Riverine Landscape of the Middle Platte River: Hydrological Connectivity and Physicochemical Heterogeneity

by

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Riverine Landscape of the Middle Platte River:
Hydrological Connectivity and Physicochemical Heterogeneity

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University of Nebraska, 2003

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Fluvial processes create diverse riverine habitats and sustain hydrological connectivity across broad floodplains of the Middle Platte River. The riverine habitats have hierarchical characteristics and distinctive temporal variability. River regulation reduces the hydrologic fluctuation and the degree of surface hydrological connectivity between the river flow and the riverine habitats in the floodplain.

Two fundamental questions are: (a) how does hydrology of riverine habitats respond to river discharge? (b) what are the riverine landscape patterns as results of the hydrological change? It was hypothesized that discharge and hydrological connectivity are the main factors controlling diversity of the riverine habitats and patterns of the riverine landscape.

The hydrological connectivity was determined by quantifying hydrological connections and interactions between the riverine habitats and the main channel in landscape scale. Multiple correlation and regression methods were used to quantify the hydrological interactions. The results suggest a rank of the hydrological connectivity between the riverine habitats and the main channel (from high to low) as: side-channel, disconnected backwater, connected backwater, wet meadow pond, riparian pond, tributary, permanent slough, and intermittent slough.

Physicochemical and spatial analysis results reveal the riverine habitat heterogeneity and landscape patterns in response to the river discharge. The hydrological connectivity serves as a driving force for biodiversity of the river ecosystem. Thus, an effective biodiversity conservation strategy should focus on sustaining hydrological connectivity, so that the river itself may maintain its braided flowpaths and maintain hydrologic and ecologic interactions among riverine landscape components.

This research contributes to our understanding of the complexity of the riverine landscape in the Middle Platte River. It is also relevant to a fundamental question: how does the hydrological connectivity affect the river ecosystems? The study results (The landscape digital maps, hydrological and physicochemical data) show clearly the riverine landscape patterns and the effects of hydrological and climatic factors on the landscape processes. These results may serve for river ecosystem assessment, planning, habitat conservation and restoration, and water resources management.

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Chapter 1. Introduction

1.1 Ecological significance of the riverine landscape in the Middle Platte River

The riverine landscape of the Middle Platte River floodplain is a mosaic of diverse habitats, including braided stream channels, backwaters, wet meadow sloughs, and ponds in riparian woodlands, grasslands, and wet meadows. These habitats are essential for wildlife and the river ecosystem due to their transitional locations between main channels of the river and croplands on the floodplains. The riverine habitats function as breeding sites and refuges for fish, amphibians, and other aquatic biota. They also provide diverse food sources and serve as a feeding ground for other wildlife on floodplains. For example, emerging aquatic insects in shallow water ponds, backwaters, and sloughs are biologically important to vertebrate groups such as birds (Gray 1993; Cox and Kadlec 1995).

The importance of survival of diverse, endemic populations of fish species is not only to support fish biodiversity of the Middle Platte River ecosystem, but also for other federally listed, endangered birds, like the least tern, that feed on the fish (U.S. EPA 1998a). Previous habitat suitability and discharge studies in early 1990's did not address the quantity or quality of the riverine setting, or that of wet meadow habitats outside the main channel (USBR 1990). Great attention in research have been given to the question of the sustainability of migratory and resident birds and other biota, but less concern was focused on how the entire river ecosystem has adjusted to changes in the stream flow.

An ignored aspect is the importance of hydrological interactions between the braided main channel network and the diverse riverine aquatic habitats in the river ecosystem, especially impacts of the channel network and stream flow changes on associated riverine aquatic habitats in the floodplain ecosystem. This lack of understandings of hydrological and fluvial geomorphological properties of the riverine habitats has been considered as a part of the reasons of failure in some conservation experiments, such as an attempt to construct a low-level dam to raise the water level for a meadow habitat (Currier and Goldowitz 1994).

1.2 Biodiversity of the floodplain river ecosystems

Biodiversity is a broad and integrative concept including four levels of organization: genetic level, population/species level, community/ecosystem level, and landscape level (Noss 1990, Ward et al. 1999b). At each of the levels, there are different diversities of the primary ecosystem attributes, i.e. composition, structure and function (Franklin 1988, Noss 1990). For example, the structure diversity may include habitat diversity at the ecosystem level, and geomorphic patterns at the landscape level. Examples of the functional (process) diversity are patch dynamics at the ecosystem level, and disturbance regimes and hydrological processes at the landscape level. Some structure and function diversity may cross different diversity levels, such as ecotone structure and connectivity function may be seen at both ecosystem and landscape levels (Noss 1990, Ward et al. 1999).

