes in the headwaters. The headwaters have fine silt and clay textured soils and water tables are near the surface. In areas where the soils are more coarsely textured and with deeper water tables, willows dominate.

The experimental forest's primary drainage is Tenderfoot Creek, which drains into the Smith River and finally into the Missouri River. In TCEF, there are 7 nested watersheds upon which different levels of instrumentation have been applied. The gauged subcatchments range in size from 350 to 22,000 ha. In general, the slopes of the subcatchments are gentler near the headwaters and steeper near the catchment outlets. Spring Park Creek (SPC) has a large riparian and wetland complex, as does Upper Tenderfoot Creek (UTC) at its headwaters. Middle Stringer Creek (MSC) and Lower Stringer Creek (LSC) have intermediate levels of riparian areas, Sun Creek (SUN) has large seeps and wetland areas near its headwaters, and Bubbling Creek (BUB) has less extensive riparian and wetland areas. Lower Tenderfoot Creek (LTC) is the largest catchment and it subsumes all the other catchments.

Tenderfoot Creek Experimental Forest is representative of mountainous headwater catchments, especially those of the Northern Rocky Mountains and areas that have topographically driven hydrology. The seven subcatchments provide research areas of varying shape and structure, as well as streamflow response across similarly sized watersheds. The varying sizes of riparian zones paired with the similarly sized watershed allows for greater understanding of the role and importance of riparian zones in mountainous watersheds.

In addition to being a good landscape representation of a multitude of environments, TCEF is also highly instrumented and studied. Hydrologic instrumentation has been logging data for a period of 3-13 years. Measurements and instrumentation include:

- 1 meter resolution airborne laser swath mapping (ALSM) high resolution DEMs, and IKONOS remote sensory imagery
- More than 150 groundwater wells and piezometers along hillslope-riparian-stream transects
- Soil water content probe arrays (5 independent nests across varying landscape positions, thermocouples, and snow temperature ladders)
- 16 tension lysimeters for soil water sampling
- 6 recording snowmelt lysimeters
- 4 total precipitation catch gauges and more than 6 tipping bucket rain gauges situated at a range of aspects, elevations, and vegetation cover
- 7 flumes and associated conductivity and temperature probes
- 2 SNOTEL sites (1996 m and 2259 m)
- 2 H_20 and CO_2 eddy covariance towers with full energy budget instrumentation and profiles (one in the upland forest and one in an upland clear-cut area)

APPENDIX B

PREVIOUS INVESTIGATIONS AND ANALYSES AT TCEF

Landscape Analysis

Pacific et al (2010) and Jencso et al (2009, 2010) calculated upslope accumulated area (UAA) using ALSM (airborne laser swath mapping) from the National Center for Airborne Laser Mapping. They derived a 10 m digital elevation model (DEM) based on analysis methods developed by Seibert and McGlynn (2007). UAA, often times referred to as local contributing area, quantifies the area upslope that drains to a particular point. UAA contributing areas ranged from 0.06 to 4.61 ha for the studied transects. Transects were mapped with a Trimble survey grade GPS 5700 receiver that was accurate to within 1-5 cm.Thalwegs and 7 sub-catchment outlets were surveyed along with well locations and riparian zone extent. Riparian zone extent was corroborated with ALSM derived DEM analysis. Field determinations of the riparian:upland boundary were based on break in slope and changing soil characteristics (gleying, depth, texture, organic matter accumulation. This landscape analysis was used to determine differences between monitored transects and watersheds and use these differences as a way to differentiate hydrology and nutrient export.

Hydrometric Monitoring

Jencso et al (2009) used extensive groundwater level measurements at both riparian and upland well positions, recording groundwater level measurements in2 of 6 wells at each transect. Upland wells were located 1-5m above the break in slope while riparian wells were located near the toe-slope (streamside of the transition between upland and riparian zones).Wells were 3.8 cm (1.5 inch) diameter PVC pipe screened from the completion depth (bedrock) to the ground surface. Completion depths ranged from 0.5-1 m in uplands and 1-1.5 m in the riparian zone. Water level capacitance rods (TruTrack, Inc., ± 1mm resolution) recorded groundwater depth continuously every 60 minutes. These measurements were checked against hand measurements using an electric water level tape and provided high resolution data about subsurface water tables in monitored transects. HRS connection duration was determined by the number of days the groundwater table was present divided by the total snowmelt period.Pre-snowmelt, snowmelt, and recession to baseflow is included in the snowmelt period of April 15 to July 15.

