Seasonal and Event-based Hydrological Response in a Hillslope-Riparian Zone setting of the Temperate Beverly Swamp

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Wetland ecosystems are an integral part of the landscape, providing vital habitat for species at risk, while providing important services in hydrological and biogeochemical cycling. Since many of the habitats and biogeochemical processes depend on hydrology, it is important to first understand hydrological functioning of these systems. Past studies have largely focused on one or two variables such as topography or antecedent moisture conditions, but fail to assess the complex interconnected factors that produce hydrologic responses of wetlands. This thesis examines the combined influence of topography, seasonal variability in antecedent moisture conditions, and natural (climatic) and anthropogenic (upstream reservoir release) event responses along the hillslope-riparian zone continuum of a temperate deciduous swamp. Results demonstrate seasonality in hydrological processes within the hillslope-riparian zone continuum where, water table position rises in response to the spring snowmelt freshet, declines gradually through the summer and subsequently rises again as evapotranspiration decreases in the autumn. During this time, event hydrologic responses vary with event properties (intensity, duration, etc.) and antecedent moisture conditions. These responses vary spatially throughout the study site, both with riparian zone topography, and with distance from the Spencer Creek that receives inputs from the Valens Reservoir, upstream of the study site. Upland sites more actively respond to precipitation events in comparison to low lying topographic positions. Low-lying sites in the riparian zone in close proximity to Spencer Creek are more temporally variable than low-lying wetlands further away from the stream; however, wetland responses at the same sites to precipitation events are dampened during flooded conditions following dam releases from the upstream Valens reservoir. Hydraulic gradients across the sites are more spatially variable than they are temporally variable. However, sites located in the middle of the riparian zone-hillslope continuum (located at the break in slope) have highly variable vertical hydraulic gradients, much more so than those of upland or riparian sites, suggesting that they could be important sites for biogeochemical processes. This thesis combines the influence of physiological, climatic and watershed management variables within one wetland to further knowledge of hydrological response along the hillslope-riparian zone continuum.

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1.0 Introduction

Wetlands cover approximately 6% of global landmass (Reddy & DeLaune, 2008), 25% of which can be found in Canada (Ducks Unlimited Canada, 2014a). These areas were once thought of as wastelands (Mitsch & Gosselink, 2007), and as such, approximately 15% of Canadian wetlands have been degraded or destroyed since 1800, with up to 98% loss in urban centres (North American Wetlands Conservation Council (Canada), n.d.). Wetlands have since been recognized for their ecosystem values (Mitsch & Gosselink, 2007), however, they continue to be lost and degraded (Zedler & Kercher, 2005). As the term ‘wetland’ suggests, these areas have many hydrologic values, including moderating water levels and system response by maintaining or enhancing base flows, reducing peak flow, and increasing the lag times between peak input and peak flow (Taylor & Pierson, 1985). As a result of such unique hydrologic properties, wetlands have an important role in modifying water chemistry and the cycling of various nutrients, including: carbon, nitrogen, phosphorus, and sulphur (Burt & Pinay, 2005; Junk, et al., 2013; Mitsch & Gosselink, 2007; Reddy & DeLaune, 2008). Wetlands are also highly biodiverse, biologically productive, and ecologically important systems with one third of the 683 species at risk of flora and fauna in Canada, relying on wetland habitat for some or all of their life cycle (COSEWIC, 2014; Ducks Unlimited Canada, 2014b; Kennedy & Mayer, 2002). Since the unique hydrologic properties of wetlands drive many of their ecological values, understanding wetland hydrology can provide insight on how to implement best management principles to protect these systems.

Many studies on the hydrology of wetlands have focused on one or two variables, and fail to assess the complex interconnected factors that produce hydrologic responses of wetlands. In recent years, many studies have investigated wetland hydrology, some of which have largely been coupled with biogeochemical studies (e.g. Burt & Pinay, 2005; DeSimone, 2009). Researchers (e.g. Devito, et al., 2004; Jencso, et al., 2009; Jung, et al., 2004; Winter, 1999) have investigated the influence of topography on hydrologic hillslope connectivity, but of the studies comparing the influence of upland topography and geomorphology, many observe processes that are located in steep or mountainous terrain which may not be transferable to other landscape types (Jencso, et al., 2009). Of those studies located in non-mountainous terrain, many make comparisons between wetlands at separate study sites rather than within a wetland (e.g. Devito, et al., 1996; Frisbee, et al., 2007; Vidon & Hill, 2004). This introduces variables that could impact hydrologic response including the composition of the underlying substrate, and in the spatial and temporal variability in antecedent moisture conditions and input event properties such as precipitation intensity, duration, and total accumulation. As a result, these studies do not truly isolate topography as an influencing factor in hydrologic processes.

There have also been studies focused on the effect of antecedent moisture conditions; however, many of these focus solely on the response to precipitation events (e.g. Biron, et al., 1999; Frisbee, et al., 2007; James & Roulet, 2009), while few studies consider variability among multiple water input sources (e.g. snow melt, upstream source, or precipitation-derived) in combination with these antecedent conditions (e.g. Woo & Waylen, 1984). Of the many studies examining hydrological responses of wetlands and riparian zones, very few combine the driving forces of antecedent moisture conditions, topography, and type of hydrological input (e.g. precipitation or increase in upstream stream discharge) to the system. This thesis provides an integrated analysis of the combined effects of multiple factors (topography, antecedent moisture conditions and seasonality, and hydrological input management) on the hydrologic dynamics of a wetland, Beverly Swamp, in southern Ontario.

1.1 Problem statement and objectives

Studies of hydrologic system response rarely separate the influence of natural climatic and anthropogenic drivers. Although much research has been conducted on Beverly Swamp, prior studies at this site have failed to separate the hydrological responses to natural (i.e. precipitation) and artificial (i.e. stream regulation by an upstream dam) input events. There are additional questions that remain unanswered, including the effect of antecedent conditions on hydrologic responses. Of the studies investigating the hydrology along Spencer Creek, only DeSimone (2009) attempted to incorporate the influence topography may have on wetland hydrological processes. The purpose of this study is to provide insight in how the various factors interact to produce hydrologic responses and be relevant for hillslope-riparian zone systems.

The objective of this study is to investigate system responses to various input events over a topographical gradient within the same riparian zone, specifically how hydraulic gradients and water table position over a topographic gradient change seasonally and in response to an upstream reservoir drawdown and precipitation inputs across a range of antecedent moisture conditions.

The specific research objectives can be summarized as follows:

1. To characterize spatial patterns in water table position and hydrologic gradients across a hillslope-riparian zone continuum, and determine if and how these change both seasonally and in response to hydrologic (event-based) inputs;

2. To determine if and how spatiotemporal patterns in water table position and hydraulic gradients differ across a riparian zone with variable hillslope topographic gradients; and
3. To determine if and how these spatiotemporal patterns differ when the input events are caused by climatic (i.e. precipitation) or upstream surface water management (i.e. reservoir drawdown) drivers.

2.0 Literature review

Wetlands are a specialized interface between aquatic and terrestrial systems often with poorly drained soils (Reddy & DeLaune, 2008). The Ontario Ministry of Natural Resources (OMNR) (2013) has developed the Ontario Wetland Evaluation System which defines wetlands as lands that are either seasonally or permanently inundated with surface water or where the water table is near the surface sufficiently to enable development of hydric soils dominantly supporting water tolerant vegetation.

Within this broad definition of wetlands, there are multiple types of wetlands, dominantly marshes (periodically or permanently inundated lands dominated by herbaceous floating and emergent vegetation, with little woody vegetation), swamps (often inundated through the spring, drying through the growing season and dominated by tall woody vegetation), bogs (peatlands dependent on atmospherically-sourced water inputs, dominated by *Sphagnum* mosses, sparse tree canopy and low plant biodiversity, often with low pH), and fens (peatlands, often groundwater-fed, dominated by sedge and moss vegetation with sparse tree canopy, with higher biodiversity and pH than a bog) (OMNR, 2013). Additionally, wetlands can be characterized as coastal (direct hydrologic connection to a large surface body of water, i.e. any of the Great Lakes or connecting waterways), lacustrine (direct hydrologic connection to a lake), riparian (direct hydrologic connection to a stream or river, including the floodplain), palustrine (intermittent or no surface inflow with permanent or intermittent surface outflow, often in headwaters) or isolated (no surface water outflow) (OMNR, 2013). With these various hydrologic, soil and biologic properties, an interdisciplinary approach is often required in order to understand wetland dynamics. The focus of this study is a riparian zone at the interface between agricultural fields (corn/soybean/cereal crops) and the Beverly Swamp, a deciduous wetland.

2.1 Basic hydrologic processes

New water is introduced to a system through precipitation which can fall directly on surface water or be intercepted by the local vegetation where it either evaporates or continues to the ground surface via throughfall or stemflow (Hendriks, 2010). This water then infiltrates to become soil water and groundwater within the saturated zone (Hendriks, 2010). This water then moves through the soil structure as groundwater flow. When this water cannot infiltrate due to surface saturation or when the rate of precipitation exceeds the rate of infiltration, overland flow is triggered (Hendriks, 2010). A hydrograph is a plot of water table position or discharge with time (e.g. bottom of Figure 2.2, 2.3), often in response to precipitation or other input events (Dingman, 2002). There are three stages to the hydrograph of hydrologic responses: the rising limb (an increase in water table position or discharge over pre-event levels), peak (maximum water table position or discharge), and falling or receding limb(a gradual decrease in water table position or discharge as water is released, returning to pre-event conditions). There is often a delay between the onset and peak of precipitation and response observed in the hydrograph, known as lag.

2.2 Hydrological role of wetlands

Wetlands are areas of water storage, either within the soil matrix, or within hollows, depressions in the soil surface (Acreman & Holden, 2013). These systems are associated with a variety of hydrological functions and services which are not linearly correlated to wetland type (Bullock & Acreman, 2003). Wetlands can be hydrologically connected to either groundwater or surface water resources, or a combination of both resources. Groundwater discharge or recharge can be a dominant hydrologic function of a wetland, however, it is possible that both regimes can be found within the same wetland, varying both spatially and temporally with hydrologic conditions and water table positioning (Brooks, 2005; Bullock & Acreman, 2003). Additional wetland functions include modifying the timing, magnitude and duration of discharge in response to input events such as precipitation and the spring freshet (Acreman & Holden, 2013). In Bullock and Acreman's (2003) review of 169 wetland studies since 1930, they found that the vast majority of studies concluded that wetlands exert significant influence on the hydrologic cycle by either increasing or decreasing event response hydrographs. Only 20% of studies reported that wetlands augment surface flows during drought conditions (Bullock & Acreman, 2003). The extent to which wetlands moderate flows and whether the wetland contributes to or attenuates the flood event is dependent on landscape positioning and hydrologic properties (Acreman & Holden, 2013).

Wetlands associated with low-order streams in headwater areas generally have low storage capacity, and therefore are generally considered to enhance floodwaters, whereas wetlands associated with higher order streams and rivers, e.g. floodplains and riparian zones, generally reduce flood events (Bullock & Acreman, 2003). In watersheds where wetlands generate flow during wet periods, and reduce flow during drier periods, wider ranges between high and low flow conditions have been observed (Bullock & Acreman, 2003). The influence of hydrologically isolated wetlands is generally restricted to their immediate surroundings; however, they may contribute runoff during periods of excessive hydrologic inputs, such as during spring snowmelt and extreme precipitation events, when storage capacity is exceeded (Brooks, 2005). The high water content of wetland soils and surface water that is often shallow when present during wet periods lead to a greater evaporative flux than surrounding terrestrial landscapes (Bullock & Acreman, 2003).

2.2.1 Hydrology of riparian zones

Riparian zones are the interface between aquatic and terrestrial ecosystems, particularly those along rivers and streams, encompassing the floodplain. While these areas may not compose a large fraction of the overall landscape, they are important for flood mitigation, and reduction of nutrient and contaminant flow from upland areas to groundwater and surface water reservoirs (Junk, et al., 2013).

Riparian zones in a headwaters position have smaller contributing areas with less hydrologic flux and greater variability in water table position between seasons (Vidon & Hill, 2004). These areas that are often the source of groundwater discharge are more likely to initiate flooding conditions as this is often the site of local groundwater discharge to feed a stream. By contrast, the riparian zones of higher order streams or those connected to regional groundwater systems are more dependent on this connectivity and therefore have less variable antecedent conditions than those which are intermittently disconnected between seasons (Jung, et al., 2004; Montreuil, et al., 2011; Todd, et al., 2006); however, there can be a wider range between high and low flow conditions (Montreuil, et al., 2011). Riparian zones that are found adjacent to higher order channels have a greater capacity to reduce peak water levels, slow flood progression, delay flood peak timing and even reduce flood volumes (Acreman & Holden, 2013; Junk, et al., 2013).

During a flood event where stream stage rises and discharges into the riparian zone soils, a groundwater ridge forms, reducing and in some cases preventing groundwater originating in the adjacent upland areas from flowing towards the stream (Jung, et al., 2004). This ridge dissipates as stream stage decreases, groundwater discharge towards the stream resumes (Jung, et al., 2004). This process is also known as bank storage (Pinder & Sauer, 1971). During extreme high water, channel bank capacity is exceeded and flood waters spread through the riparian zone as surface flow. This flow has a much larger wetted area than a large deep channel might, thus slowing the velocity of the flood waters, and reducing peak discharge of the event (Acreman & Holden, 2013; Woo & Valverde, 1981). Regular periods of inundation are of critical importance in for supplying nutrients and organic matter to the soils, thereby providing habitat for local flora and fauna, and periodically resetting vegetational succession (Carpenter, et al., 1992). This slower moving water that is relatively shallow enables a greater surface area for evaporative loss and a greater wetted area which can lead to soil infiltration, if underlain by permeable sediments (Acreman & Holden, 2013). Additionally, the presence of surface water on the riparian zone can enable contaminants to bypass the riparian zone from upland areas as overland flow without interacting with the soils that would otherwise remove contaminants (Burt, 2001).

2.3 Factors controlling riparian zone hydrologic response

There are many factors that, together, control the rapidity, magnitude, and duration of response to hydrological inputs. Physical attributes of riparian zones and their adjacent uplands such as topography, geomorphology, and vegetation communities determine the range of possible responses to any given event (Devito, et al., 1996; Jencso, et al., 2009). The characteristics of the input event, such as intensity, magnitude, and duration, combined with the riparian zone's hydrological state including relative water level and antecedent conditions will determine the actual response triggered for the event (Acreman & Holden, 2013; Décamps, 1993). Anthropogenic disturbances further complicate event responses within managed systems.

2.3.1 Physical attributes of a riparian zone

The physical attributes of a riparian zone are important factors in determining how a system may respond to hydrological inputs. These attributes such as topography, geomorphology and vegetation cover generally do not change rapidly (vegetation changes seasonally) (Jung, et al., 2004) unless there is a large-scale disturbance such as fire, which can reset vegetation succession and create hydrophobic soils which inhibit infiltration (Brady & Weil, 2010). Surficial geology and soil structure influence the infiltration capacity and saturated hydrologic conductivity of the soil matrix, and the presence of macropores, enhances groundwater flow (Hendriks, 2010). Such attributes determine hydrological connectivity including surface and subsurface preferential flow paths, and reproduce similar event response patterns (Jung, et al., 2004).

Surficial topography has long been believed to be an important driver in both surface and groundwater movement (Winter, 1999), with that of both the adjacent hillslope and the riparian zone influencing local hydrology , particularly in areas with hillslope gradient greater than 5%, resulting in down slope flow (Vidon & Hill, 2004). Upslope hill shape influences riparian zone water table depth in that concave profiles lead to greater surface and subsurface mixing and convex profiles lead to deeper water tables (Devito, et al., 2000; Vidon & Hill, 2004). Upland slope length may also exert influence on hillslope discharge to riparian zones (Vidon & Hill, 2004). Additionally, the topography within a riparian zone relates to the degree of hydrologic connectivity between surface flows and local groundwater, with flat riparian zones having a strong relationship between stream stage and groundwater elevation and a negligible relationship where streams are adjacent to the hillslope (Burt, et al., 2002b).

Recent studies have indicated however, that subsurface topography and stratigraphy, the spatial distribution of underlying sediments, in both upland and lowland areas is a more dominant driver of hydrologic flow than surficial topography (Ali, et al., 2011). Groundwater flow paths are altered at the interface between sediments with varying hydraulic conductivities (Hendriks, 2010), complicating hydrologic processes in heterogenic soils. Hydrologic connectivity in riparian zones is highly dependent on geomorphic controls such as topography and depth of permeable soils, both upland from, and within the riparian zone (Vidon & Hill, 2004). In a comparison study of eight sites in southern Ontario, Vidon and Hill (2004) found there to be a threshold depth of upland permeable sediments of approximately 2 m, where depths less than 2 m resulted in intermittent hydrologic connectivity between the riparian zone and adjacent upland areas, while depths greater than 2m resulted in permanent connectivity. Devito, et al. (1996) found a similar connectivity threshold of 2-3 m of permeable sediment overlying the bedrock of the Canadian Shield.

Many wetlands are underlain by a layer with very low permeability which inhibits soil drainage thus initiating wetland formation. In riparian zones with shallow confining layers, there is less storage capacity than in a riparian zone with a deeper confining layer. The depth of a confining layer within a riparian zone will influence its storage capacity, which in turn determines how the system will respond to hydrologic inputs (Vidon & Hill, 2004). One of the sites studied by Vidon and Hill (2004) was found to be anomalous, as there was intermittent hydrologic connectivity between the hillslope and riparian zone due to a shallow confining layer, but the steep topography and highly permeable soil structure resulted in hydrologic response comparable to sites that were hydrologically connected to larger aquifers.. Heterogeneous layers within the riparian zone can cause areas of preferential flow (e.g. through gravel or sand) and restrict groundwater flow in areas with low hydraulic conductivity (Vidon & Hill, 2004).

Landscape position is another factor controlling the way in which a stream and riparian zone will respond to hydrologic inputs. This position determines the degree of hydrologic connectivity between a riparian zone and local surface water and local or regional groundwater. Strong connections, characteristic of larger contributing areas, maintain high water levels in the riparian zone, restricting the depth to which the water table may fluctuate during dry conditions (Vidon & Hill, 2004). This connectivity is often correlated to channel morphology, with unconfined streams (systems with shallow channels where small hydrologic contributions often exceed bankfull capacity) generally being found near the headwaters of low order streams, with increasing channelization in a downstream progression towards higher-order streams and rivers. Unconfined channel flow enables greater interaction with a well-developed riparian zone (Warren, et al., 2001). In highly channelized stream systems, there is less frequent inundation of the riparian zone, and therefore greater fluctuations in riparian zone water table elevations, compared to those of an unconfined stream (Warren, et al., 2001). Figure 2.1 illustrates the differences in the range of water table position between a confined and an unconfined stream in close proximity to one another.

Vegetation type influences the roughness of a riparian zone, which impacts its effectiveness in slowing floodwaters and therefore reducing peak discharge during a flood event (Thomas & Nisbet, 2007). Reducing the velocity of floodwaters reduces their carrying capacity, depositing nutrient-rich sediments within the riparian zone. Larger and robust vegetation such as trees have a greater effect on reducing flooding through resistance to surface flows than an area

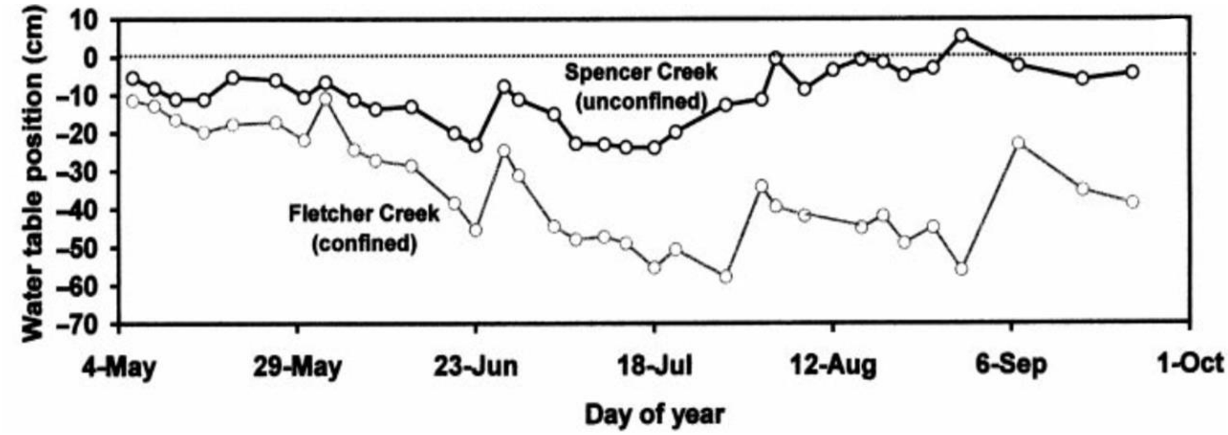

Figure 2.1: Comparison of mean riparian zone water table position in nearby confined and unconfined creeks (Source: Warren, et al., 2001)

of herbaceous vegetation, such as grasses. As mature trees die and fall to the forest floor, they continue to restrict the movement of surface water through the riparian zone (Thomas & Nisbet, 2007). Decomposing trees contribute to the formation of hummocks and hollows which provide surface storage to retain floodwater (Acreman & Holden, 2013; Junk, et al., 2013). In a modelling study of a 100-year flood on the River Cary, UK with discharge rates of 15.2 m^3/s in a 16 m wide and 2 m deep channel with a potential flooded width of 400 m, Thomas and Nisbet (2007) found that if 133 ha of riparian zone, comprising less than 2% of a catchment area was reforested, the presence of trees, understory vegetation and associated debris could increase storage capacity by 71% while delaying downstream flood peak arrival by 140 minutes.