Floodplain rivers are among the most diverse environments of the world, because they are disturbance-dominated ecosystems and characterized as high level spatiotemporal heterogeneity, and habitat and biota diversities (Junk et al. 1989; Petts and Amoros 1996; Ward and Stanford 1995b; Ward et al. 1999b). As Ward, Tockner, and Schiemer (1999) stated, "the fluvial action of flooding and channel migration create a shifting mosaic of habitat patches across the riverine landscape. Ecotones, connectivity and succession play major roles in structuring the spatiotemporal heterogeneity leading to the high biodiversity that characterizes flood plain rivers" (Ward, Tockner, and Schiemer 1999).

Hydrological connectivity refers to the transfer of water between the river channel and the floodplain and between surface water and groundwater system. It has important significance for biodiversity patterns and processes (Ward, Tockner, and Schiemer 1999). Therefore, maintaining and restoring hydrological connectivity between backwaters, wet meadows and river main channels through surface flows were set as management objectives to support key ecological functions and native biodiversity in the Middle Platte River (Nebraska Game and Parks Commission 1993a; Zuerlein 1993; U. S. EPA 1997).

1.3 Hydrological influence to the riverine landscape and the biodiversity

Recent study results suggested that hydrological fluctuation in the aquatic habitats could be an important environmental factor that is responsible for the changes of aquatic biotic species composition. Goldowitz and Whiles (1999a, 1999b) reported that the types of the aquatic habitats used by aquatic invertebrate, amphibian, and fish communities in wet meadow sloughs and the seasonal patterns of biomass emergence depended on the hydrologic regime of wet meadows and adjacent river channels. The dominant amphibian species occupied distinctly different breeding habitat among the ephemeral wetted, permanent wetted, and intermittent wetted sites. Richness and biomass production of emerging aquatic insects were highest at intermittent sites, while, fish only used the intermittent site in spring as a spawning and nursery area. They also found that the highest species richness of fish was at the perennial site, but the species composition changed dramatically over the study period (Goldowitz and Whiles 1999a, 1999b). Consequently, it is ecologically important to understand patterns of the hydrologic fluctuation and hydrological linkages between the river main channel and the riverine habitats.

Influence of river discharge on hydrology of wet meadow habitats has been studied, and a number of research projects conducted in the Middle Platte River mainly focused on changes in the groundwater table in several large wet meadow areas (Goldowitz and Whiles 1999a, 1999b; Henszey and Wesche 1993; Hurr 1983; Sidle 1989; Sidle and Faanes 1997). It was recognized that groundwater hydrology in wet meadows is driven by river stage, precipitation, and evapotranspiration (Henszey and Wesche 1993; Hurr 1983). Currently however, there still is a lack of knowledge on hydrological linkage and interaction between the main channels and those wet meadow sloughs and other types of riverine aquatic habitats, such as backwaters and side-channels in the braided river landscape.

To meet the objectives of maintaining and restoring hydrological connectivity between riverine habitats and the main channels through surface flows, it is critical to understand the hydrological connection among the riverine habitats, their spatial and temporal changes, and interactions of surface water and groundwater under the habitats in this braided flow system. A fundamental knowledge and interdisciplinary theory are needed for better management and restoration of the riverine aquatic habitats for biodiversity of the river ecosystem.

1.4 Research questions, goals, and objectives

From viewpoints of hydrology, river morphology, and ecosystem processes, specific research questions relevant to fundamentals of sustaining or rehabilitating the riverine landscape for biodiversity are: (a) What types of riverine habitats exist on the braided floodplain of the Middle Platte River? (b) What are the characteristics of riverine habitats in a braided river? (c) How do the riverine habitats respond to the river discharge regime? (d) Are there any differences among the diverse riverine habitats in terms of their morphological, hydrological and physicochemical features? The presented study focuses on the above questions. In this study, riverine habitat diversity was analyzed in the context of a braided river floodplain ecosystem, with emphases on hydrological connectivity and physicochemical attributes at the habitat and landscape scales.

The goals of this research were to understand the hydrological interaction between the main channel and diverse riverine habitats on the Middle Platte River floodplain; and to integrate this knowledge with other information to evaluate the hydrologic effects of surface water changes on target habitat areas at a riverine landscape scale.