Measurements were collected at the outlets of all of the sub-catchments within TCEF (MSC, LSC, UTC, LTC, BUB, SUN, SPC) in addition to the 22 transects installed in Stringer and Tenderfoot Creek watersheds above the catchment outlets. The transects represent both sides of the stream and have measuring equipment in riparian and upland zones, as shown in Figure 1.

Stream discharge at catchment outlets was measured at flumes to determine hydrologic outputs from the watersheds. Stage was recorded at 30 minute intervals with float potentiometers (installed and maintained by the USFS) as well as with capacitance rods at 60 minute intervals (TruTrack, Inc.).Snow water equivalent (SWE) measurements were taken hourly from National Resource Conservation Service snow survey telemetry stations (Snotel).The stations, Onion Park and Stringer Creek, are located in TCEF at 2,259 m elevation and 1,996 m elevation respectively. The higher station corresponds with the elevation of the headwaters of Stringer Creek and the lower Snotel station is the same elevation as the Tenderfoot Creek outlet.Snotel stations, along with rain gauges placed throughout the watershed, were used to quantify timing and amount of precipitation in the watersheds.

Riparian Turnover Modeling

Jencso et al (2010) distinguished hillslope, riparian shallow groundwater, and riparian saturation overland flow using specific conductance measurements. These specific conductance measurements were validated using major cation concentrations in stream, riparian, hillslope, and snowmelt grab samples. Using IC analysis, they found a strong linear relationship between specific conductance (SC) and Ca ($r^2 = 0.92$) and Mg ($r^2 = 0.89$) for the different spatial sources, which supports the use of specific conductance as a surrogate tracer for calcium and magnesium concentrations.

Modeling riparian groundwater turnover required a mixing model, specifically a continually stirred reactor model (Ramaswami, 2005)to estimate riparian turnover times from hillslope water table development and the subsequent HRS connectivity. A continually stirred reactor model refers to the assumption that the riparian zone is not stratified, has a homogenous concentration, has a defined volume, and volume imputed is accounted for by volume outputted. Jencso et al (2010) fit an exponential decay line of best fit to each transect’s riparian well decline in SC time series. The slopes of the regression lines are the turnover constant for that riparian zone. The turnover constant can also be thought of as how fast solutes in the riparian zone are turned over or mixed with more dilute hillslope inputs. By taking the inverse of the slope of these regressions, they calculated the turnover constant or the length of time, in days, the riparian zone took to be decreased to 37% of its initial value.

A more intuitive way to describe exponential decay is the half-life of the riparian zone, or the time it takes for 50% of the volume to be turned over. Riparian volumes being exported from a particular transect were also calculated using the connectivity duration and the turnover constant.

Nutrient Monitoring and Analysis

Pacific et al (2010) collected nutrient water samples in 250 ml HDPE bottles approximately every 3 days from the flumes during snowmelt. Before and after the snowmelt period weekly samples were taken. The water samples were filtered through a 0.45 µm filter into 30 ml amber HDPE bottles within 1-12 hours of collection, acidified to pH 1-2 with 6 M HCL and kept in a cooler during transport to Montana State University (MSU) where they were frozen at -20°C until they were analyzed.

They calculated cumulative stream export from the 7 sub-catchments of the TCEF for dissolved organic carbon (DOC), dissolved organic nitrogen (DON), ammonium (NH_4), and nitrate (NO_3).Daily stream concentrations of all nutrients were estimated with linear interpolation from field measurements. Cumulative export was calculated annually (April 15, 2007-April 15, 2008), and for two 91 day periods, snowmelt (April 15-July 15, 2007), and baseflow (July 15-September 13, 2007).Cumulative stream nutrient export for sub-catchments within Stringer Creek catchment was determined by subtracting the contribution of upstream catchments. Cumulative export was calculated to compare across watersheds and relate to landscape variables.

Landscape analysis, hydrometric monitoring, riparian turnover modeling, and nutrient monitoring were combined to develop a conceptual model for hydrology in headwater systems. Through understanding differing landscapes across watersheds and how that affected hydrologic connectivity, riparian turnover, and nutrient export, we could show that landscape position is a primary driver on hydrologic connectivity, riparian turnover and nutrient export and encourage its use in hydrologic models.