2.3.2 Event input characteristics

Event input characteristics, such as event magnitude, duration and intensity, narrow the range of possible responses for any given wetland or riparian system. While considering overall event magnitude or duration are important factors, it is their combined measure of intensity that appears to have a greater influence on observed hydrologic responses. The magnitude of response has been correlated to precipitation intensity (Heliotis & DeWitt, 1987) where high intensity events can trigger responses expected of lower intensity, higher magnitude events

(Waddington, et al., 1993). Similarly, precipitation events with the greatest intensity result in the greatest hourly discharge rates (Inamdar, et al., 2006).

There are multiple types of hydrologic input events that can trigger responses. Often, precipitation is assumed to be the source of "new" water to a system. While this may often be the case, other events such as those that occur upstream (e.g. dam release or failure or upstream precipitation that increases river discharge) should also be considered, and may not exhibit the same response as on-site precipitation events (Bates, et al., 2000; Vidon, 2012).

2.3.3 Seasonal variations in hydrologic conditions

Long-term, annually repetitive trends in hydroclimatic conditions are often responding to seasonality. There are three main types of hydrologic seasonality: precipitation uniformly distributed through the year; peak precipitation coinciding with maximum solar radiation (i.e. "summer"); and peak precipitation coinciding with minimum solar radiation (i.e. "winter") (Anderson & Strahler, 2008). The variation between maximum and minimum monthly precipitation accumulation can range from minimal, when precipitation is evenly distributed, to extreme, where the wet season can receive up to 600 mm or more of precipitation per month in excess of monthly precipitation during the dry season (e.g. in areas experiencing monsoons) (Anderson & Strahler, 2008). The timing of such seasonal variability may or may not coincide with astronomical seasons, and may vary from year to year; therefore, discussion relating to seasonality here refers to trending hydroclimatic conditions.

Snow accumulation and the timing of snowmelt are additional elements that are highly influential on the hydrologic cycle of Ontario (Macrae, et al., 2010). Stream discharges tend to be low through the winter, when much of the precipitation is stored as snow and ice on the landscape (Ashmore & Church, 2001; Huntington, et al., 2009), with regular periods of snowmelt contributing to a slightly augmented baseflow (Burn, et al., 2008). Peak annual flows occur during the snowmelt freshet, potentially contributing more than half of a catchment's annual outflow within a short period of time (McDonnell & Taylor, 1987; Russo, et al., 2012; Todd, et al., 2006). This is followed by decreases in discharge as evapotranspiration exceeds precipitation through the growing season, with the lowest discharge rates occurring in the late summer or early autumn (Ashmore & Church, 2001; Burn, et al., 2008; Huntington, et al., 2009). Finally, there is a secondary increase in discharge corresponding to an increase in precipitation and decrease in evapotranspiration rates through cooler temperatures and vegetation senescence, characteristic of the autumn (Ashmore & Church, 2001; Huntington, et al., 2009).

The range between the annual maximum and minimum water table position and whether mean annual conditions are wetter or drier than the 30-year mean climate is also variable. In southern Ontario, winter 2012, for example, brought lower September to March snow accumulations than normal, with some parts of the region receiving only one third of normal snowfall (snow accumulation at Pearson International Airport was 40.4 cm, compared to the long-term mean of 109.7 cm) (Environment Canada, 2012). This led to a reduction in water stored in the snowpack available to be released during the freshet. Compounding the hydrological effects of this lack of moisture were province-wide record high temperatures (March mean temperature for Hamilton was 6.7 ºC, 7 ºC warmer than the monthly mean of -0.3 ºC)(Environment Canada, 2012), enabling an earlier, and smaller than normal freshet, that would lead to early initiation of the drying period through the growing season. Unless wetter than normal conditions were to follow, it is likely that a drier than normal trend such as that of 2012 would extend through the growing season. A study comparing an abnormally wet year with the following year's abnormally dry conditions several kilometers downstream of the site used in this study indicated that outflows can vary greatly from 200 per cent above to approximately 40 percent below 30-year mean discharge values within the timespan of one year (Kaufman, et al., 2005). Moderate interannual seasonal changes in conditions can result in considerable alterations of flow responses (Biron, et al., 1999).

While it is acknowledged that the freshet is an important factor setting up conditions for the remainder of the hydrological year, the research presented in this thesis was not designed to include the hydrological response of riparian zones during snowmelt; literature pertaining to riparian zone responses during these conditions has therefore not been further reviewed.

2.3.4 Antecedent moisture conditions

Antecedent moisture conditions define the hydrologic state of a system prior to an input event, influence water delivery mechanisms including source water origin and flowpaths (James & Roulet, 2007). Studies have shown that there is a non-linear hydrological response to input events along a moisture gradient, and that antecedent moisture conditions may have a more significant role in determining hydrologic response than other factors, including physical attributes and event characteristics (e.g. Biron, et al., 1999; James & Roulet, 2007; James & Roulet, 2009; Jung, et al., 2004; Kaufman, 2002; Macrae, et al., 2010; Montgomery & Dietrich, 1995; Tramblay, et al., 2010). In heterogeneous landscapes with areas of greater and lesser storage capacity, a 'fill and spill hypothesis' has been derived, where during precipitation events, the upslope storage capacity threshold must be met before a downslope hydrological connection will be made, thus spilling (Tromp-van Meerveld & McDonnell, 2006).

In order for a hydrologic event to trigger a flashy response the water table must be close enough to the ground surface such that it can quickly respond to the inputs (Frisbee, et al., 2007). During periods of high flows and wet antecedent conditions, elevated water table position reduces the capacity of riparian zones to retain moisture within the soil structure (Montgomery & Dietrich, 1995). This reduced storage availability, will trigger rapid response in both surface and subsurface flow (Biron, et al., 1999; Devito, et al., 1996; Heliotis & DeWitt, 1987; Jung, et al., 2004; Montgomery & Dietrich, 1995; Taylor & Pierson, 1985; Woo & diCenzo, 1988). The resulting increased occurrence of overland flow reduces interactions between the soils and water passing through the area, thereby increasing peak flow and decreasing the chemical buffering through reduced soil interactions within the riparian zone (Acreman & Holden, 2013; Décamps, 1993; Macrae, et al., 2010; Montgomery & Dietrich, 1995).

During periods of drier antecedent conditions, low water table position contributes to increased storage capacity available within the system, resulting in a limited hydrologic response including decreased response times (Martin, 2011) and reduced runoff from system inputs (Kaufman, et al., 2005; Macrae, et al., 2010; Montgomery & Dietrich, 1995; Shanley, et al., 2002). Event water moving through the soil matrix flows slower than surface water, and therefore it enters storage, displacing pre-event water, to later be released during a drier period (Burt, 2001; Burt & Pinay, 2005) d. In riparian zones that are not responsive to hydrologic inputs as a result of dry antecedent moisture conditions, chemical composition of discharge will be indicative of comparatively little “new” event water (Frisbee, et al., 2007).

In a direct comparison among storms with similar properties during both wet and dry antecedent moisture conditions, it was found that both the volume of runoff and the ratio of total event discharge to throughfall (runoff ratio) could be as much as two orders of magnitude greater

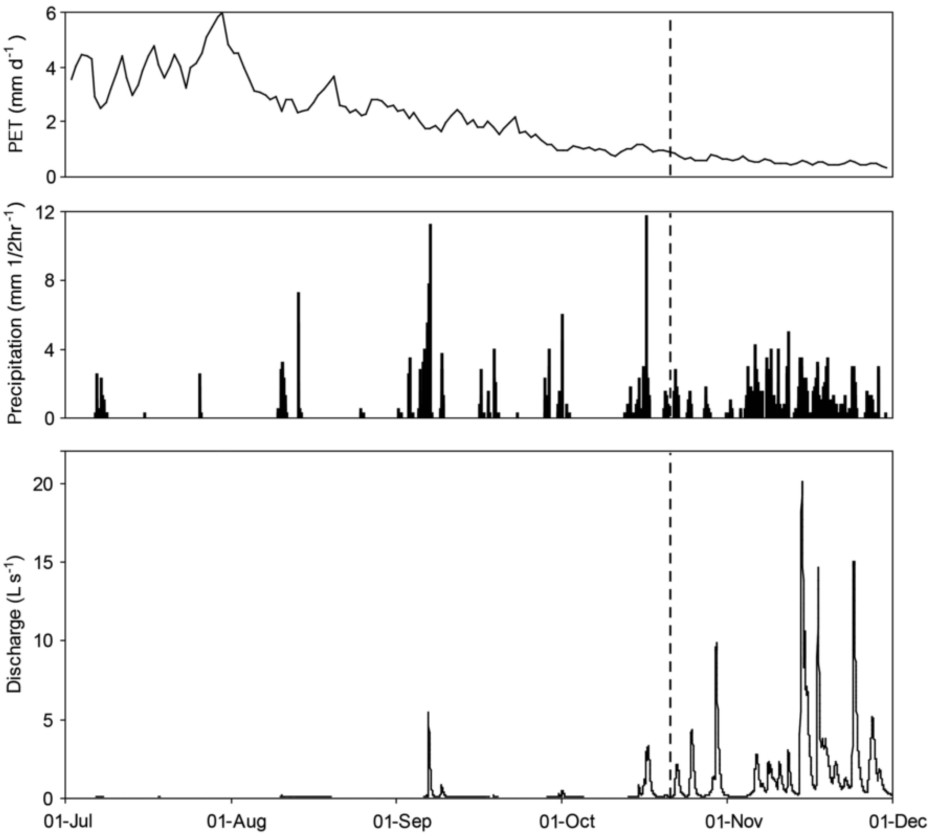

Figure 2.2: Potential evapotranspiration (top), precipitation (middle), and discharge (bottom) of a forested swamp in British Columbia, comparing event response during a range of antecedent moisture conditions. Progression from dry conditions to wet conditions on October 21 is indicated by the dashed line (Source: Martin, 2011)

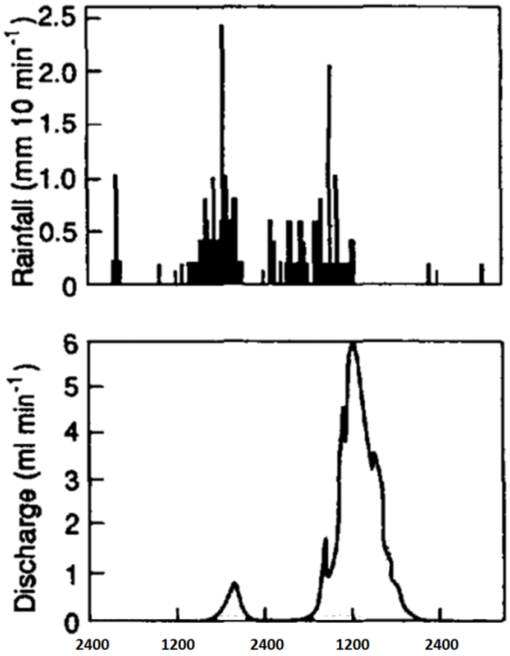

Figure 2.3: Successive precipitation events over two days in November 1987 with increasing discharge rates. Modified from McDonnell, et al. (1991)

during the wet conditions (Martin, 2011). Successive precipitation events generally increase runoff ratios, regardless of antecedent conditions, as a result of increasingly wet conditions. The periods with the greatest discharge directly related to precipitation events with overlapping hydrographs with multiple peaks as a result of close temporal proximity to one another (Kaufman, 2002; Macrae, et al., 2010; Martin, 2011; Montgomery & Dietrich, 1995). Figure 2.2 illustrates both the variable response to high and low intensity precipitation with varying antecedent moisture conditions, and the multiple peaks related to individual events in the overlapping hydrograph of events through November. Figure 2.3 illustrates similar findings with high-resolution data outlining a smaller initial discharge increase followed by a non-proportionate increase in discharge in response to additional precipitation over a 72 hour period.

2.3.5 Watershed management techniques

The regular occurrence of flood pulses in floodplains and riparian zones enables the deposition of nutrient-rich sediments in the floodplain (Junk, et al., 1989). Over 77% of streamflow has been artificially regulated in Europe, the former Soviet Union, and North America, excluding Mexico (Dynesius & Nilsson, 1994) by controlling when water enters and leaves upstream floodplains to protect downstream areas, through constructing levees to prevent flood waters from reaching human developments built on riparian zones and constructing dams and reservoirs to regulate stream flow (Acreman & Holden, 2013). Dams are often constructed for a variety of reasons including flood reduction for downstream areas (Russo, et al., 2012). All dams reduce surface water discharge within a river or stream, modulating hydrographs (Brandt, 2000). In order to have the capacity to capture and retain the spring runoff events, the water level in the reservoirs behind these dams must be lowered in the autumn, potentially creating an excessive flood of greater magnitude than what would otherwise be present at this time of year.

Artificially managed systems can also cause elevated water tables than would naturally be found, especially during drought conditions (Warren, et al., 2001), thus the presence of a dam regulating flow can play a considerable role in determining downstream antecedent hydrologic conditions (Leach, 2009).

Modified hydrologic regime of a watershed trigger additional changes and feedbacks through the entire system. Flood mitigation efforts to reduce the magnitude and frequency of peak discharge reduce sediment and nutrient deposition and threaten wetland equilibrium (Zedler & Kercher, 2005). Control structures have been built along the Mississippi River, preventing floodwaters from entering the floodplain. Wetland subsidence resulting from the lack of sediment deposition has been recorded in the Mississippi Delta (Mitsch & Gosselink, 2007; Zedler & Kercher, 2005), enhancing vulnerability to sea-level rise. The effects of reduced annual peak discharge and flooding of the Peace-Athabasca Delta has resulted in a loss of surface ponding and a dramatic shift from herbaceous to woody vegetation in a relatively short period of time (Keddy, 2010). Reduced variability in water level fluctuations will reduce plant biodiversity and habitat for many species (Keddy, 2010). In watersheds where wetlands and riparian zones have been removed, there is a greater occurrence of flood events (Mitsch & Gosselink, 2007). These various modifications complicate system response to hydrological input events.

2.4 Responses to hydrologic inputs

The factors mentioned through section 2.3 generally control the magnitude and timing of event response. Antecedent moisture conditions strongly influence event response, particularly during the onset and rising limb of the hydrograph (Jung, et al., 2004). Riparian zones and other wetlands that are strongly linked to deep groundwater or surface water sources have less variable antecedent conditions and therefore less variability in hydrologic responses (Vidon & Hill, 2004). Event response in riparian zones have been characterised to have a rapid rising limb, followed by an extended receding limb (Woo & Valverde, 1981). This is indicative of storage of event water that is re-released post-event. Provided that the riparian zone becomes saturated during the event, the characteristics of the post-event water table decline are similar between events regardless of input characteristics (Jung, et al., 2004).

Generally, there are three processes that will trigger hydrologic response in riparian zones. These are: soil infiltration, increasing discharge from upslope, or rising stream stage that increases riparian zone water table (Jung, et al., 2004). The dominant source of event water will determine how the riparian zone may respond. Subsurface stormflow response is often a combination of macropore and matrix flow mechanisms when soils are permeable, deep and have relatively high pre-event soil moisture content (Burt & Pinay, 2005). In soils with low storage capacity due to high antecedent moisture conditions, low permeability, or low topographic relief stormflow can be dominated by overland flow (Burt & Pinay, 2005). Precipitation events that occur onsite will generally trigger more rapid response in the hillslope area, while increases in stream discharge from upstream sources will result in more rapid response nearest the stream (Vidon, 2012). Many studies do not isolate and compare hydrologic riparian responses from upslope and upstream sources.

Any given riparian zone has a dominant direction of groundwater flow, either discharging (flowing towards a stream) or recharging (receiving flow from a stream). During extreme flood or drought periods, reversals of the dominant process and direction of flow can be observed (Bates, et al., 2000; Kaufman, et al., 2005; Russo, et al., 2012; Warren, et al., 2001). It has long been recognized that hyporheic zones are a source of “leakage,” particularly during flood events, effectively reducing the peak flow, and extending flood duration (Pinder & Sauer, 1971) as water is stored and then re-released to the stream during the event's falling limb. This bank storage process reduces the magnitude of the flood wave with distance from the source (i.e. dam) (Macrae, et al., 2011). In a modelling study coupled with field observations, Bates et al. (2000) and Burt, et al. (2002a) found that dominant peak flow processes involve flow perpendicularly from the stream; however, during both the rising and falling limbs a down-gradient flow direction becomes evident. These findings are supported by Vidon (2012), who observed partial groundwater flow reversal from hillslope-to-stream to become converging hillslope and stream-to-riparian zone which then flowed down valley.

As a flood wave propagates downstream, flow velocity rapidly increases (Pinder & Sauer, 1971) and discharge to the streambed and riparian zone increases (Russo, et al., 2012). As stream stage increases above the riparian zone water table, a kinematic wave pushes 'old' water through the riparian zone, increasing the water table position and preventing hillslope water from discharging into the riparian zone (Burt, Bates, et al., 2002; Bates, et al., 2000; Jung, et al., 2004; Vidon, 2012). Many studies have found chemical signatures indicating that older groundwater and new event water mix before discharging from the system (Roulet, 1991; Shanley, et al., 2002; Waddington, et al., 1993). This is further supported by Vidon and Smith (2007) who found that the chemical composition of water in the riparian zone more closely resembles the signatures of hillslope groundwater than those of surface water or precipitation.

Once water levels exceed bankfull capacity, spillover initiates surface water infiltration into the unsaturated riparian zone (Russo, et al., 2012). Rising water table and infiltrating surface water combine to saturate the riparian zone from both above and below. Many streams have effluent characteristics which are effectively reversed, though temporarily, through these processes. Post-flood, this reverses to resume the pre-event flow patterns, elongating the event hydrograph with upstream areas discharging stored water to the stream, while downstream areas may still be influenced by the flooding regime (Jung, et al., 2004; Russo, et al., 2012).

Figure 2.4 demonstrates groundwater flow reversals resulting from an upstream dam release event. Pre-flood groundwater potential (Figure 2.4a) indicates discharge to the stream, which reverses to recharge during the flood event (Figure 2.4b and c) before returning to pre-event gradients (Figure 2.4d), even though the post-flood water tables remain higher than those of pre-event (Russo, et al., 2012).