The specific research objectives were to:

(a) Classify the diverse riverine habitats and braided flow network system from hydro-geomorphological perspective;

(b) Examine the riverine habitat hydrology and fluvial geomorphology in response to the instream flow changes at the habitat and landscape scales;

(c) Analyze the hydrological dynamics of the riverine aquatic habitats, and identify key environmental factors driving the interactions between the main channel instream flow and the riverine habitats at habitat and landscape scales (statistical modeling);

(d) Analyze the riverine landscape spatial patterns using "simultaneous" remote sensing images on one study site (GIS modeling), and link the spatially explicit changes of the landscape patterns to the hydrological dynamics; and

(e) Determine heterogeneity of the braided river landscape from physicochemical perspective in context of the aquatic habitats and at the bimonthly scale.

Chapter 2. Review of Theories and Approaches to the Riverine Landscape

2.1 Basic theories of ecological Approach to streams and rivers

2.1.1 The river-continuum concept

The river-continuum concept (RCC) (Vannote et al. 1980) was initially formulated from observations of undisturbed, stable, forested watersheds. It describes the longitudinal structure of a forested river system from the headwaters to the mouth. The concept predicts the structure and function of biotic communities along the river continuum based on the variability of the environmental factors and the source of energy for biological production (Vannote et al. 1980).

Ward and Stanford developed a corollary of the RCC, the "serial discontinuity" concept in 1983, which addresses the effects of dams on rivers (Ward and Stanford 1983).

During the 1980's and 1990's, the hypothesis of the river-continuum concept was tested in many streams and rivers. The results suggested that the applicability of the RCC to large rivers is limited, particularly rivers with floodplains (Johnson et al. 1995; Sedell et al. 1989). In addition, because the RCC does not consider interactions between the river channel and its floodplain, the predictions of the RCC relate only to the main channels of rivers, ignoring backwaters, wet meadows, and floodplain lakes (Johnson et al. 1995). To overcome these shortcomings, both of the river continuum concept and the serial discontinuity concept were modified by considering lateral, vertical, and temporal dimensions (Sedell et al. 1989; Ward 1989; Stanford and Ward 1993; Ward and Stanford 1995a). These modifications led to considerations of interactions between aquatic and terrestrial ecosystems as land/water ecotone studies (see below for detail).

2.1.2 The flood-pulse concept

In contrast to the RCC, the flood-pulse concept (FPC) (Junk et al. 1989) introduced a lateral dimension to the dynamics of large rivers. The FPC describes interactions among aquatic and terrestrial organisms, nutrients, and sediments associated with the annual flood pulse in a large river, which extends the river onto the floodplain (Bayley 1995; Johnson et al. 1995; Junk et al. 1989).

According to the FPC, the lotic system includes the main channel, off-channel water bodies, and periodically flooded areas. Floods act as the principal agent controlling the adaptations of most of the biota. Regular flood pulses enhance biological productivity and maintain biodiversity in both the floodplain and main channel (Bayley 1991, 1995). Aquatic organisms migrate out of the channel during a flood and onto the floodplain to use available habitats and food sources. A fresh supply of nutrient-rich sediment is deposited on the floodplain with each flood pulse event. When floodwater recedes, various newly produced biomass, organic matter and nutrients from the floodplain are transported back into the main channel, side channels, and backwaters (Junk et al. 1989; Johnson et al. 1995). Consequently, the floodplain is highly productive and contains a variety of aquatic habitats, such as backwaters, riparian woodlands, wet meadow, wetlands, and shallow lakes. Therefore, Bayley (1995) argued that: "the flood pulse is not a disturbance; instead, significant departure from the average hydrological regimen, such as the prevention of floods, should be regarded as a disturbance" (Bayley 1995).

The FPC hypothesizes that the typical annual hydrological process is the principal driving force, and that a gradient of plant species adapted to seasonal degrees of inundation, nutrients, and light exists along the aquatic/terrestrial transition zone, which is subsequently referred to as the floodplain (Bayley 1995; Junk et al. 1989). However, a river system on a floodplain is spatially and temporally complex and largely organized as a nested hierarchy (Johnson et al. 1995; Frissell et al. 1986). In a nested hierarchy, physical and biological processes, functions, and organization are heterogeneous and scale-dependent (Naiman and Decamps 1990). The appropriate scale for analysis of the aquatic/terrestrial transition zone, later here referred as the riverine ecotone on the floodplain, must be determined by research objectives and studied field settings.