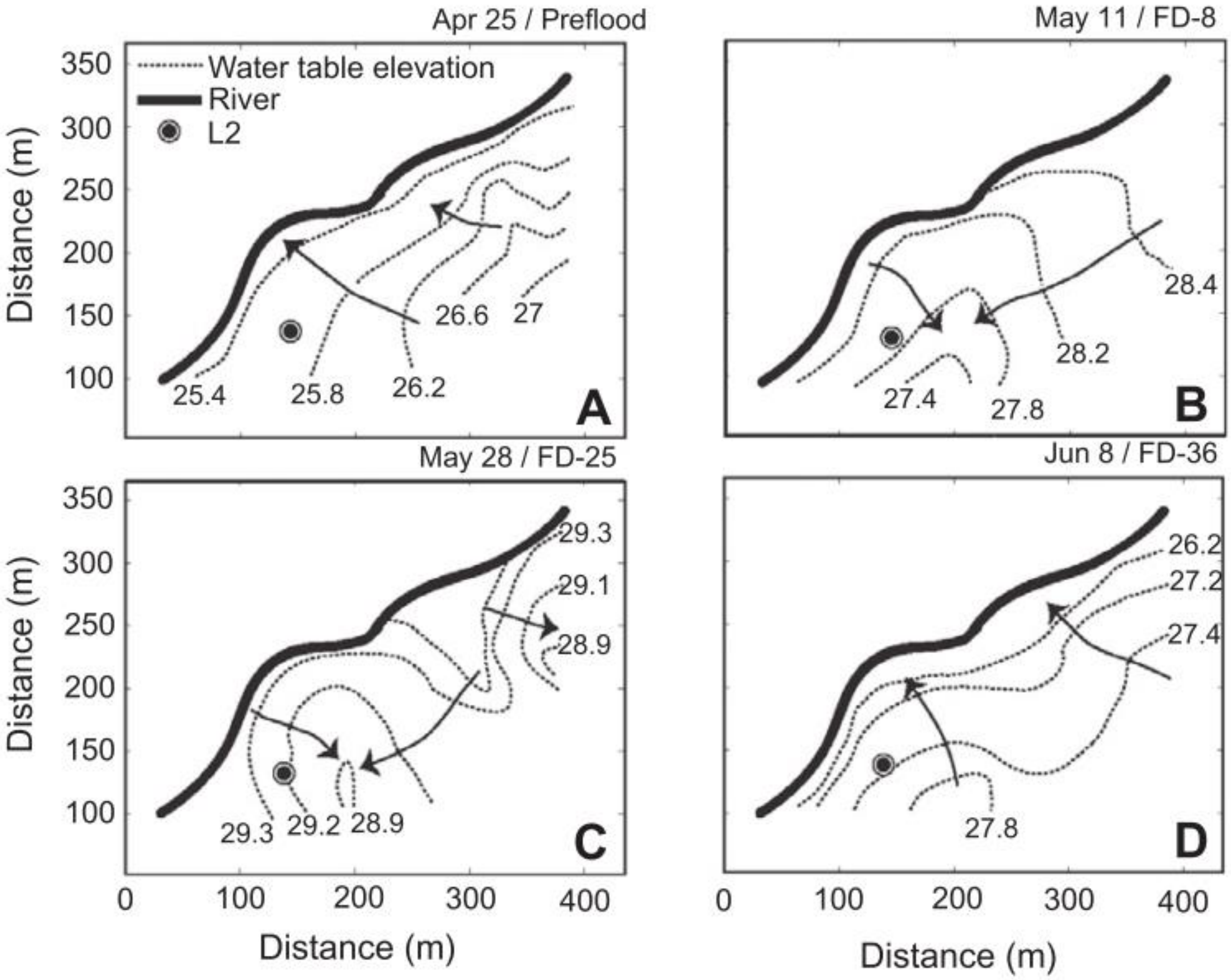

Figure 2.4: Flow reversal in the riparian zone of the Tuolumne River, California, associated with a release event from the O'Shaughnessy Dam. Contours represent groundwater potential in relative elevation (m). A-D indicate the order in which groundwater potential was measured (Source: Russo, et al., 2012)

2.5 Hydrologic conditions of the study site: Beverly Swamp

This research project is focused on the hydrological response of a temperate wetland in southern Ontario, Beverly Swamp. This site has been investigated in the past through several studies pertaining to various aspects of the system. This section summarizes what is currently known about the hydrological dynamics of Beverly Swamp.

2.5.1 Physical conditions in Beverly Swamp affecting hydrology

At 2 400 hectares, Beverly Swamp is the largest relatively intact wetland in southern Ontario (Hamilton Conservation Authority, 2012a; Kaufman, 2002), and is drained by three separate watersheds; Fairchild Creek in the west, Spencer Creek in the centre, and Bronte Creek in the east (Hamilton Conservation Authority, 2012a). Previous studies have focused on Spencer Creek and its tributary, Fletcher Creek, see Figure 2.5 (e.g. DeSimone, 2009; Kaufman, 2002; Leach, 2009; Smith and Woo, 1986; Warren, et al., 2001; Woo and Valverde, 1981; Young, 2001; Zhang, 2007). Such studies have shown that the hydrology of Spencer Creek is complex as a result of the combination of natural features and watershed management.

Beverly Swamp is surrounded by agricultural lands and has been bisected by linear features including roads, a power line transmission corridor (Figure 2.5), and a gas pipeline (not shown). There has been minimal research into the effects of such disturbances on the swamp; however, it is believed that there were localized, short-term hydrologic impacts on Spencer Creek and adjacent swamp, resulting from the construction of the transmission line towers in 1975 and 1976 (Fenton & Welch, 1982; Woo, 1979a; Woo, 1979b). While there have been no subsequent studies to specifically investigate recovery of hydrological processes at these sites, Kaufman (2002) suggests that dense root structures from vegetation regrowth within the transmission line corridor and decomposition of the corduroy road used during construction have affected relative water table position on either side of the corridor. There are no publicly available studies on the impact of the pipeline through Beverly Swamp.

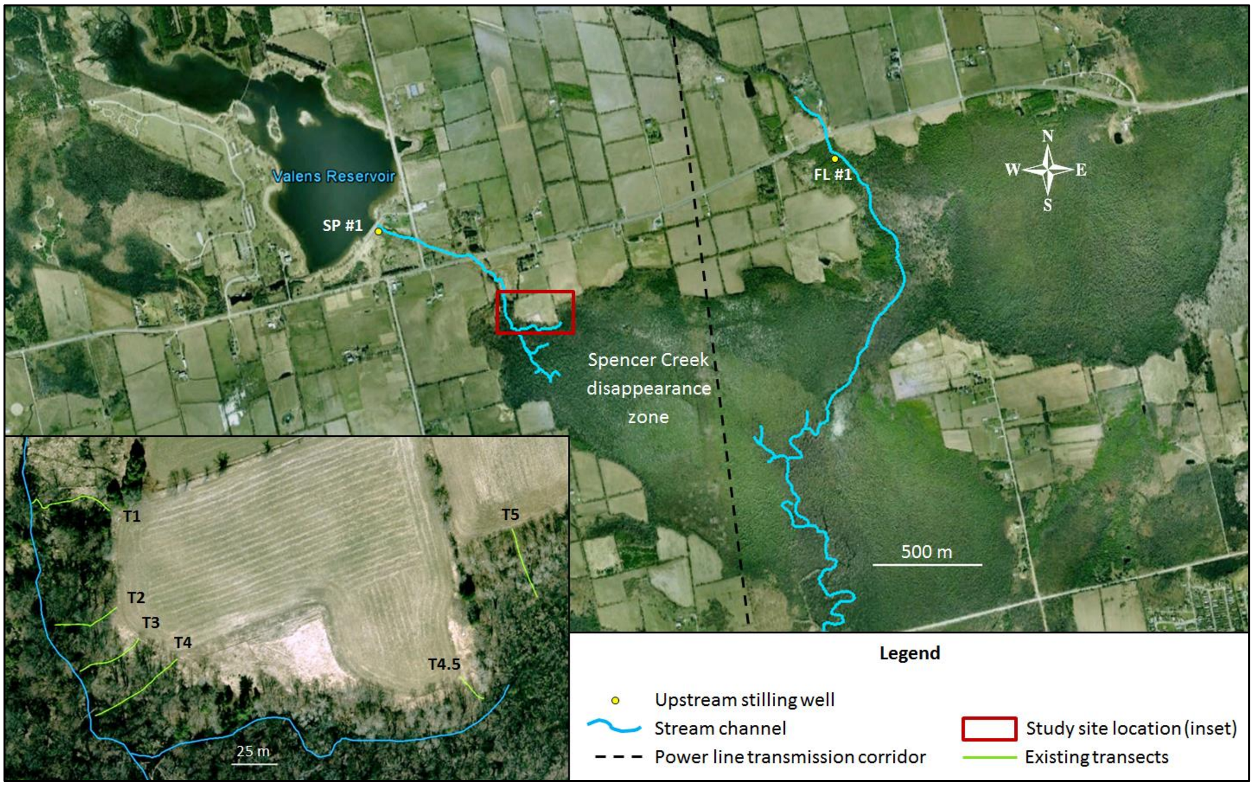

Figure 2.5: Map of Beverly Swamp encompassing the disappearing Spencer Creek (from the Northwest) and highly channelized Fletcher Creek (from the Northeast), with inset of existing transect placement (Google Earth, 2004).

A series of borehole samples collected from the power line corridor right-of-way indicate that the soils of Beverly Swamp are predominantly peat, which at a depth of 1-2 m is underlain by marl, a 0.5 m to 1 m thick confining layer with underlying non-uniform layers of sands, silts, clays and gravels, to a depth of approximately 15 m over dolomite bedrock (Woo, 1979b). The layer of marl maintains an elevated water table through the year, although during extreme dry conditions, the water table may fall below this layer (Woo, 1979b). Additional investigations into the riparian zone soil in proximity to the current study (see Figure 3.2) site have found heterogeneous soils, consistently finding a range of saturated hydrologic conductivity representative of a mixture of poorly sorted sand-silt-clay to sand, contributing to complex hydrological properties and flowpaths at this site (DeSimone, 2009; Leach, 2009; Macrae, et al., 2011).

2.5.2 Hydrological conditions within the Spencer Creek watershed

Situated in a temperate climate with a cold winter, it is expected that water levels would be highest during the spring in response to snowmelt, and lowest in the late summer from high rates of evapotranspiration. This natural regime has been altered in Spencer Creek as a result of the upstream Valens reservoir and dam, which retains much of the stream flow during the spring freshet, to artificially augment flows through the summer, and release surplus water in the autumn to increase storage capacity for the following spring freshet (Hamilton Conservation Authority, 2012b; Vidon & Hill, 2004). Below the dam, Spencer Creek enters Beverly Swamp as a confined stream, but becomes unconfined with many distributaries that disappear underground, re-emerging approximately 1 km downstream, above the confluence with the larger and more channelized Fletcher Creek (Kaufman, et al., 2005) (Figure 2.5). Discharge from Fletcher Creek exceeds that of Spencer Creek, except during periods of high discharge from the Valens Dam (Kaufman, 2002), where the influence of a reservoir drawdown event can increase water table position by 15cm throughout the extent of the wetland (Munro, et al., 2000). Figure 2.6 illustrates water table position relative to ground surface through a calendar year, as

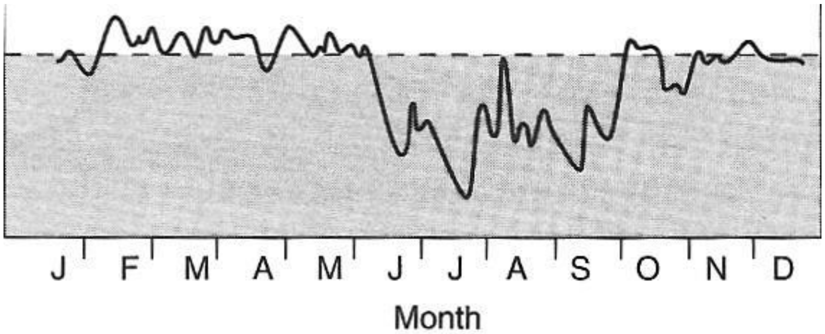

Figure 2.6: Water table position relative to ground surface typical of a Canadian swamp [Source: Mitsch & Gosselink (2007), as modified from Smith & Woo (1986)]. Water table position had a range of between 0.18 m above to 0.65 m below ground surface (Smith & Woo, 1986).

observed by Smith and Woo (1986). This data was collected downstream of the confluence of Spencer and Fletcher Creeks, dampening the effect of the autumnal reservoir drawdown on water table position, occurring in October.

2.5.3 Site-specific hydrology of the riparian zone in the upper reach of Spencer Creek

Many of the studies focusing on watershed-scale biogeochemical and hydrological processes have encompassed both Spencer and Fletcher Creeks to downstream of their confluence (e.g. Kaufman, 2002; Warren, et al., 2001; Woo & Valverde, 1981; Young, 2001), while the studies focusing on riparian biogeochemical processes and greenhouse gas fluctuations incorporating some hydrological processes have taken place in the upper reaches of Spencer Creek as it enters Beverly Swamp (e.g. DeSimone, 2009; Leach, 2009; Zhang, 2007). The existing studies in this riparian zone are largely confined to a low lying and relatively flat section of the riparian zone with very low hydraulic gradients, dominated by downstream horizontal hydraulic gradients (Macrae, et al., 2011) (T1, T2, T3, T4, Figure 2.5 inset).

Leach (2009) identified several dominant hydrological regimes in the area around T3 and T4 (Figure 2.5). She reported that during moderately wet conditions, hydraulic gradients were dominated by slope discharge to the riparian zone, but this reversed during dry conditions to stream-to-field gradients as the field edge became drier than the riparian zone (Leach, 2009). A third flow regime was identified by Leach (2009) following the drawdown of the upstream Valens reservoir during the annual autumn rewetting period. During this third regime, water table height rapidly increased, more rapidly in the mid-riparian zone than near-field area, enabling stream-to-field gradients to persist (even during a wet period), supported by downwelling with slight horizontal movement into the riparian zone, away from the main channel of Spencer Creek. This is observed in Figure 2.7c before becoming dominantly parallel to Spencer Creek, fed by the upstream riparian marsh and reservoir (Leach, 2009; Macrae, et al., 2011; Zhang, 2007). In a study encompassing a larger portion of this same riparian zone, it was found that groundwater flow in the confined riparian zone was dominated by longitudinal flow, approximately parallel to the stream channel under all flow conditions (Macrae, et al., 2011; Zhang, 2007).

Comparisons between stream discharge at the Valens dam and as Spencer Creek enters Beverly Swamp have demonstrated that this reach of the stream recharges groundwater (Leach, 2009; Macrae, et al., 2011), findings supported by observed dominant downwelling in the hyporheic zone of the upper reaches of Spencer Creek within Beverly Swamp, as illustrated in Figure 2.7 (Warren, et al., 2001; Young, 2001; Zhang, 2007). Figure 2.7b also illustrates elevated water table position nearest Spencer Creek during the driest conditions; further supporting the findings of Zhang (2007) and Leach (2009) that Spencer Creek recharges local groundwater. The artificial maintenance of discharge in Spencer Creek may be artificially creating a discharging stream in this setting, influencing both hydrological and biogeochemical processes in this system (Leach, 2009). This is further supported by Young (2001) who found that chemical composition of stream water of Spencer Creek through to the confluence with Fletcher Creek was dominated by water from the upstream reservoir, regardless of antecedent conditions. Chemical composition of stream water remained reservoir-dominated during response to precipitation events with notable stream hydrographs, particularly during periods of stable upstream dam discharge (Young, 2001). Conversely, studies conducted downstream indicate that groundwater discharge is dominant (Woo & Valverde, 1981; Young, 2001),

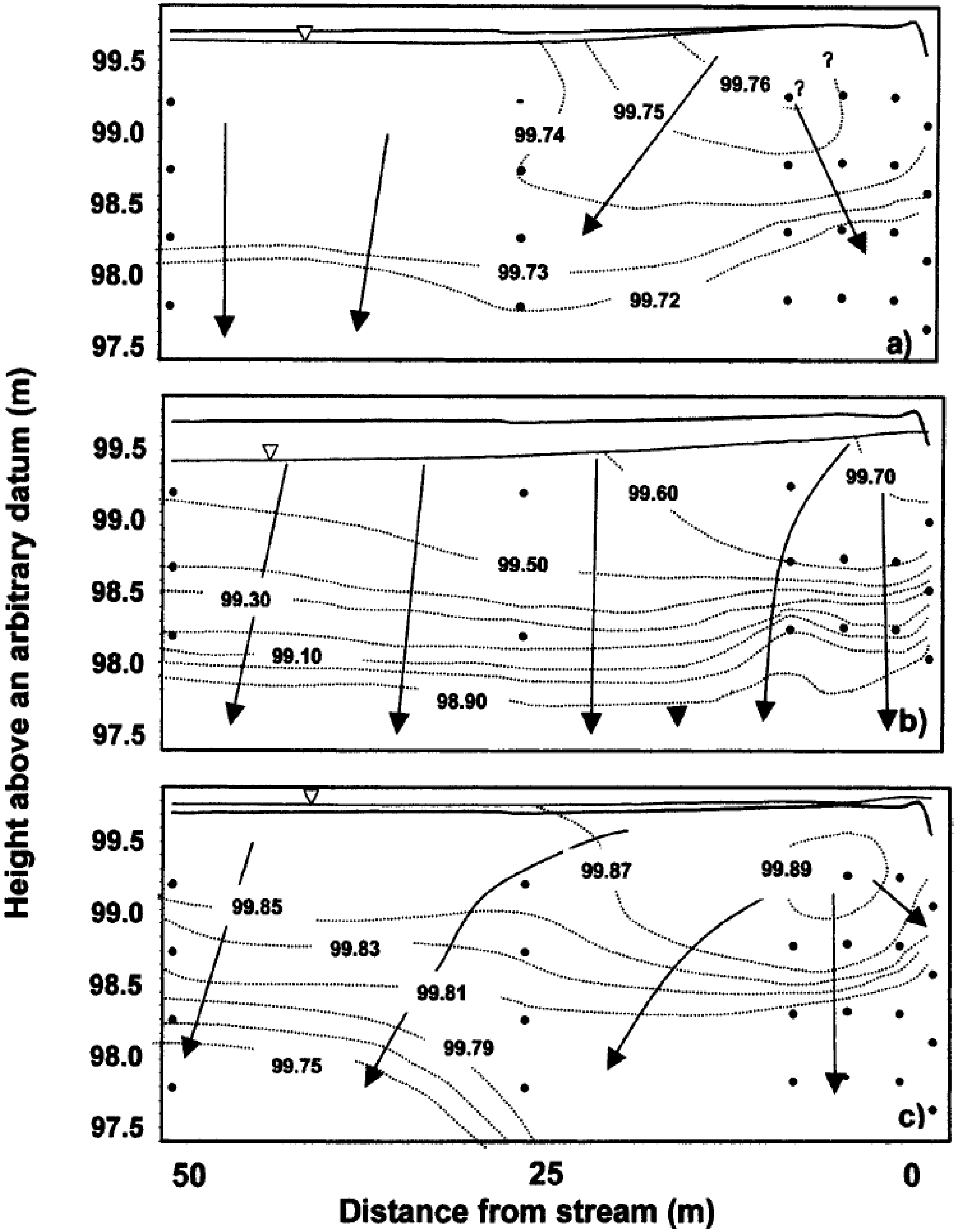

Figure 2.7: Groundwater flow nets during a dry year (1999) from a) early May, b) peak drought in July, and c) wet conditions in August (Warren, et al., 2001)

highlighting the spatial variability of hydrological processes within Spencer Creek and the Beverly Swamp.

The studies previously conducted at this site have largely considered seasonal trends and the upstream reservoir drawdown, with minimal emphasis on individual event response. Focusing on greenhouse gas fluxes, DeSimone (2009) found that high concentrations of nitrogen species were mitigated within 5-10 m of the field edge; likely due to anoxic conditions and organic soil, and, the loss of nitrate occurred where a break in slope was observed, and the riparian zone was flat with a higher water table position. This was the only previous study that attempted to incorporate topography as a process driver at this site, although, it was not found to be related to fluxes of nitrous oxide (N_2O; the focus of the DeSimone, 2009 study). It was also suggested that antecedent moisture conditions may have contributed to N_2O fluxes, and the lack of relationships between topographic position, groundwater nitrogen species (NO_3 and NH_4), and N_2O fluxes because her study took place during a very dry summer. Unfortunately, antecedent conditions were not systematically incorporated into the study by DeSimone (2009).

Zhang (2007) considered only the dominant hydrologic regimes of dry baseflow or peak flooding conditions at this site, but was the first study to show that dominant groundwater flow was longitudinal through this portion of the riparian zone, parallel to Spencer Creek. Leach (2009) built on the work by Zhang, and noted complex interactions between stream and hillslope-sourced responses to precipitation inputs before concluding that the artificially elevated water table in the near-stream zone could prevent nitrates from entering the stream through denitrification. However, for the study by Leach (2009), transect placement was approximately perpendicular to channel flow, with only a short transect running obliquely from the field edge into the riparian zone, along a flow line as approximated by Zhang (2007). This additional transect however, did not extend far into the riparian zone. The studies by Zhang (2007) and Leach (2009) focussed on transects extending from the agricultural fields to Spencer Creek (T1 to T4, Figure 2.5, where flow was found to be heavily influenced by Spencer Creek and the upstream reservoir). However, slightly downstream from these field sites, the field edge becomes nearly an East-West orientation, with increasingly steep topography, while the main channel of Spencer Creek continues to flow to the Southeast (Figure 2.5, 3.1). This change in geomorphology, topography, and relative streamflow direction could alter the hillslope-riparian zone-stream hydrological dynamics.

Finally, Figure 2.1 illustrates that the unconfined Spencer Creek has a moderated response through the growing season in comparison to its confined tributary, Fletcher Creek, both of which are second order streams, with drainage areas of 1.7 x 10^6 m^2 and 3.1 x 10^6 m^2 at their downstream confluence (Kaufman, et al., 2005). Warren, et al. (2001) concluded that this moderation in water table fluctuation was the result of differences in channel morphology, as discussed in section 2.3.1. Leach (2009) later found that reservoir discharge at this site is a dominant driver in stream stage, indicating that the water table moderation may be a result of upstream surface water management. It remains unclear to what extent the unconfined channel morphology as suggested by Warren et al. (2001) may influence groundwater flow.

3.0 Site description

The research into variable hydrologic responses to natural and anthropogenic events through seasonal changes in antecedent moisture conditions and along a topographic gradient for this thesis was conducted at the hillslope-riparian zone interface of Spencer Creek at the outer edge Beverly Swamp, adjacent to agricultural lands, located between the cities of Hamilton and Cambridge, Ontario.

3.1 Climate

The climate of southern Ontario can be classified as humid continental with hot summers and no particular wet or dry season (Christopherson & Bryne, 2006). Mean annual temperature is 7.9 °C ranging from mean daily temperatures of -5.5 °C in January to 20.9 °C in July (Environment Canada, 2014b). Mean annual total precipitation is 930 mm, which is fairly evenly distributed through the year, ranging from a low of 64 mm in January, mostly in the form of snow, to 101 mm in July (Environment Canada, 2014b). This study focuses on the growing season, during which there is a consistent mean precipitation accumulation of approximately 80 mm per month (Environment Canada, 2014b), as shown in Figures 5.1 and 5.2.

3.2 Hydrologic setting

The headwaters of Spencer Creek form on the southern face of the Galt Moraine (Karrow, 1983), which flows into the Valens Lake reservoir which is regulated by the Valens dam. The study site is approximately 1 km downstream from the Valens Lake reservoir, dam, and Conservation Area, operated by the Hamilton Conservation Authority. The Valens dam is an earth fill dam constructed in 1966 with a concrete drop inlet spillway, to mitigate downstream flooding, augment flow during dry periods, and store water within the watershed, while the

Valens Lake reservoir is used for outdoor recreational activities (Hamilton Conservation Authority, 2012b). Downstream of the reservoir, Spencer Creek flows into the Beverly Swamp (see Figure 3.1) as a second order stream (DeSimone, 2009). Past studies, notably Zhang (2007) and Leach (2009), have indicated that the groundwater movement does not move laterally through the riparian zone (field to stream) and instead flows parallel to Spencer Creek in the section north of "T4x" (Figure 3.1).

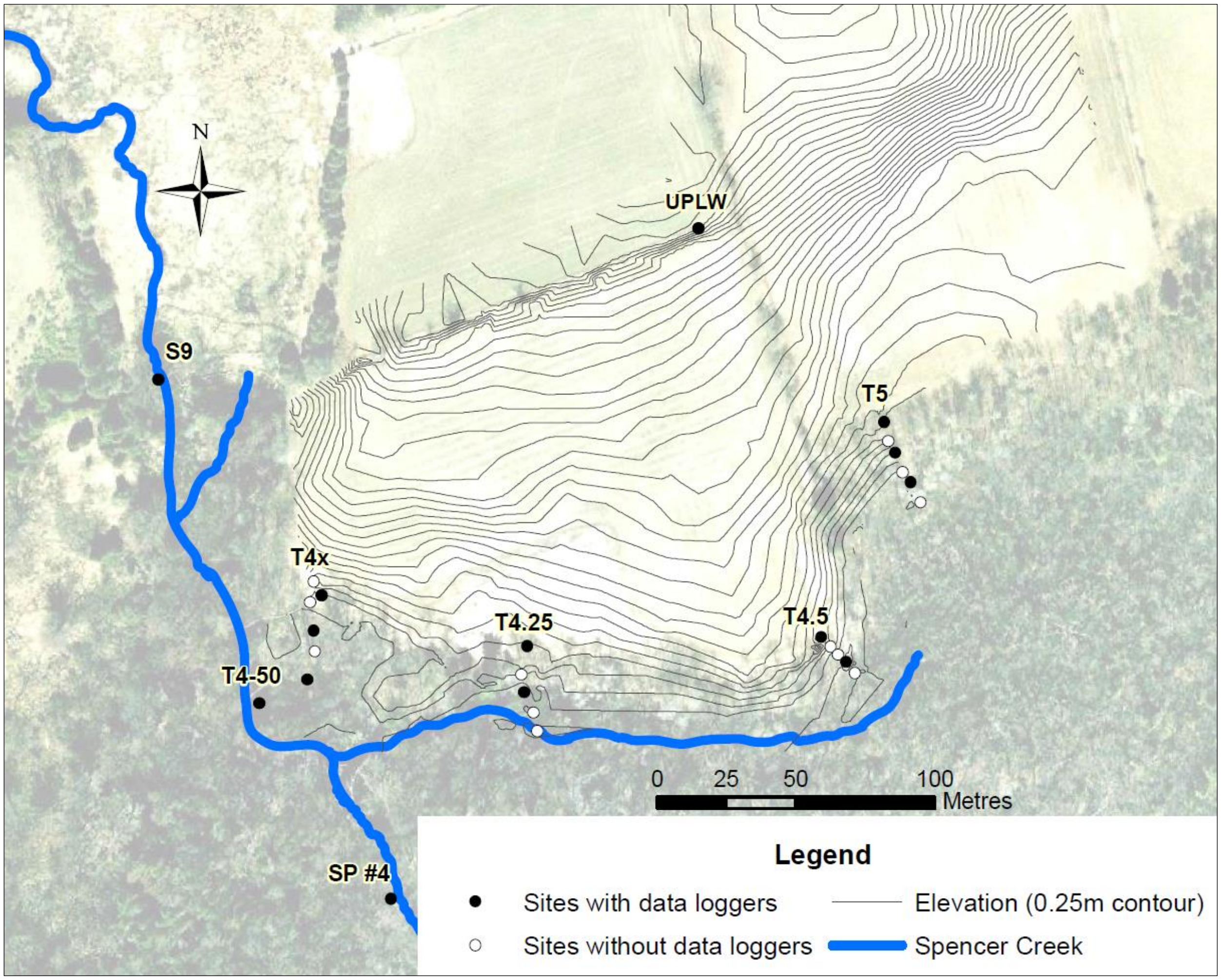

Figure 3.1: Site map illustrating placement of transects and additional wells monitored with known main (to the southeast) and ephemeral (east, along the field edge) channels of Spencer Creek. Elevation contours are illustrated in 0.25 m intervals. Aerial imagery was georeferenced and sourced from Google Earth (2004).

Through the study site, the riparian zone is approximately 35 m wide at T4x, increasing to 80 m near T4.25, and widening further through T4.5 and T5 which are situated along one of numerous ephemeral distributaries of Spencer Creek (Figure 3.1), while the main channel flows to the southeast before becoming a disappearing stream.

3.3 Soil

The area surrounding Beverly swamp is primarily composed of Wentworth Till, known as being comprised of a stony sandy silt mix (Karrow, 1983). The adjacent agricultural fields are composed of sand (Leach, 2009) and are not tile-drained. Beverly Swamp itself is composed of peat and muck, generally up to 1.5 m thick (Warren, et al., 2001), and is confined by a layer of marl, which separates the organic soils from underlying inorganic layers and dolomite bedrock (Karrow, 1983; Presant, et al., 1965). This muck can be characterized by well decomposed surface deposits that are black and friable, while less decomposed woody debris is commonly found at depth (Presant, et al., 1965). DeSimone (2009) conducted a detailed soil analysis at several transects which overlap those used in this study. Figure 3.2 illustrates the heterogeneity of soils in this system where Figure 3.2a is representative of T4, modified in this study as T4x, crossing T4 at T4x-D (formerly T4-23, the middle site) and Figure 3.2b is representative of the soil profile at T5-A, T5-C and T5-E. Saturated hydraulic conductivity as measured in this study is presented in Figure 3.3, with overall transect hydraulic conductivity decreasing from T4x through to T5.

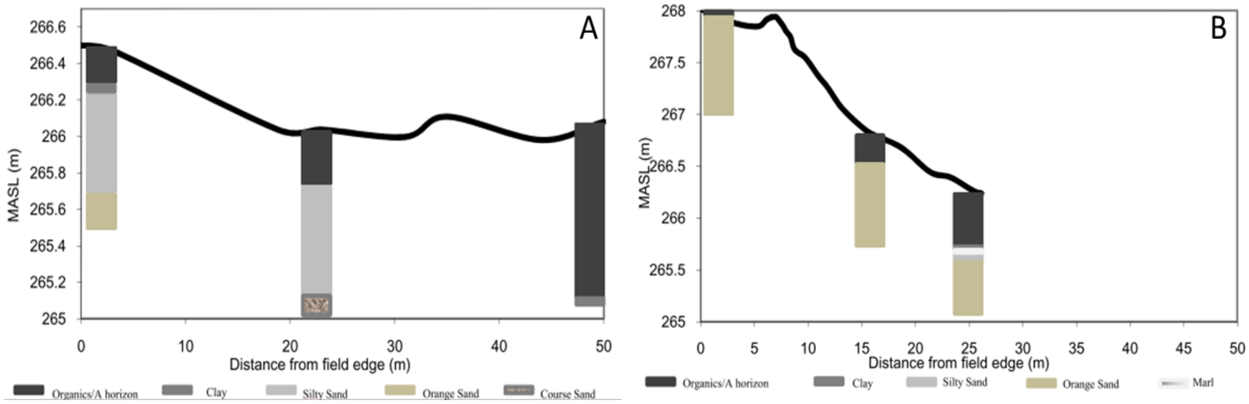

Figure 3.2: Soil profile heterogeneity between A) T4 and B) T5 (DeSimone, 2009)

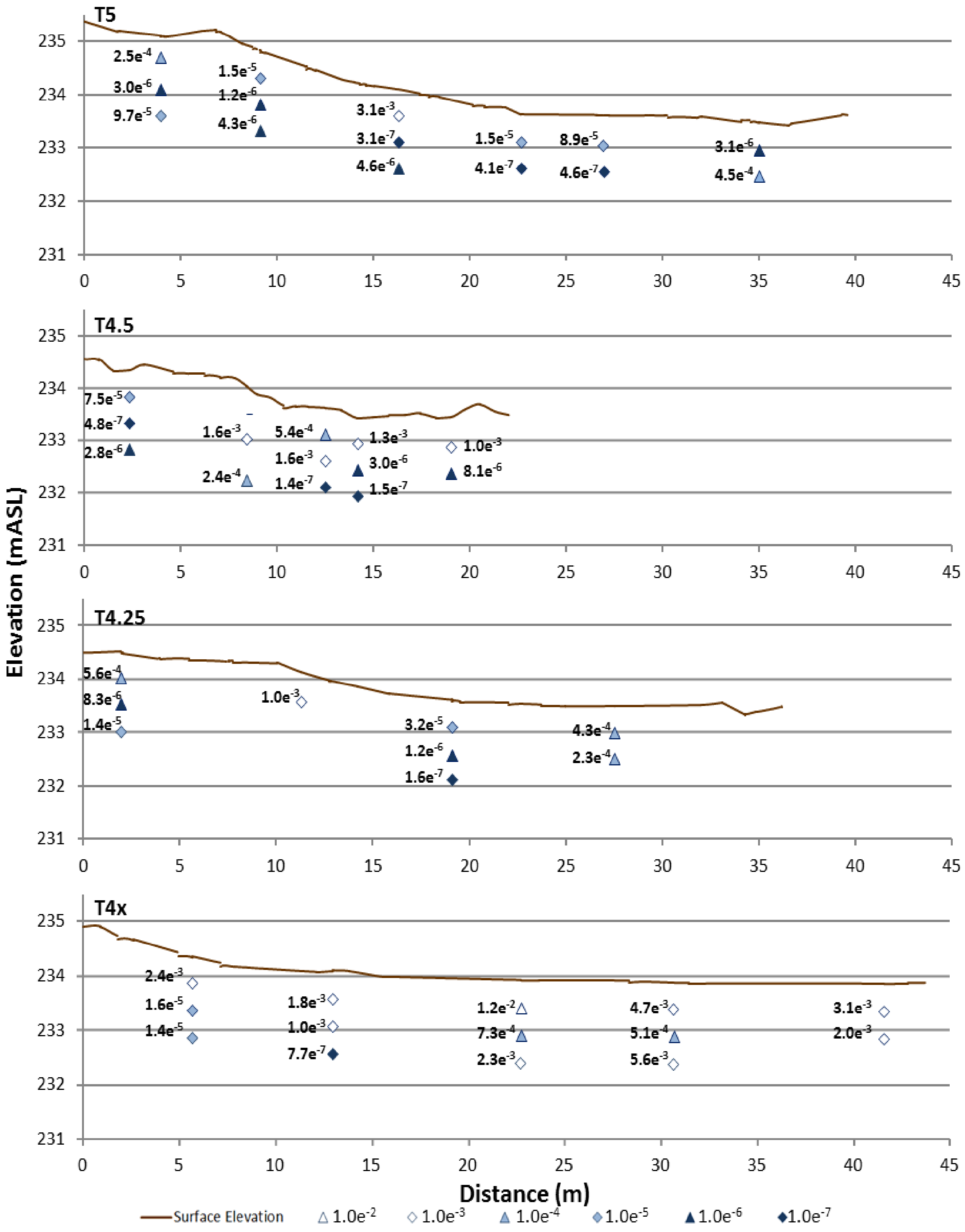

Figure 3.3: Saturated hydraulic conductivity (K$_{sat}$) by transect (cm/s). T4.5-B-P50 was frozen during K$_{sat}$ testing.

3.4 Vegetation

There is a wide range of vegetation communities within Beverly Swamp, ranging from open deciduous forest with herbaceous understory to dense coniferous (primarily cedar) stands. The areas through which the transects for this study pass are similar in characteristics at the outside edge of the swamp. The forest canopy is dominated with deciduous trees including silver maple (*Acer saccharinum*), black ash (*Fraxinus nigra*), yellow and white birch (*Betula alleghaniensis* and *B. papyfifera* respectively), with a mixed forest around T4.5 and T5, adding trembling aspen (*Populus tremuloides*), tamarack (*Larix laricin*a) and eastern white cedar (*Thuja occidentalis*) trees. The undergrowth in this area is composed of grasses, sedges (*Carex sp.*), wood nettle (*Laportea canadensis*), jewelweed (*Impatiens capensis*), marsh marigold (*Caltha palustris*), tall meadow-rue (*Thalictrum pubescens*), sensitive fern (*Onoclea sensibilis*), and poison ivy (*Toxicodendron radicans*), particularly on hummocks. Additional species in the area include mayapple (*Podophyllum peltatum*), jack-in-the-pulpit (*Arisaema triphyllum*), deadly nightshade (*Solanum dulcamara*), yellow lady slipper (*Cypripedium calceolus*), tufted loosestrife (*Lysimachia thyrsiflora*), and lesser duckweed (*Lemna minor*) in areas with low velocity surface water movement. Upland areas are additionally vegetated by wild rose (*Rosa sp.*), Canada anemone (*Anemone canadensis*), cow parsnip (*Heracleum lanatum*), raspberry (*Rubus idaeus*), ostrich fern (*Matteuccia struthiopteris*), Queen Anne’s lace (*Daucus carota*), and common blue-eyed grass (*Sisyrinchium montanum*) and several species of goldenrod (*Solidago sp.*) and aster (*Aster sp.).*

4.0 Methods

4.1 Experimental Design

Four transects with topographic gradients ranging from 4% to 9% located along flow lines from the field to riparian zone were instrumented with a series of wells and piezometer nests. Measurements of water table position and hydraulic head were recorded weekly to capture seasonal changes in hydraulic gradients, with additional field visits to capture event response during baseflow and flood conditions. Due to the unknown variability and duration of the autumnal reservoir drawdown event, the frequency of site visits increased to twice per week through late October and November.

4.2 Field Methods

4.2.1 Transect placement and well and piezometer construction

Existing transects T1 to T4 (Figure 2.5) were not used for this study because they have been found to not be oriented along a groundwater flow line. There is also little topographic variability in this section of the riparian zone and adjacent hillslope. Transects used in this study are labelled from west to east as follows: T4x, T4.25, T4.5 T5 (Figure 3.1). Transect nomenclature was chosen to coincide with that of existing infrastructure at the site. T4x is an extension of a transect used by Leach (2009), which runs at an angle oblique to the channel and field boundaries, and is presumed to fall along a groundwater flow line. The remaining transects were installed perpendicular to the field edge towards the riparian zone, also presumed to be along flow lines. The transects differed topographically with gradients for each transect: T4x = 4%; T4.25 = 5%; T4.5 = 7%; and T5 = 9%. Hillslope gradients for each transect were calculated for the area between the upslope nest and the nest closest to the break in slope at the leading edge of the riparian zone.

Topographical data for this study were collected in early December 2013 using a combination of a differential GPS and a total station. The data collected for this study indicates that the riparian zone elevation is consistently around 233.5 – 234 mASL, however, all previous studies in the area indicate that the mean elevation of Beverly Swamp is in the range of 267 mASL (e.g. Kaufman, 2002; Leach, 2009; Warren, et al., 2001; Valverde, 1978). It is unknown why this inconsistency occurred, however, it does not affect the results of this thesis. All water level data displayed in this thesis are presented in metres above sea level (mASL).

Four to six well and piezometer nests were installed along each transect, labelled alphabetically with “A” situated nearest the field edge. Each transect was designed to have a well and piezometer nest upslope, next to the field edge, mid-slope, at the break in slope at the edge of the riparian zone, and well within the riparian zone. Additional nests were installed in the upper to mid slope along T4.5 and T5, (where slope changed rapidly) and additional nests were installed deeper within the riparian zone for T4x (extending towards the adjacent stream), to ensure good representation of hydraulic conditions along the transect. There was also a well monitored several metres upslope of the T4x-A nest to capture water table dynamics between the field edge and riparian zone on this largely flat transect. Each nest comprised of a well and a series of piezometers installed to mid-screen depths of 50cm (P50) and 100cm (P100), with upslope sites having an additional piezometer installed to a mid-screen depth of 150cm (P150). Manual soil augers were used for installation of wells and piezometers. Each well and piezometer that did not contain an active pressure transducer from previous studies was purged prior to data collection.

With few exceptions of some pre-installed wells and piezometers, all wells and piezometers were constructed using 1” PVC pipe (2.6-2.9 cm ID, 3.4 cm OD). Where possible historic well and piezometer nests were incorporated into this study to reduce installation requirements. All piezometers were constructed with a 15cm screened length, and all wells were perforated for their entire subsurface length. All wells and piezometers were triple-wrapped with fiberglass screening.

Additionally, four stilling wells were installed in Spencer Creek. They were situated immediately downstream of Valens Dam (SP #1, Figure 2.5), at the entrance to the forested riparian zone (S9, Figure 3.1), an extension of T4x (T4-50, Figure 3.1) and slightly farther downstream (SP #4, Figure 3.1). These wells were instrumented with pressure transducers (HOBO U20, Onset Computer Corporation) to record stream water levels at 15-minute intervals. Due to challenges in collecting topographic data at the stilling wells, and given that data collected from T4-50 was representative of the others along Spencer Creek, it is the only one referenced in this thesis. It was not possible to monitor Spencer Creek farther downstream, due to the stream configuration, breaking into many small distributaries before becoming a disappearing stream (Kaufman, et al., 2005).