2.1.3 Hyporheic zone and groundwater/surface water ecotone concepts

Water flows in streams and rivers are not only longitudinal and lateral, but also vertical through the streambeds and bank sediments. The "hyporheic zone (HZ)" and the "groundwater/surface water (GW/SW) ecotone" are two ecological terminologies that have been used in studies of streambed or shallow ground water eco-hydrology.

A "hyporheic zone (HZ)" is a subsurface area of a stream where shallow ground water and stream water interact. Ecological research in the hyporheic zone began in the mid

1960's and mainly described the biological community and hydrology of the hyporheic zone as an integral part of the fluvial ecosystem (Brunke and Gonser 1997).

A functional interpretation of the term "ecotone" was provided by Holland (1988), emphasizing all exchanges (i.e. water flow, biotic and abiotic fluxes) between adjacent systems. Most of the land/water ecotone studies have focused especially on the riparian zone and its effects on land-water interchanges (e.g. Malanson 1993, Naiman and Decamps 1997). At the First International Workshop of Land/Water Ecotones in May of 1988, Janine Gibert initially presented the "groundwater/surface water (GW/SW) ecotone" concept, which has been developed with this later perspective of ecotone that emphasizes exchanges (Di Castri et al. 1988; Vervier et al.1997). Therefore, in floodplain rivers, ecotones may occur over a range of scales, forming boundaries between land and water, surface water and groundwater, and even between in-stream habitat patches (Ward et al. 1999)

A main conceptual difference between the hyporheic and ecotonal concepts is the way that each is studied (Vervier et al. 1997). One has to locate a hyporheic zone by its definition before studying the processes and exchanges that occur within this zone. These processes in the HZ are often studied alone without considering relation to or effect on adjacent systems. GW/SW ecotone, on the other hand, is identified by where the shallow ground water and surface water systems interact, and is always intrinsically connected to these adjacent systems (Vervier et al. 1997; Decamps 1993). Another difference is that HZ is specific term used for stream study, while term of GW/SW ecotones can be used anywhere interaction of surface water and ground water occurs. We may consider the hyporheic zone as a special form of the SW/GW ecotone that occurs in stream and rivers. Understanding the differences and the similarities of these concepts would be helpful for making conceptual models, designing research plans, and selecting methodologies in research relevant to shallow ground water study in stream, wetland, and other ponding surfaces.

Interactions and exchanges occurring in GW/SW ecotone are strongly influenced by hydrological processes (Gibert et al. 1990; Hakenhamp et al. 1993). As a fluvial boundary of a stream, the interaction of surface water and ground water results in increased solute storage and retention (Harvey and Fuller 1998; Triska et al. 1989). Below a streambed, the hyporheic zone plays an important role in reactive solute reaction and transportation in drainage basins (Harvey and Fuller 1998). Indeed, the role of the GW/SW ecotone is strongly controlled by direction and flux of water flow through the ecotone. The flux of water and direction of flow are determined by hydrology of both the adjacent systems (Vervier et al. 1992). Thus, a broader perspective of the surface water and groundwater interactions across and between surface water bodies is needed (Sophocleous 2002). Recent developments in hydrogeologic and fluvial geomorphologic disciplinaries have advanced the study of the SW-GW interactions.

2.2 Hydrogeological approach to the river-aquifer interaction

Over the last ten years, hydrogeologists began to shift their focus to near river channel and in-channel exchanges of water between an aquifer and a river. A floodplain and associated channel systems are no longer treated by hydrogeologists as recharge or discharge zones for regional groundwater systems (Winter et al. 1998; Woessner 2000) when biological and ecological processes are the research focuses. Brunke and Gonser (1997), Hayashi and Rosenberry (2002), and Sophocleous (2002) provided comprehensive reviews on interactions between groundwater and surface water and effects of that on the hydrology and ecology of surface water. It has been emphasized that characterizing the SW-GW interaction near a river in large scale and estimating direction and extent of the groundwater systems become very critical steps in studies of the river ecosystem.