There were several sites that had special challenges. The soil at T4.25-B where the mid-slope site was to be installed had a coarse layer of till that was very challenging to get through, and as a result, only a P50 and a well were able to be installed here. While both were monitored through the season, only the measurements obtained from the well are being used in this study. Initially only a well was installed near the break in slope location along T5, but it was soon discovered that there was a large difference in observations from T5-C and T5-E, so two additional piezometers (P50 and P100) were installed at T5-D at the end of August. The final site that was modified during the study period is T4x-C, where the P150 piezometer that was initially installed became clogged. A new piezometer was installed at the same location on September 9.

4.2.2 Collection of field hydrologic data

Manual water table and hydraulic head measurements were recorded weekly using a Solinst water level indicator, with additional field visits to target post-event hydrologic conditions. A selection of upland and riparian zone wells contained Hobo U20 pressure transducers recording on a 15-minute interval to create time series data; capturing overall seasonality and event response of the system (Figure 3.1). The instrumented wells at the upland well (UPLW) and along T4x have been monitored continuously through multiple studies and therefore have a complete data set; the other water level loggers were installed in mid-June after all new wells and piezometers had been installed and purged. Installed pressure transducers were downloaded monthly, and raw data was calibrated through HOBOware software using barometric data from Environment Canada's Kitchener/Waterloo meteorological station. The resulting value of depth of water above the pressure transducer was converted to mASL using physical water level measurements collected during site visits.

4.2.3 Meteorological data

Meteorological data were obtained from nearby weather stations. 15-minute interval precipitation data was obtained through the Hamilton Conservation Authority from a rain gauge installed at the Valens Dam, located approximately 1km upstream from the study site. Hourly air temperature data was obtained through Environment Canada (2014a), from the Guelph Turfgrass station, 20km north of the study site, while hourly barometric pressure data was collected from Environment Canada's (2014c) Kitchener/Waterloo station, 21km northwest of the study site. Climate normal (1981-2010) data was collected from Environment Canada's (2014b) Hamilton A station, 27km south southeast of the study site, which is the closest station to have historic data that meet the United Nations World Meteorological Organization standards of missing no more than 3 consecutive and no more than 5 total records for either precipitation or temperature over a 30-year period (Environment Canada, 2014b). A brief spatial comparison of 30-year climate normal data for 1981-2010 was conducted between the Hamilton A, Kitchener/Waterloo, and Guelph Turfgrass stations. While there are spatial differences in precipitation accumulation of individual events and some smaller convective events which were not observed at all stations, it was found that long-term climate trends and amounts were very similar among recording stations, concluding that the distant Hamilton A station could accurately represent mean climate data for Valens. Empirical Thornthwaite (1948) methods, which may underestimate evapotranspiration rates (Mitsch & Gosselink, 2007), were used to calculate monthly potential evapotranspiration (PET) in mm to determine monthly moisture deficit to highlight seasonal trends. This method may provide a balance of most accurate estimate of PET with the least amount of required instrumentation (Mitsch & Gosselink, 2007).

5.0 Results

In this section, weather conditions from 2013 are compared to the 30-year mean climate, followed by an interannual comparison of 2011 to 2013 to provide context for how results from this study season relate to overall wetter and drier than normal years. Long-term seasonal fluctuations, including the reservoir drawdown event are then presented, followed by short-term event-based hydraulic response to four precipitation events with contrasting precipitation event properties and antecedent moisture conditions.

5.1 Seasonality in climate drivers and riparian zone hydrology

The climatic conditions of 2013 were near normal when compared to the 1981-2010 30-year mean climate, as illustrated in Figure 5.1. It is notable however that there was nearly 50 mm less precipitation accumulation in both March and November, and nearly 50 mm more precipitation accumulation in October than the 30-year average. For much of the year, temperature trends on the other hand were cooler than normal, with early spring, late summer, and late autumn being at on average at least 2 °C cooler than normal.

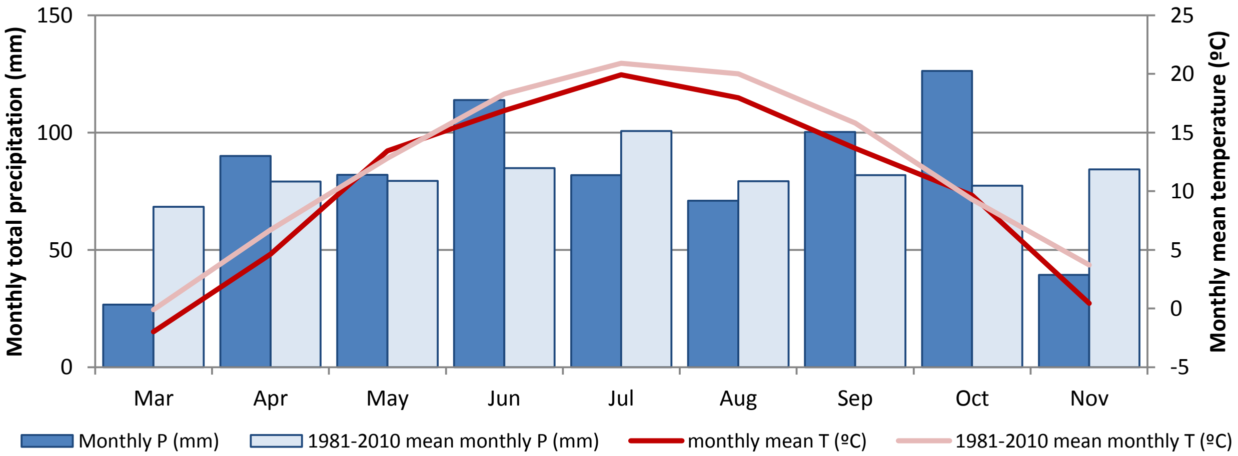

Figure 5.1: Climograph comparing observed monthly mean temperature as recorded at the Guelph Turfgrass station (Environment Canada, 2014a) and monthly precipitation (Hamilton Conservation Authority, unpublished data) with 1981-2010 climate normal from the Hamilton A station (Environment Canada, 2014b)

5.1.1 Interannual climate variability and corresponding hydrologic conditions

Continuous water table elevation data collected in wells along T4x (Macrae and Bourbonniere, unpublished data) has enabled an interannual comparison of hydrological conditions to provide context for a possible range of water table responses under varying climate drivers, as 2011 was wetter than average, 2012 was drier than average, and 2013 was near average (Figure 5.2). Variable precipitation received over the three years led to variable hydrologic responses in the riparian zone (Figure 5.3). Of note are the exceedingly wet months of April and May 2011 which were followed by extreme drought in July with a monthly precipitation accumulation nearly 86 mm less than normal, nearly negating the wet spring; however, 2011 remained cumulatively wetter than normal. Between September 2011 and March 2012, the Hamilton area received only 58% of normal snowfall to contribute to the spring freshet and exceedingly warm temperatures through March (Environment Canada, 2012). This resulted in an early and lower peak spring water table in 2012, particularly when compared to that of spring 2011 (Figure 5.3b). Monthly precipitation through the remainder of 2012 remained below normal except during September and October, resulting in cumulative precipitation of nearly 300 mm less than normal through the growing season (Figure 5.2). Precipitation accumulation through 2013 remained much closer to the 30-year mean, with the exception of above average precipitation in October and below average precipitation in both March and November. It should be noted that had the 27 mm precipitation event of October 31, 2013 begun mere hours later, the observed deviations of October and November would have been greatly reduced.

Monthly moisture deficits (Figure 5.3a), determined from P-ET (with ET estimated using the approach of Thornthwaite) reflect precipitation patterns in Figure 5.2 demonstrating wet spring and autumn seasons, and dry summer seasons. The dry conditions in 2012 resulted in a larger moisture deficit than was observed in 2011 or 2013. However, surprisingly, extreme lack of precipitation in July of 2011 resulted in a greater moisture deficit than 2012 for that month. The moisture deficit is very similar for all three years between August and October.

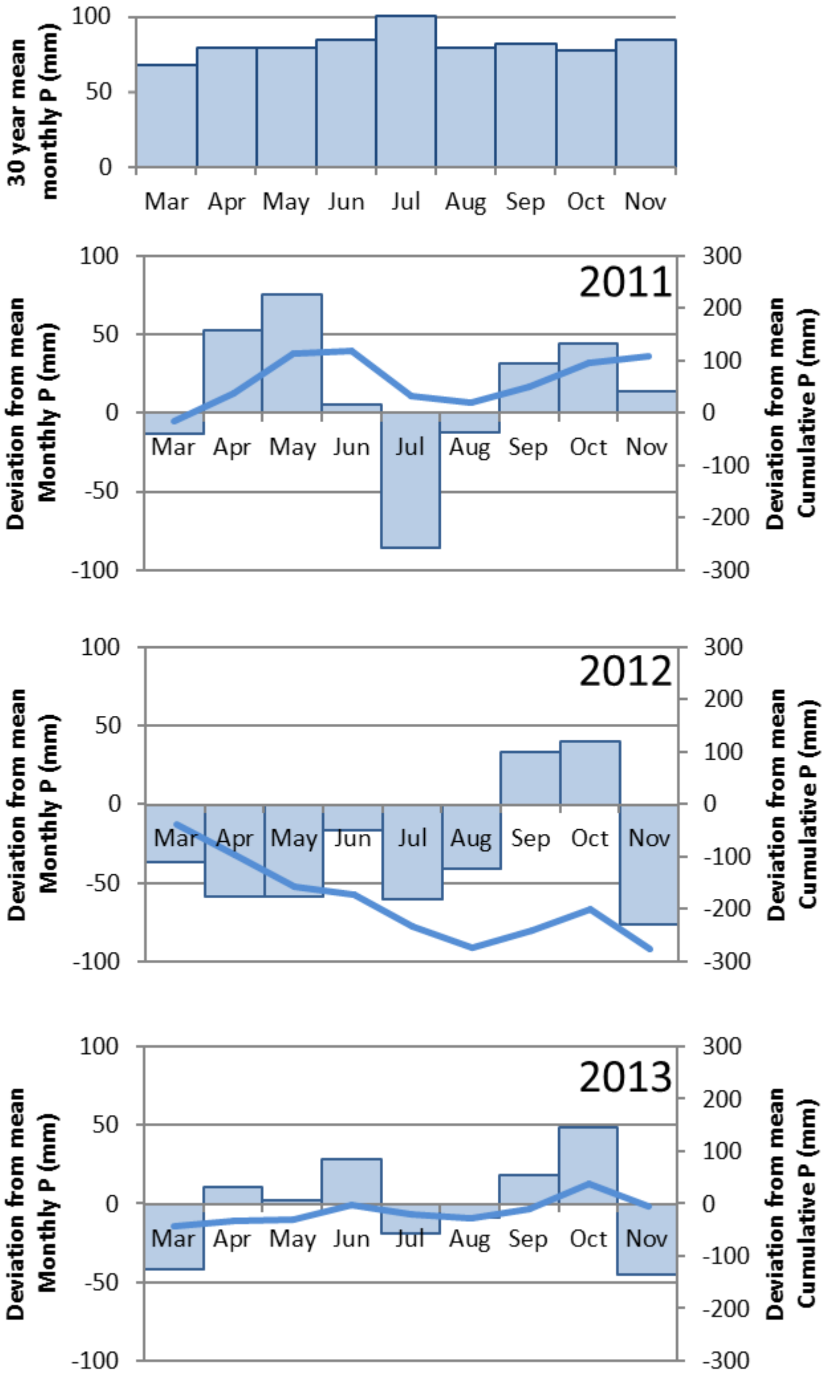

Figure 5.2: Interannual precipitation comparison with 1981-2010 mean monthly precipitation (top; Environment Canada, 2014b), and monthly (bars) and cumulative (lines) deviation from mean precipitation at the Valens Conservation Area (Hamilton Conservation Authority, unpublished data).

It is apparent from the water table variability displayed in Figure 5.3 that streams and nearby riparian sites (i.e. T4x-E and T4-50, and Fletcher Creek) have greater hydrologic connectivity with one another as they seem to fluctuate synchronously, which is not closely mirrored in the upland sites (i.e. UPLW and W32), regardless of interannual climatic variabilities. The influence of precipitation events on water table position is dampened in low lying sites (e.g. early June 2012, July 2013, and September 2012, down arrows, Figure 5.3) in comparison to upland sites, whereas, stream-sourced hydrologic events such as an upstream reservoir release event, often characterized by a plateau-shaped hydrograph, are more distinct in the near-stream and riparian zone sites, with a dampened signature towards the hillslope sites (e.g. early April 2012 and 2013, and October 2012, up arrows, Figure 5.3). The reservoir drawdown event captured in this study (mid-October to mid-November 2013) is less prominent on the comparative hydrograph (Figure 5.3) because there were wetter antecedent conditions and a gradual increase in discharge from the dam over a two week period, while the reservoir drawdown in October 2012 had much drier antecedent conditions and was part of a flood pulse experiment during which time the reservoir discharge was instantaneously increased to full capacity.

While watershed management techniques modify the timing and magnitude of the seasonal fluctuations, they do not eliminate the natural seasonal trends as seen in the comparisons between T4-50 and the unregulated Fletcher Creek in Figure 5.3e and f, respectively. Regardless of the variability in climatic drivers that modify magnitude and timing, there are overarching seasonality trends whereby the spring is the wettest, followed by drying trends through the summer and rewetting in the late summer and through the autumn in Ontario.

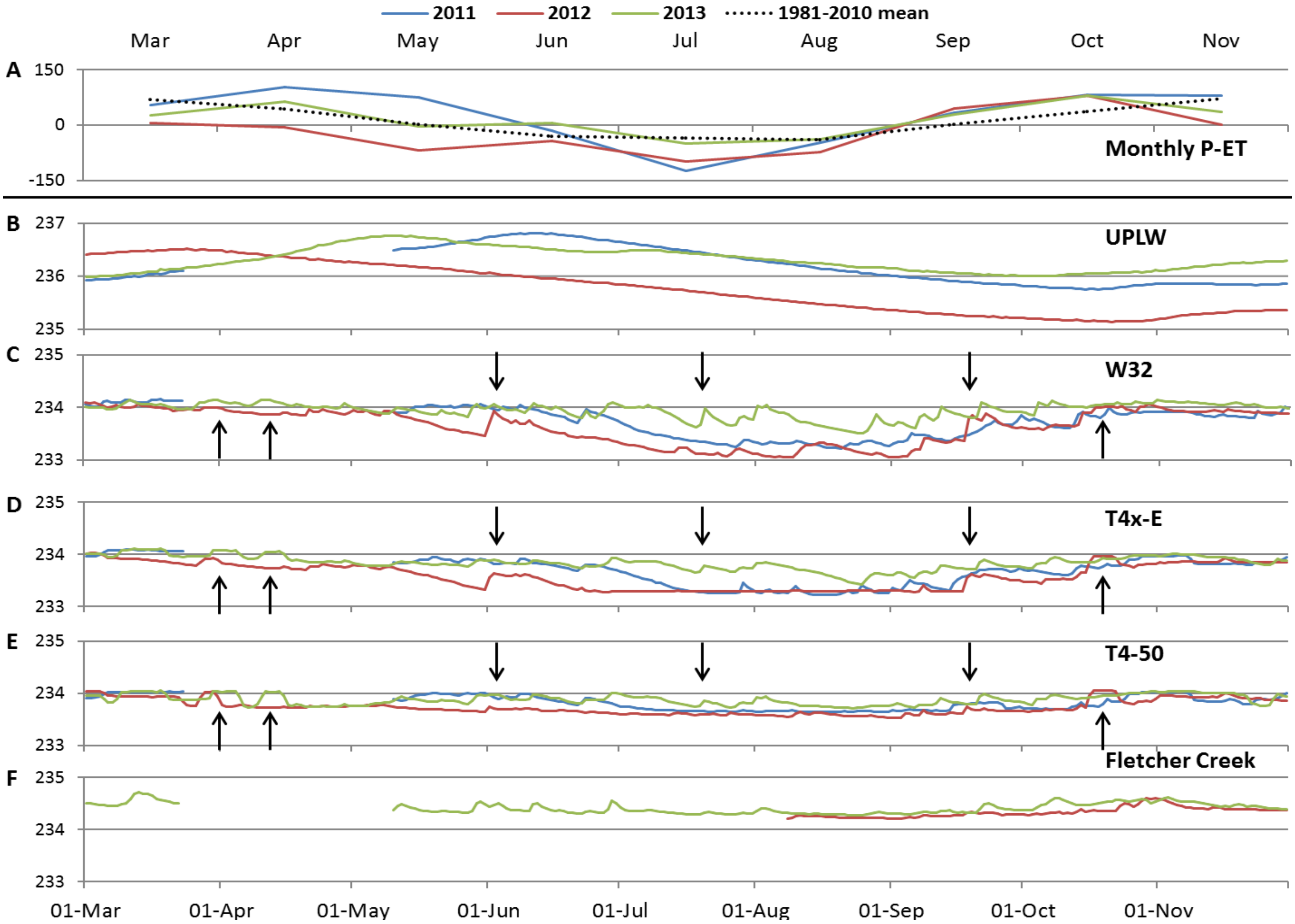

Figure 5.3: Interannual comparison of (A) monthly moisture deficit, calculated as precipitation minus potential evapotranspiration; mean daily water levels at (B) the deep upland well, along T4x at (C) W32 the well representing T4x-A and (D) T4x-E; (E) the hyporheic zone of Spencer Creek near T4x; and compared to (F) the nearby unregulated Fletcher Creek (Figure 2.5). Up arrows illustrate response to notable dam release events which dampen towards the hillslope and down arrows illustrate response to notable precipitation events which dampen towards the riparian zone and stream.

5.2 Spatiotemporal variability in water table position and hydrologic gradients: longer term, seasonal patterns

Hydrologic behaviour at this site varies temporally and spatially, both along and between monitored transects. For this study, seasonality refers to dominant long-term hydrologic trends of wetting and drying and the annual upstream reservoir drawdown. The timing of seasonality shifts is superimposed on the daily mean water level elevations illustrated in Figure 5.4. UPLW is a deep groundwater well, recording water levels nearly 6 m below ground surface, and does not respond to individual precipitation events (Figure 5.4). This well could be used as an approximation of seasonal water level trends (e.g. wetter or drier than normal, and the relative timing of wetting to drying and drying to wetting); however, there is a delay in response at this site when compared to the trends found in riparian zone and local groundwater levels.

This study began mid-June, during the dry out period which is estimated to have begun around April 4, after peak water levels in response to the annual snowmelt freshet, and persisted through July and most of August. The wet up period of increasing baseflow levels was triggered by a small precipitation event on August 26, following a three-week drought. This season would have naturally continued through the autumn, had it not been interrupted by the annual upstream reservoir drawdown event which started on October 21, and ended on November 21. The drawdown event is considered to be equivalent to a seasonal effect in this study. Even though it is a single input event, it has a month-long duration and it occurs annually at this site. The hydrological behaviour of the system during this time of increased surface discharge is also compounded by precipitation events.

Hillslope-riparian zone dynamics and their seasonal development are examined first. Precipitation events are discussed in further detail in section 5.3. The timing of these events is

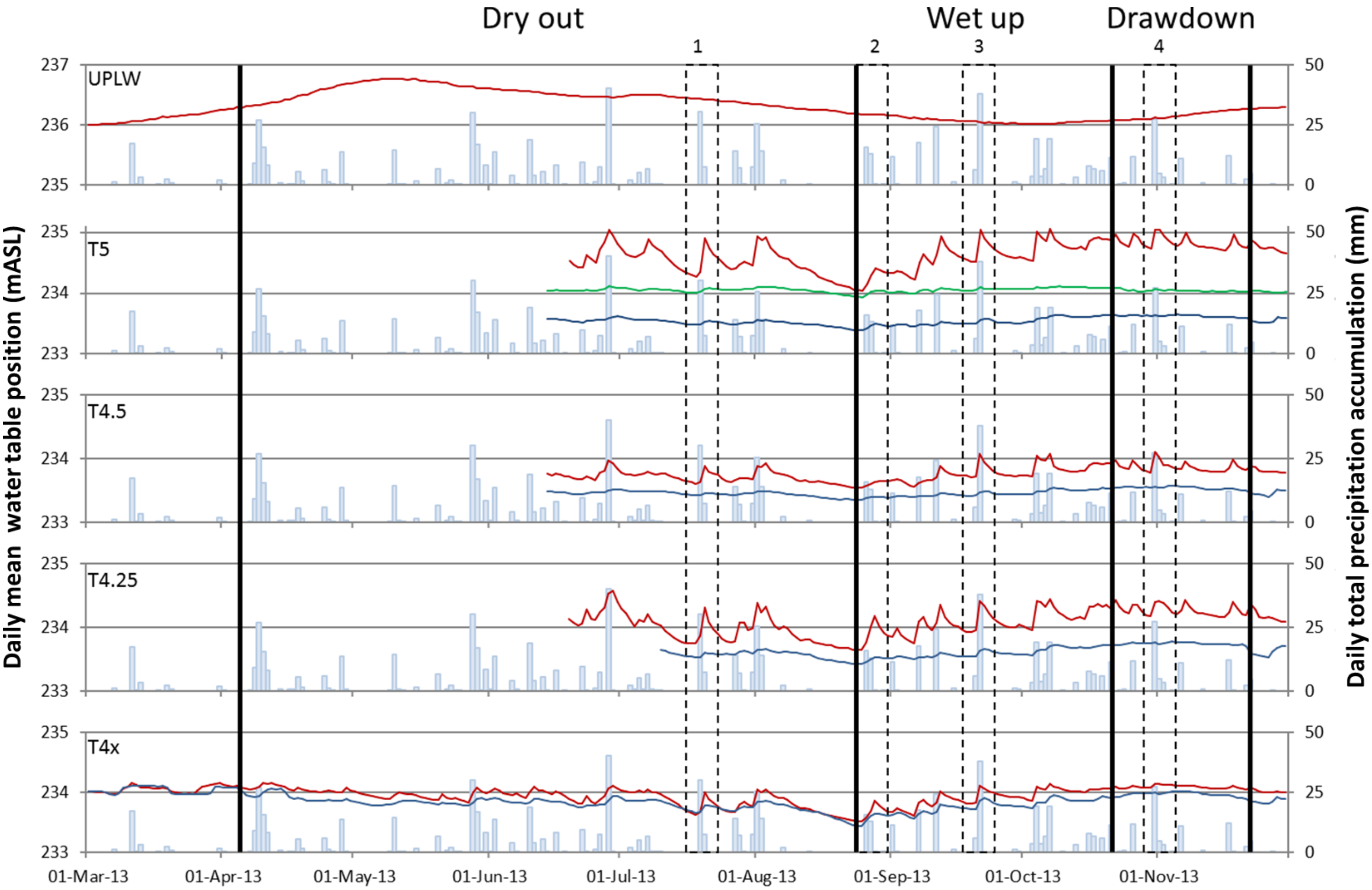

Figure 5.4: Daily mean water level in mASL as recorded both upland (red) and in the riparian zone (blue), with seasonal timing (i.e. dry out, wet up, reservoir drawdown) and targeted events for event response (numbers 1 to 4) highlighted. Additionally, mid-slope data is presented for T5-C (green). Data presented was recorded from: the deep groundwater upland well (UPLW); T5-A, T5-C, and T5-E; T4.5-A and T4.5-D; T4.25-A and T4.25-C; and W32, representing T4x-A, and T4x-E.

outlined by hashed lines in Figure 5.4 as follows: Event 1 (July 19-20); Event 2 (Aug 26-27); Event 3 (Sept 20-21); and Event 4 (Oct 31-Nov 2).

Hydraulic gradients across the riparian zone transects (Figure 5.5) and water table positions (Figure 5.4, 5.6) indicate that groundwater dominantly flowed from field to stream. Hydraulic gradients were steeper with steeper topography (Figure 5.5, 5.6). The transect profiles of two-dimensional hydraulic gradients displayed in Figure 5.5 (for one day over the study period) are representative of the dominant gradients observed throughout the study period. Although the general direction of flow was from field to stream, some exceptions were observed, notably at T4.5 (Figure 5.5). The strong upwelling gradients in the midslope of T5 and the strong converging gradients towards the break in slope at T4.5 persist through all hydrologic conditions, while both T4x and T4.25 develop similar areas of convergence at depth near the break in slope only during wetting conditions.

The seasonal progression of water table elevation along the transects during baseflow conditions for both the drying and wetting periods, for T4x and T5 is displayed in Figure 5.6. These periods are also shown in Figure 5.4. Water table dynamics across the riparian zone differed both with topography, and whether or not the climatic conditions were on a “drying” or “wetting” trend. In flat areas of the riparian zone (T4x, Figure 5.6), as well as in T4.25 and T4.5 (not shown), the water table fell in a uniform fashion across the riparian zone. The notable exception to this trend is in the riparian zone near the break in slope of T4x (Figure 5.6), where, during exceptionally dry conditions, there appeared to be a convergence of groundwater, suggesting that the adjacent Spencer Creek may have been recharging the riparian zone at this time. This trend was not observed at the other sites which were not located adjacent to the stream.

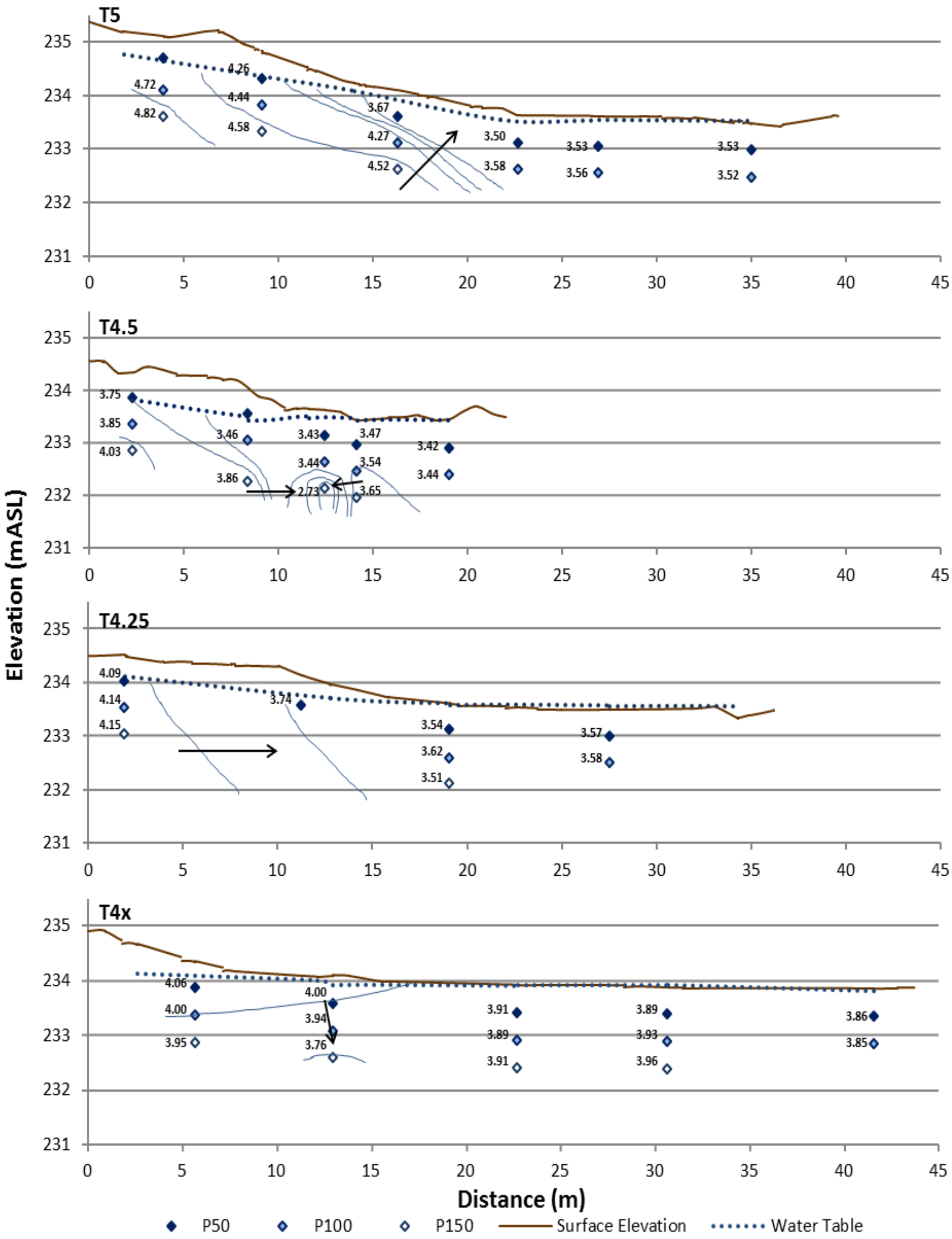

Figure 5.5: Profile view of typical hydraulic gradients by transect at this site. Numbers represent hydraulic head recorded at each piezometer such that 4.72 at T5-A-P100 indicates that hydraulic head was recorded as 234.72 mASL. Isoline scale is 0.25 m. Data presented here collected during wet up period on Sept 24, 2013, but are representative of the study period.

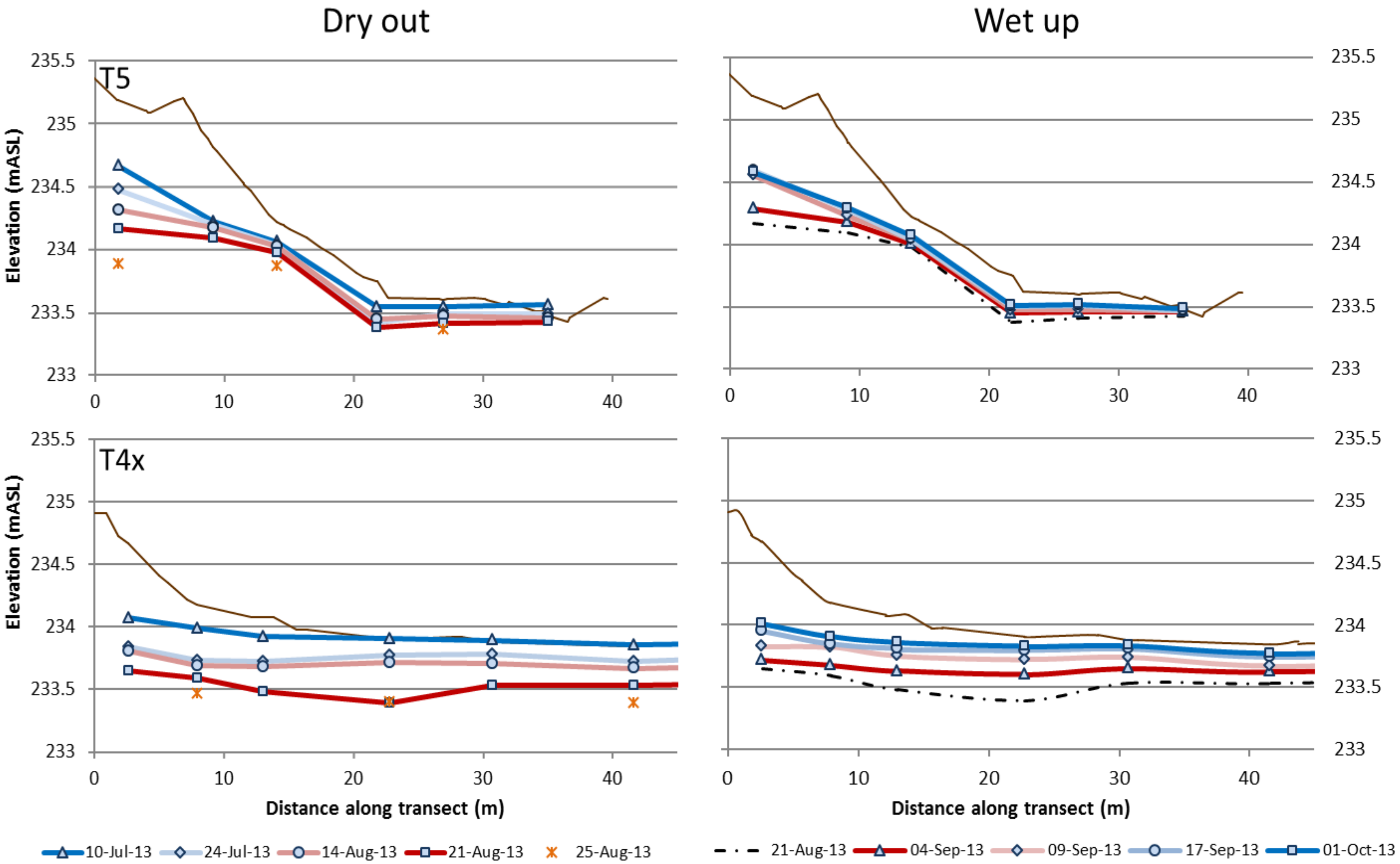

Figure 5.6: Profile view comparison of seasonal response of water table position to dry out (left) and wet up (right) at T5 (top) and T4x (bottom), superimposed on transect topography (thin solid line). Driest conditions were on August 25, as recorded by pressure transducers. In the figure, wet conditions are shown in blue and dry conditions are shown in red. Water table positions are assumed to be indicative of baseflow conditions as precipitation events did not occur within several days of data collection for each data point.

Water table dynamics at T5 exhibited wider ranges (Figure 5.4, 5.6) than were observed at T4x, and the water table did not recede uniformly across the riparian zone. The drawdown of the water table varied with slope position. In steep upland areas, the water table fell by nearly 1 m over the drying period. This is much greater than the 0.1 to 0.37 m decline in the water table observed at the field edges in the flatter and riparian areas. In contrast, water table position in the midslope site on the steep transect (T5-C) did not vary. However, the water table fell in a uniform manner in the flat sections at the base of T5 (D, E, and F) as was observed in the other transects (Figure 5.6).

High-frequency data from pressure transducers indicate a threshold response to drying conditions triggering diurnal water table fluctuations at all sites that are amplified with decreasing mean daily water table position. Similar to trends in water table position, these diurnal fluctuations have the greatest amplitude of 30 cm at T5-A (upslope position, field edge). This amplitude decreases to 12 cm or less in all other transect locations, and is as low as 3 cm in low lying areas of the riparian zone.

Spatial patterns during the wet up period were similar to those of the dry out period at both T4x and T5, although the rebound of water table position was faster than decline during the dry out period. During the wet up period, water levels along T4x rose fairly uniformly, increasing water table position from the driest conditions by approximately 30 cm throughout the length of the transect, with the exception of the mid-riparian zone position (T4x-C, Figure 5.6). In all other transects, however, there was a very subtle increase in water table position in flat sections of the riparian zone (between 6 cm and 12 cm) with a much larger increase in water table position at the upland field edge sites (17 cm to 41 cm) during this time.

5.2.1 Influence of overbank flooding from release of upstream dam

Every year, when the recreational season has ended, the Hamilton Conservation Authority reduces the water level in the Valens Lake reservoir to remove the stop logs in the dam prior to the winter season. This allows for an increase in storage capacity within the reservoir to reduce downstream flooding events during the snowmelt freshet. The signature of such an event would appear as a plateau on a hydrograph, with sustained high water levels for a period of time, as highlighted in Figure 5.3. The reservoir drawdown began on October 21 with a progressive release, such that the spillway pipe was opened to ¼, with further opening to ½ on October 23, and to ¾ on October 24. The spillway pipe was completely opened on November 4, where it remained for the duration of the reservoir drawdown. The stop logs were removed from the dam once the reservoir water level was below the concrete structure late in the day on November 21, at which point the spillway pipe was more or less closed.

As would be expected from a gravity fed drawdown, the discharge to Spencer Creek initially increases before slowly decreasing as the difference in the water levels between the reservoir and creek lessens through the duration of the drawdown. This is seen in the water levels of Figure 5.7, particularly within the riparian zone of each transect, where the initial water level increase is followed by slight decreases. From the variability in water level response at each transect, it is clear that the reservoir drawdown influences the entire riparian zone in addition to hillslope sites that are near the break in slope (Figure 5.7). Water table positions at the upslope sites, however, did not change throughout the dam release period. Water table position is less variable overall through the reservoir drawdown (Figure 5.7) than through the dry out or wet up periods (Figure 5.6). Upon the termination of the drawdown event on November 21, water levels returned to be at or below pre-drawdown levels by November 26.

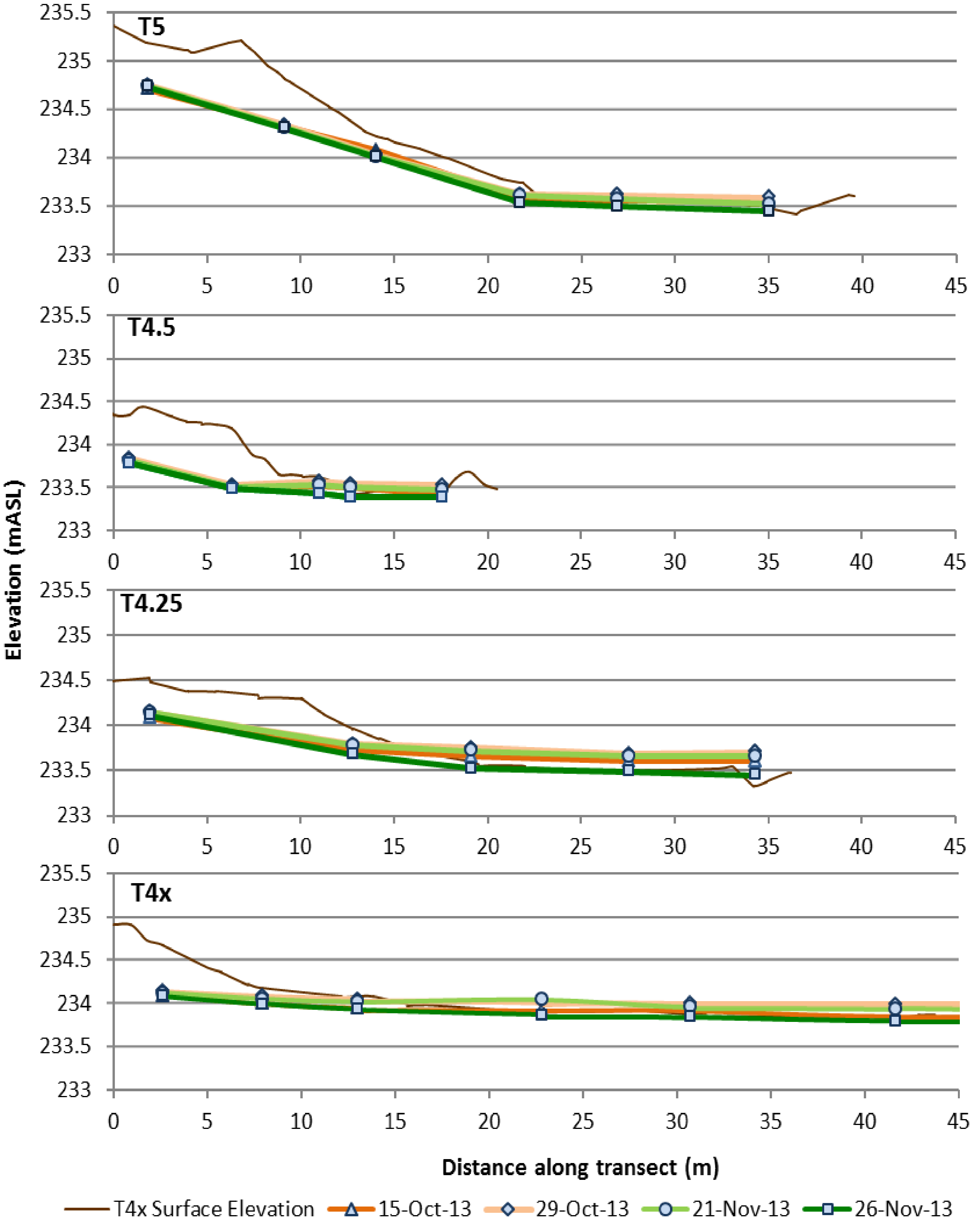

Figure 5.7: Profile view of water table (mASL) by transect during baseflow through the autumn reservoir drawdown. Data was collected on November 21, prior to closing the spillway pipe. Nov 26 is presented here representing post-drawdown conditions as observations of November 22 were compounded by a precipitation event.

Vertical hydraulic gradients (not shown) at most sites were not affected by the onset of the reservoir drawdown, although changes to hydraulic head largely mirrors trends in water table position. Upslope and riparian sites largely maintained pre-flood vertical gradients, of near zero, except the upslope site of T4.5-A, and the midslope sites on the steeper two transects, T4.5 and T5, which maintained positive vertical hydraulic gradients (indicative of upwelling). Only the low slope sites on T5 and T4.5 and the break in slope sites on all transects had varying hydraulic gradients during the reservoir drawdown period. At these sites the overall downwelling gradients from pre-flood conditions lessened through the reservoir drawdown period, becoming close to zero at both T4x and T5. Post-flood, gradients tended to return to pre-flood conditions, except at the break in slope at T4.5 and T5, which more closely resembled the stronger downwelling of the onset of the flood. These vertical hydraulic gradients at the break in slope are later presented in Figure 6.1.

5.3 Spatiotemporal variability in water table position and hydrologic gradients: short-term event-based variability

Four main precipitation event responses were analysed to characterize short-term hydrologic responses. The distribution of these events through the hydrologic seasons of the study period is highlighted in Figure 5.4. These events were chosen to illustrate how variable antecedent moisture conditions and event characteristics influence system response to hydraulic inputs. The first event (Event 1) occurred during the drying period, on July 19-20, when 37.6 mm fell during a high intensity precipitation event over the span of several hours. The second event (Event 2) was a combination of two smaller events at the height of the drying season, where 15.7 mm fell on August 26, followed 22 hours later by an additional 13 mm on August 27, for a combined total of 28.7 mm. Prior to this event, water levels in the Valens Lake

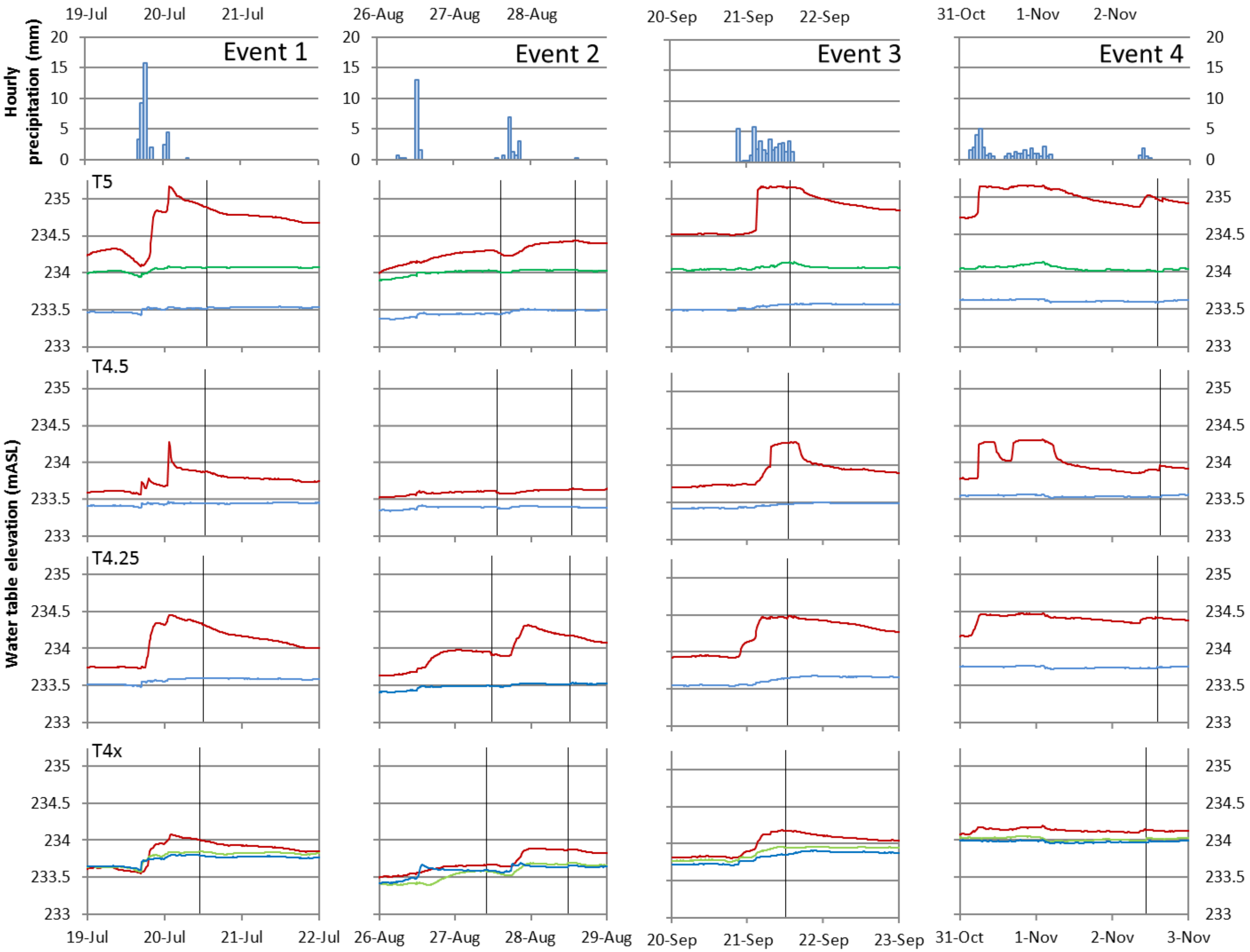

Figure 5.8: Event response hydrographs with hourly precipitation (mm) and 15-minute[1] interval water level (mASL) response at top of hillslope (red) and within the riparian zone (blue). Additional pressure transducers (green) were installed midslope in T5, and in the riparian zone near the break in slope at T4x. Vertical lines represent timing of during or immediately post-event manual field observations.

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[1] Hobo loggers at T4x-A (W32), T4x-E and T4.5-A, installed prior to this study, recorded data on 20-minute interval.

reservoir had declined to below the elevation of the stoplogs and the precipitation during this event was insufficient to cause spillover, reducing the influence of the dam on event response. Spillover at the dam occurred during all other events. Event 2 triggered the beginning of the wet up season. The third precipitation event (Event 3) was on September 21, when there was a long, steady precipitation event of 44.0 mm. The final precipitation event (Event 4) was that of October 31, during peak flood conditions of the autumnal reservoir drawdown when 32 mm fell and was followed by an additional 3.2 mm a day later. An overview of these precipitation events and corresponding response hydrographs is presented in Figure 5.8, followed by a detailed comparison between event response in water table position and vertical hydraulic gradients for the contrasting Events 2 and 3. Event 2 was a two-part precipitation event where the first part of the event can be characterized by high intensity precipitation on extreme dry antecedent conditions. Event 3 was a steady, long duration precipitation event on wet antecedent conditions. This data is presented in Figures 5.10 and 5.11, demonstrating the pre-event, mid-event, and post-event hydrologic conditions along all transects; timing of the mid-event measurements is illustrated as vertical lines on Figure 5.8.

Water table position and vertical hydraulic gradients in low-lying riparian sites tended to have subtle responses to precipitation (Figure 5.8 to 5.11), with little variation to hydrologic response among events, with vertical hydraulic gradients remaining close to zero (Figure 5.10, 5.11). Riparian sites with the greatest variability in water table position were those situated in the riparian zone of transects nearest Spencer Creek, particularly T4x (Figure 5.8). During extreme dry conditions (Event 2), a small groundwater ridge appeared to form in the riparian zone of this flat transect (T4x, Figure 5.10). This, coupled with more rapid response to precipitation under dry conditions than upland sites (T4x, Events 1 and 2,Figure 5.9), suggests that the proximity of Spencer Creek influences water table position in the adjacent riparian zone, which is further supported by Figure 5.3, where it was observed that stream-sourced events had a greater response in the lowland sites of the adjacent riparian zone.

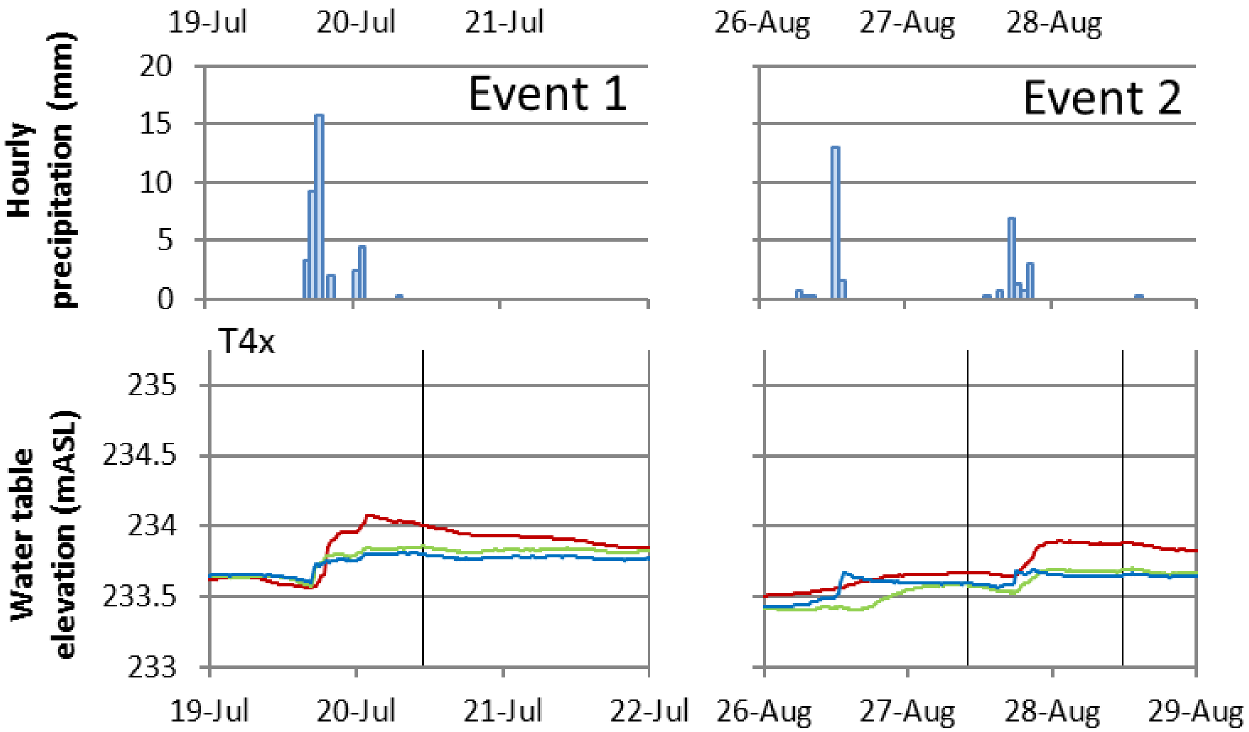

Figure 5.9: Larger display of event response of T4x during Events 1 and 2, as shown in Figure 5.8

Hydrologic response in upslope sites, in contrast to low-lying riparian sites , had greater ranges in water table position and variable response to precipitation events, particularly on the steeper transects (T4.25, T4.5, and T5, Figure 5.8), yet there was generally little variability in vertical hydraulic gradients (Figure 5.10, 5.11). Water table response time decreased and magnitude increased with increasing antecedent wetness; however, the high-intensity event on dry conditions (Event 1) triggered hydrological responses similar to those of the lower intensity event on wet conditions (Event 3, Figure 5.8). The exception to this was during Event 4 (32 mm of precipitation during flooded conditions) along the flat T4x (Figure 5.8), where minimal response was recorded due to antecedent conditions of extensive inundation. During extreme dry conditions, significant rainfall amounts can also elicit little response (Figure 5.8, Events 1 and 2) where subsequent precipitation triggers a greater response, suggesting that these sites may exhibit threshold responses once a moisture level is met. The falling limb of the response hydrograph in the upslope sites of T4.5 is generally more rapid upon the cessation of the precipitation, particularly notable in the Event 4 response (Figure 5.8) before transitioning to a gradual decline of water table position, unlike the other sites which exhibited only a gradual decline in water table position. Peak water tables at upslope sites in response to Events 1, 3, and 4 were very similar in elevation (Figure 5.8). The field observations from September 21 (Event 3, Figure 5.11) demonstrate that water table position at this time was at or slightly above the ground surface at this time, enabling overland flow to transport excess water downslope to the riparian zone. This shallow ponding at the field edge and overland flow was notably observed at T4.5 during this time.

Between the low and flat riparian zone and the upland sites is the break in slope, where steeper slopes transition into the riparian zone. This is generally the point around which the more responsive water table at upland sites transitions towards the less the responsive characteristics of riparian zone (Figure 5.10, 5.11). As was noted with vertical hydraulic gradients in Section 5.2.1, the break in slope is the position with the most variable, and occasionally locally-reversing, vertical hydraulic gradients, particularly during dry conditions (Figure 5.10, 5.11). In the comparisons of water table and corresponding vertical hydraulic gradient, it is apparent that changes in one did not correspond to changes in another. Water table position at T4.5 had minimal response to Event 2 (Figure 5.10), and yet, this corresponds to the greatest variability in vertical hydraulic gradients, both at this site, and through the study period. Conversely, site-wide water table response during Event 3 (Figure 5.11) did not correspond to

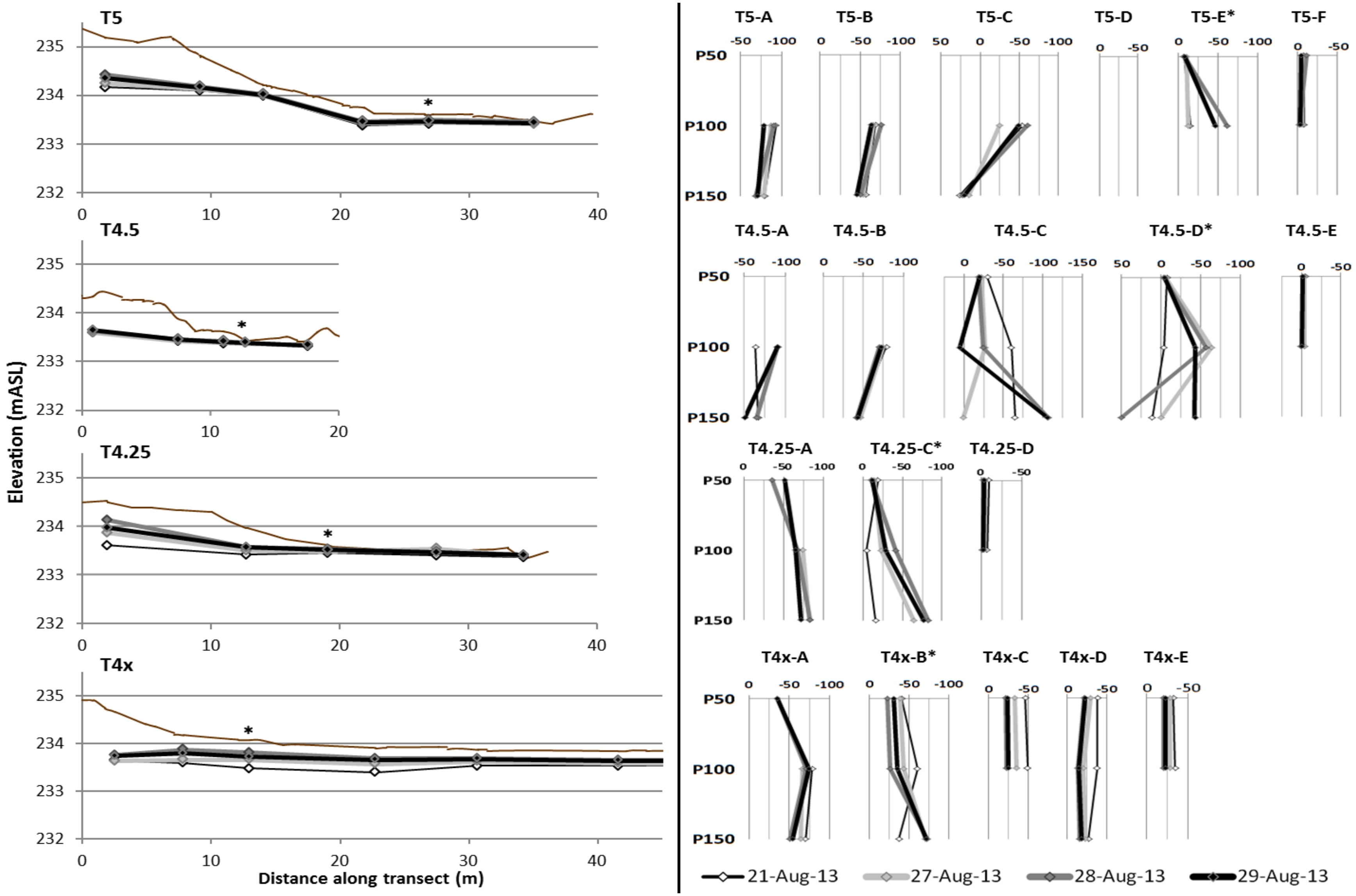

Figure 5.10: Water table and vertical hydraulic gradient response to Event 2. Vertical hydraulic gradients are plotted as hydraulic head realtive to ground surface (x) with depth (y). P50 piezometers were dry in upland sites of T4.5 and T5; piezometers had not been installed at T5-D prior to this event. Asterix marks break in slope site.

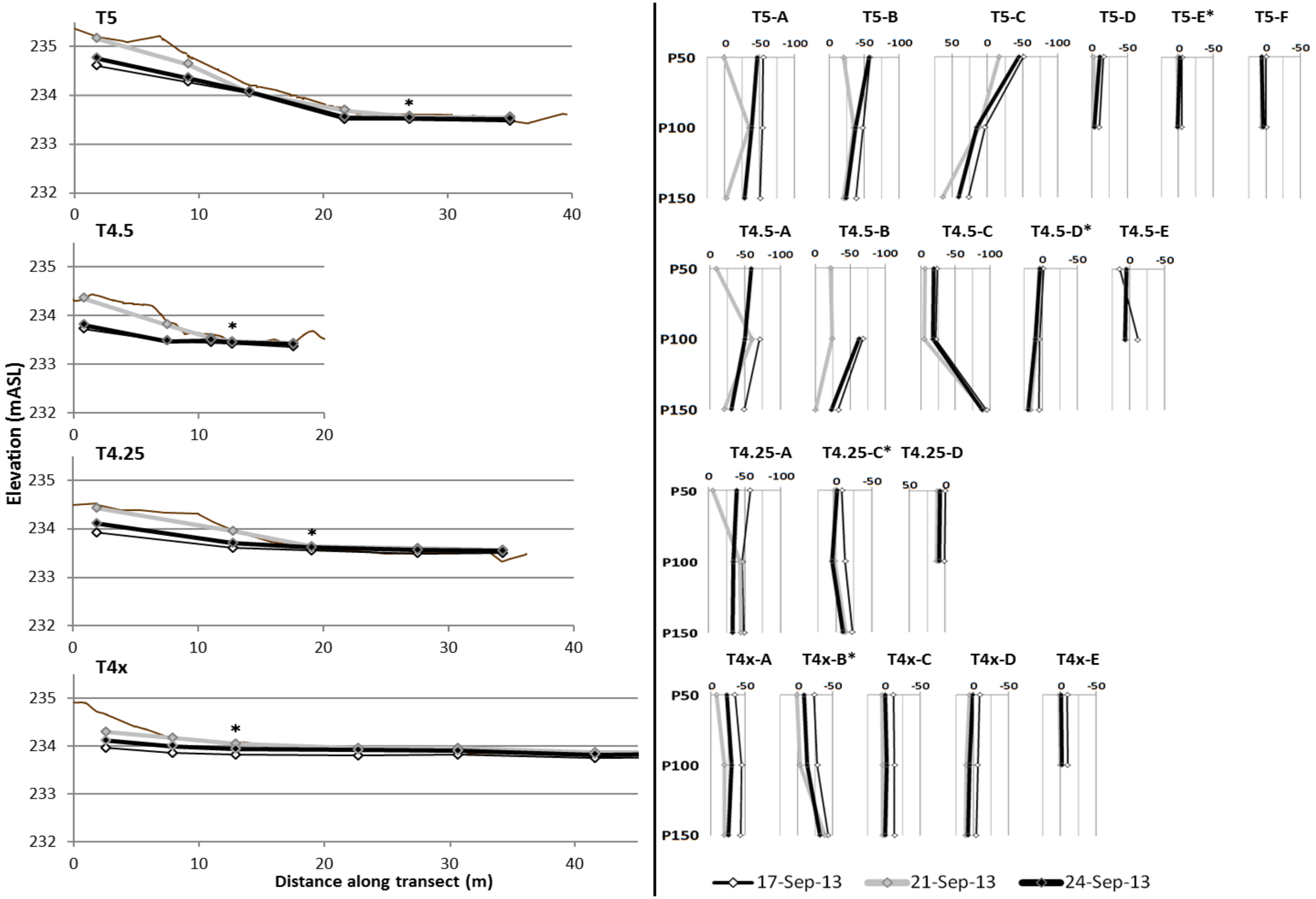

Figure 5.11: Water table and vertical hydraulic gradient response to Event 3. Vertical hydraulic gradients are plotted as hydraulic head realtive to ground surface (x) with depth (y). Asterix marks break in slope site

large shifts in vertical hydraulic gradients except at upslope sites where water table position was at the ground surface. In summary, upslope topographic gradient was not found to be a controlling factor of seasonal nor event response, a gradual drying period was followed by a more rapid wetting period, precipitation event response was dependent on antecedent moisture conditions and event properties, and the reservoir drawdown event triggered unique responses that were unlike seasonal and short-term event response.

6.0 Discussion

In this section, the influence of topography and hillslope will be discussed, followed by seasonal variability in hydrologic conditions and the effect of antecedent conditions on event response. Finally, the hydrologic response to the reservoir drawdown event is compared to natural seasonal and event responses at this site, before discussing the significance of this study for future hydrological and interdisciplinary research.

6.1 Influence of topography on hydrologic response

Previous studies investigating the role of site topography have indicated that surface topography could be a dominant factor in hillslope hydrology (e.g. Vidon & Hill, 2004; Winter, 1999). The previous study exploring topography as a driver in greenhouse gas flux in the hillslope-riparian zone area at this site was inconclusive (DeSimone, 2009). In the current study, it was believed that the experimental design based on frequent monitoring of transects over a topographic gradient would lead to the observation of a gradient in the seasonal and event-based changes in hydrologic conditions following the topographic gradient of these transects. The results show that this was not the case. While differences between the flattest (T4x) and steepest (T5) transects were observed, the two transects with moderate slope (T4.25 and T4.5) did not follow the same pattern. The responses recorded, particularly in the upslope areas of T4.25 and T4.5 were reversed from what would have been expected if topographic gradient was the dominant controlling factor, where the less steep T4.25 had greater responses than the steeper T4.5.

Additional factors that are expected to influence hydrologic response at this site include soil structure, and hillslope shape. Soil structure, shown to be highly variable both among and within transects in Figure 3.2, influences local hydraulic conductivity and hydrologic connectivity. Vidon and Hill (2004) found that the depth of upslope permeable soils influences the connectivity between upslope and riparian zone areas, where permeable sediments to a depth of at least 2 m facilitates permanent connectivity. At this field site, the upslope agricultural fields are underlain by at least 4 m of sandy till (Leach, 2009), and hydrologic data collected through the study support permanent hydrologic connectivity between the hillslope and riparian zone. Hillslope shape (i.e. concavity) has been shown to influence hydrologic properties by Devito, et al. (2000) and Vidon and Hill (2004). T4.25 was situated within a concave area of the adjacent field, in close proximity to the natural swale, increasing its upslope contributing area, while T4.5 was situated in a convex area of the field on an outside corner, restricting its upslope contributing area (Figure 3.1). It is likely that concavity was influential for event response at these transects, particularly at the upslope sites, where T4.25 consistently had greater water table fluctuations to both seasonal progression and event response than T4.5. This is also consistent with the findings of Jencso et al. (2009), where upland contributing area was the dominant variable controlling hydrologic response, with hillslope shape and topographic gradient, antecedent conditions, vegetation cover, and variability in precipitation accumulation also influencing watershed response.

6.2 Influence of landscape position on hydrologic response

Regardless of season and event inputs, the spatial pattern in water table position across the riparian zone, and through the lower portion of the adjacent hillslope, largely remained consistent through the study period. Vertical hydraulic gradients also remained consistent through the study period, maintaining very low gradients. An exception to this was observed at the position in the hillslope where the slope “broke” from steep to flat topography. These break in slope sites were much more responsive to both seasonal hydrological variability and to precipitation events (Figure 6.1) than either upland or riparian sites, which often maintained pre-event gradients through event responses (e.g. Figure 5.10, 5.11). Hydrologic response in break in slope sites is further discussed in the context of seasonal fluctuations, antecedent conditions, and event response in sections 6.3, 6.4, and 6.5, below.

Landscape position within the riparian zone was also found to affect hydrologic responses. In contrast to the findings of Montreuil et al. (2011), where low order streams have greater hydrological connectivity to hillslope hydrology, and high order streams have greater connectivity to adjacent streams water table position in riparian sites (particularly along T4x) was influenced by Spencer Creek. This is likely the result of artificial management of the discharge from the Valens Dam. The influence of Spencer Creek on riparian hydrology decreased with distance from the main channel. DeSimone (2009) also found that the stream stage of Spencer Creek influenced water table position in the area of T4x, and that this influence was not observed at T5. Duval and Hill (2006) found that perennial surface streams could influence riparian hydrology up to 25 m inland in similar glacial till landscapes. During periods of overland flow through the riparian zone for the current study, it was observed that surface water around the transects flowed faster and surface water elevation increased more around T4x, where the riparian zone was relatively narrow, compared to the other transects where the riparian zone becomes increasingly wide. Surface water in the riparian zone of T5, when present, remained stagnant through the study period. It could be expected that the hydrologic behaviour of Spencer Creek would have less influence on such more distant areas of the riparian zone, especially since they are not located parallel to the main channel (flowing to the southeast; Figure 2.5, 3.1).

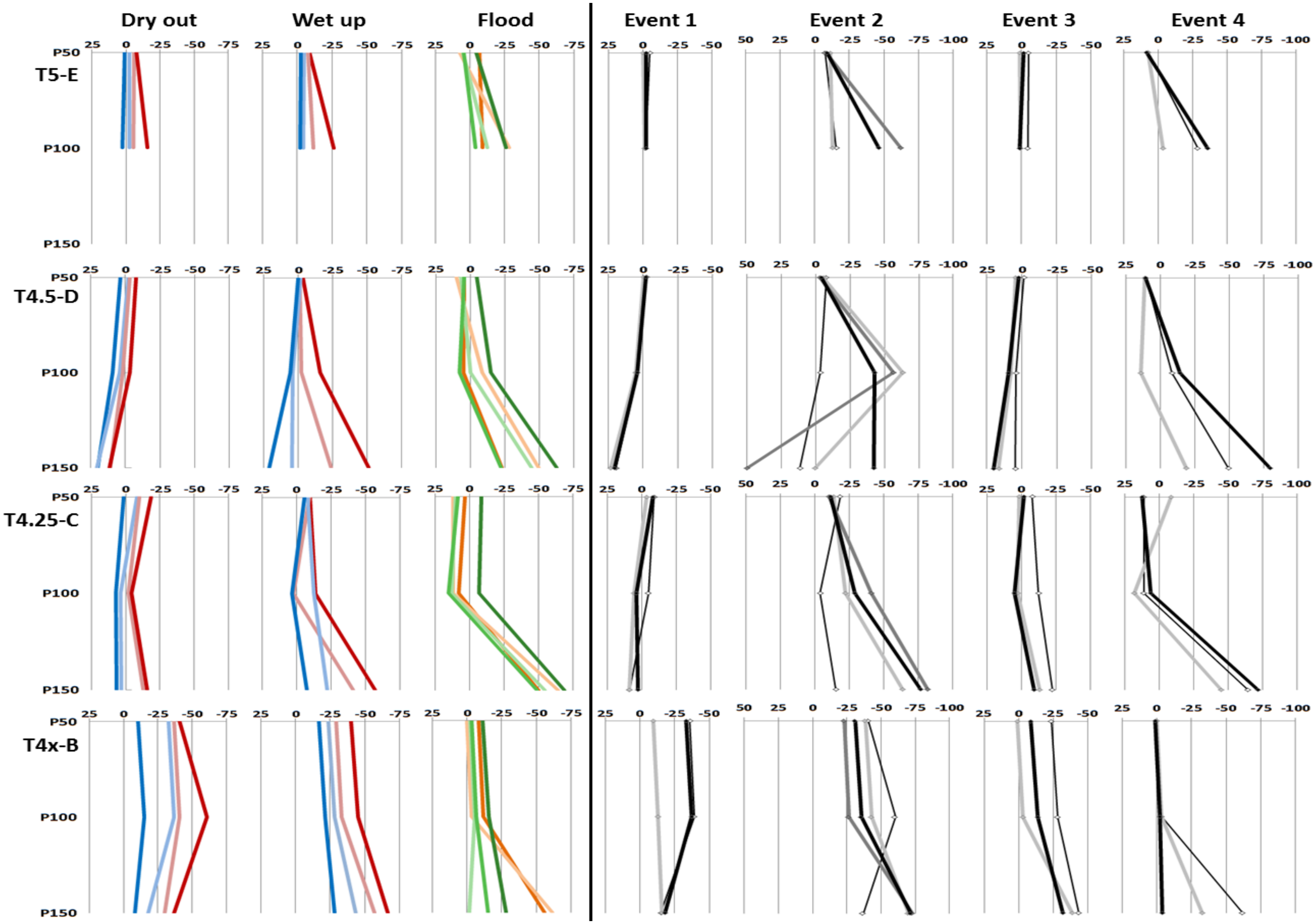

Figure 6.1: Comparison of vertical hydraulic gradient (plotted as hydraulic head realtive to ground surface [x] with depth [y]) between seasonal progression and event response at the break in slope position for each transect. Drying and wetting periods are coloured along progression between wet (blue) and dry (red) conditions. Flood period is coloured from antecedent wet (orange) to flood (green) and post-flood (dark green) conditions. Event response data is shaded from pre-event (thin black line, open point), "during" (light to dark grey line) and several days post-event (thick black line).

Hydrologic response at the break in slope, and low-slope positions for T4.5 and T5, were the most variable for both seasonal trends and event response as shown in Figure 6.1. Shallow vertical hydraulic gradients (i.e. between P50 and P100) are very similar, particularly between T4.5 and T5. Data showing the high variability of these gradients at depth (i.e. between P100 and P150) at T4.5 C and D (Figure 5.10 to 6.1) indicate that it is not unlikely that similar gradient fluctuations might have been found at depth in the low-slope and break in slope sites of T5 had the P150 piezometers been installed.

6.3 Seasonal variability of hydrologic conditions

Overall, drying conditions indicate slight upwelling to minimal vertical gradients at the break in slope position. During very dry conditions along T4x (Figure 5.10, pre-event water table position), a slight groundwater ridge appears to have formed in the mid-riparian zone, indicative of the influence of the adjacent Spencer Creek in this section of the riparian zone. There were no sites, however, that indicated strong riparian zone to hillslope water table gradients to indicate true flow reversals. Water table positions during the summers of 2011 and 2012 (Figure 5.3), however, indicate that a stronger and longer lasting groundwater reversal to stream-to-field flow pattern could develop during drier summers when water table elevation was recorded to be 0.23 mASL higher in the riparian zone than in the hillslope at T4x. This would be consistent with the findings of Duval and Hill (2006) and Burt, et al. (2002a), where groundwater reversals can be observed without flooded conditions and persist for longer periods of time.

As Leach (2009) found in her study, a gradual dry out period was followed by a more rapid wet up (also found in the current study). During this time, wetting conditions triggered a reversal in the vertical hydraulic gradients at the break in slope, particularly at T4x and T4.5 (Figure 6.1), from an overall signature of upwelling towards downwelling, supportive of recharging groundwater. As the wetting season progressed, vertical hydraulic gradients return to early drying trends.

6.4 Influence of antecedent moisture conditions on hydrologic response

Event response across the transects was similar for both high and low intensity events on dry (Event 1) and wet (Event 3) antecedent conditions, respectively, both in terms of water table fluctuation (Figure 5.8) and vertical hydraulic gradients (Figure 6.1), except for gradients at depth in the break in slope of T4x. The effect of dry antecedent moisture conditions in hydrologic response was exemplified by Event 1 at in the upslope sites of T4.5 and Event 2 most notably at T4x and T4.25, where the precipitation in the second part of the events elicited a disproportionate response in water table position than during the first part of the precipitation events (Figure 5.8). Events 3 and 4 exemplify the more rapid responses that are characteristic of wet antecedent conditions. Similar responses to varying antecedent moisture conditions have been reported in previous studies (e.g. Kaufman, 2002; Macrae, et al., 2010; Martin, 2011; Montgomery & Dietrich, 1995; Tromp-van Meerveld & McDonnell, 2006).

Event 2 triggered the initiation of the wetting period and was unlike the other precipitation events, with notable gradient changes, and occasionally, vertical hydraulic gradient reversals at the break in slope. Event response, particularly vertical hydraulic gradients, during Event 4, precipitation during flooded conditions, has a progression that is very similar to that of the flooded period. It is likely that any response observed in the riparian zone and break in slope during this time was more greatly influenced by the onset of the reservoir drawdown than the precipitation event during this time.

6.5 Hydrologic response to an upstream reservoir drawdown

The reservoir drawdown event resulted in a unique hydrological response at this study site. Contrary to the hydrological response during the natural wetting and drying periods, when water table position was most variable in the upslope areas of all transects (Figure 5.6), water table position remained constant in the upland areas with greater variability in the low-lying riparian zone during the reservoir drawdown period (Figure 5.7). Responses observed in vertical hydraulic gradients, however, largely resembled those of the wet up period (Figure 6.1). These gradients return to pre-flood conditions within several days after the flood in the two transects (T4x and T4.25) located closest to Spencer Creek, however, post-flood, vertical hydraulic gradients at the break in slope of the more distant transects (T4.5 and T5) elicit stronger downwelling trends than the wet pre-flood conditions.

The only notable exception to the trends in water table position during the reservoir drawdown event occurred at the midslope site on T5. Hydrologic properties of this site were unique as the water table position here was very stable through the study period with consistently strong upwelling gradients from depth; however, upon the onset of the reservoir drawdown, while vertical hydraulic gradients remained consistent, there was an unexpected, although slight, decrease in water table position (Figure 5.4, 5.7). Water table position in the mid-slope site on T5 did not return to pre-flood conditions in the post-flood days, unlike the riparian and low slope sites. This could be an indication that the Valens Lake reservoir and drawdown events, which could be as much as 949, 000 m^3 between recreational summer storage and minimum storage capacities (Hamilton Conservation Authority, 2012b), influence not only local water table position in the riparian zone, but that they also influence large-scale regional hydrological processes. Such large-scale connectivity is beyond the scope of this thesis, but is a topic that could be investigated in subsequent studies.

6.6 Significance

This thesis has used an integrated approach, combining the effect of landscape structure, seasonal variability in baseflow and antecedent moisture conditions, precipitation events and an anthropogenic reservoir drawdown causing long-term flooding of the site. Consistency in temporal trends within and between transects allowed spatial differences to become more apparent. This led to finding that landscape position, both along the hillslope-riparian zone continuum and proximity to a perennial stream channel in the riparian zone, has a strong influence on hydrologic response, for both water table position and vertical hydraulic gradients, with upslope concavity and contributing area influencing the magnitude and timing of hydrologic responses. Water table position is most variable, yet predictable, in upland sites, and vertical hydraulic gradients are most variable in break in slope sites, particularly for event response during dry antecedent conditions. The results of this study indicate that the hillslope gradient was not influential on riparian hydrologic responses; however, distance of the riparian site from the perennial stream, was shown to influence hydrologic response. This should be further examined in a study where similarly variable hillslope conditions might be present with a less variable riparian zone width, to reduce the unequal influence of surface water on the adjacent riparian zone. It is also suggested that a study be conducted on non-mountainous terrain with a range of steeper (greater than 9%) hillslope gradients, as topography could become a more dominant driver under steeper conditions.

6.6.1 Limitations of this study

There are several limitations to this study. Transects, with the exception of T4x, did not have P150 piezometers installed within the riparian zone, nor did the break in slope site of T5. As a result, vertical hydraulic gradients could not be measured below 1 m below the ground surface. The behaviour at the break in slope sites indicate that the gradient between the P100 and P150 piezometers (Figure 6.1) indicate that vertical hydraulic gradients can be greater below the P100 piezometer. Findings indicating that T4x was more strongly influenced by the nearby Spencer Creek than the riparian areas of the other transects indicates that the very low vertical hydraulic gradients observed at depth in the riparian zone of T4x (Figure 5.10, 5.11) may not be representative of those in the riparian areas of the more distant transects particularly T4.5 and T5.

Previous studies at this site had indicated that the dominant flowpath in riparian zone around T4x flow obliquely from the field towards the stream (Leach, 2009; Zhang, 2007). T4x is believed to be placed along this flow line, however as no parallel transects were monitored in this area, it cannot be confirmed that this transect follows the flow line. Similarly, the other transects running parallel which are believed to be along the flow line did not have a second parallel transect nearby to confirm this. The distance between monitored transects was too great to reliably attempt to infer site-wide groundwater flow paths.

6.6.2 Application to interdisciplinary research

Hydrological processes in wetlands are an integral part of their ecosystem functioning, particularly in nutrient cycling (Burt & Pinay, 2005; Junk, et al., 2013; Mitsch & Gosselink, 2007; Reddy & DeLaune, 2008), but such biogeochemical processes are spatially and temporally variable, and have often been suspected to be situated near the interface between terrestrial and aquatic systems (McClain, et al., 2003), which is approximated in this study as the break in slope sites. DeSimone (2009) found that nitrogen species were mitigated within 10 m of the field edge, which on most transects at this site would represent the break in slope. McClain et al. (2003) suggest that “hot spots” and “hot moments”, spatially and temporally localized periods of high biogeochemical processes, correspond to converging flowpaths and hydrological disturbances. Findings from this study indicate that the hydrological processes in the break in slope are unlike upland or riparian processes occasionally with converging in-situ vertical hydraulic gradients (e.g. T4.5-D, Event 2, Figure 6.1), and could be influential on biogeochemical processes. Additionally, since the changes in water table position and vertical hydraulic gradients do not appear to be co-dependent, studies attempting to draw conclusions regarding biogeochemical processes should monitor both water table position and vertical hydraulic gradients.

7.0 Conclusions and recommendations

Few studies had previously attempted to incorporate multiple variables such as seasonal variability in antecedent conditions and natural (climatic) and anthropogenic (reservoir release) event response along a topographic gradient to understand complex hydrologic processes in the hillslope-riparian zone continuum. The purpose of this study was to investigate combined influence of these variables on hydrological responses in both water table position and vertical hydraulic gradients.

Hydrological seasonal trends of highest water levels during the spring followed by decreasing water levels as evapotranspiration increases through the spring and summer, and rewetting through late summer and early autumn storm events coinciding with decreases in evapotranspiration are clear within this site with an artificially modified hydrological regime, regardless of whether seasons are wetter or drier than normal. It is also clear that event response is strongly influenced by the combination of antecedent moisture conditions and precipitation intensity and duration.

Spatial variability within the study site was found to be much greater than temporal variability. Hydrologic variability, both water table position and vertical hydraulic gradients is low in the riparian zone, although the influence of fluctuating stream stage in Spencer Creek is observed in the transect situated in closest proximity. Overall, there is a low variability of vertical hydraulic gradients in upslope areas, although this is where water table position is most variable, particularly on the steeper transects, where the upslope sites are elevated sufficiently to be minimally influenced by processes within the riparian zone. These sites are also more responsive to precipitation events than the low-lying riparian areas. Seasonal progression and event response did not follow the topographic gradient along which the transects were placed. It is believed that while slope steepness may be a contributing factor in hydrologic response, additional factors including upland concavity, catchment area, and soil heterogeneity also influence hydrological response.

The sites that were located at the break in slope had the most variable vertical hydraulic gradients, which were heightened under extreme conditions such as dry antecedent conditions or excessive inundation resulting from the reservoir drawdown. Anthropogenic flooding on wet antecedent conditions results in a greater response with lasting influence. The monitored precipitation event that coincided with mid-flood conditions was indistinguishable from surrounding flood conditions.

Future studies should consider the influence of upslope concavity in transect placement to select areas that would have similar upslope properties, reducing the influence of this variable on results. The high variability found in break in slope sites, suggests that both water table position and vertical hydraulic gradients should be monitored in order to fully comprehend hydrological characteristics of a site. Monitoring such sites at depth would also be beneficial, based on the apparent high variability between shallow and deep vertical hydraulic gradients as observed in T4.5. Further studies to investigate the influence a reservoir drawdown type event might have on the regional water table in upland areas are also recommended.

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