2.2.1 Control factors on the river-aquifer interaction and groundwater flow systems

Large-scale surface water and groundwater (SW-GW) interaction in streams and rivers is primarily driven by three control factors: geomorphology, geology, and climate (Toth 1970). The magnitude and direction of a river flow in its channel are affected by the riverbed slope, roughness, channel geometry and position, sediment, and water input from rainfall, snowmelt, and groundwater discharge. Groundwater flow systems in a river valley are developed according to the topography, which determines the distribution of the water-table surface, and affects the distribution of the sediment. Climatic factors (such as precipitation, temperature, evapotranspiration, etc.) affect groundwater recharge and discharge. All three factors have to be taken into account for a comprehensive understanding the surface water-groundwater interaction (Sophocleous 2002).

As the control factors change over a watershed, directions of groundwater systems may vary place to place depending upon spatial and temporal scales. Three types of hierarchical nested groundwater flow systems may be recognized at a river basin scale (Toth 1963): local, intermediate, and regional flow systems. A local flow system discharges to a nearby stream or river. A regional flow system covers large areas of the basin, travels greater distances than the local flow system, and drains to a main river or to sea or a big lake. The intermediate flow system may be observed at a reach scale with varying landscape positions between its recharges and discharge areas (Sophocleous 2002).

Larkin and Sharp (1992) presented a classification scheme for alluvial aquifers based on predominant regional groundwater components. First, they defined two Darcy flux end-member components for describing the groundwater flow directions: (a) the "baseflow component" moves perpendicular to a river, either toward or away from the river; and (b) the "underflow component" moves parallel to the river and in the same direction as the river flow. Based on their analysis and modeling results on relationship between river-basin geomorphology, alluvial aquifer hydraulics, and groundwater flow directions in 24 fluvial systems, they classified stream-aquifer systems into three types: the baseflow component dominated, the underflow component dominated, and the mixed. The analysis results of Larkin and Sharp (1992) suggest that:

(a) There are varied predominant baseflow, underflow, or mixed flow conditions in near-channel areas depending on temporal and special scales, in response to change in the river stage.

(b) The underflow and mixed flow components "can be dominant on floodplains where the lateral valley slope is negligible" and "may also develop when there is a high degree of connection between the aquifer and the river" (Larkin and Sharp 1992).

Woessner (2000) summarized the complex interaction between streams and groundwater systems at the fluvial plain and channel scales. He illustrated four forms of the surface-water and groundwater (SW-GW) exchanges occurring near-channel and in-channel in the high hydraulic conductivity fluvial plain at a reach scale: gaining, losing, parallel-flow, and flow-through reaches. An important next step, as Woessner pointed out, is to examine the SW-GW exchange processes in large stream-fluvial plain systems over multiple geomorphic and climatic conditions (Woessner 2000).

2.2.2 Mechanism of the stream-aquifer interaction

As Sophocleous (2002) pointed out, the direction of exchange flow varies as a function of the difference between the river stage and the aquifer head. Rushton and Tomlinson (1979) considered a simple mechanism that controls the groundwater flow between the river and the aquifer as leakage through a semi-impervious stratum in one dimension. Based on Darcy's law, this mechanism can be expressed as:

$$q = k_1 \Delta h + k_2[1 - \exp(-k_3 \Delta h)], \tag{2-1}$$

where q is flow between the river and the aquifer (positive for baseflow -- for gaining streams; and negative for river recharge -- for losing streams); k_1, k_2, and k_3 are constants representing the streambed leakage coefficients (hydraulic conductivity of the semi-impervious streambed stratum divided by its thickness); $\Delta h = h_a - h_r$ (h_a is aquifer head, and h_r is river head) (Sophocleous 2002).

In reality, nature of the river-aquifer exchange processes is multidimensional. Spatial variation of both the river morphology and fluvial sediment properties may affect the stream-aquifer interaction. As Sophocleous et al. (1995) summarized, three significant factors need to be considered in solving the river-aquifer problems. They are: stream penetration, streambed clogging, and aquifer heterogeneity. Numerous one-dimensional, analytical solutions have been developed to incorporate the first two factors, for examples, fully penetrating stream without streambed clogging (Theis 1941; Jenkins 1968) and with streambed clogging (Hantush 1965), and partially penetrating stream with streambed clogging (Zlotnik and Huang 1999). For a better understanding of the stream-aquifer process, multidimensional solution and simulation are needed to count for effect of the aquifer heterogeneity and variability of the stream morphology. Unfortunately, most of the multidimensional models today cannot deal with the local phenomena related to flow near domain boundaries (Sophocleous 2002). Another alternative is using statistical estimation and evaluation methods on the spatial distribution of groundwater tables (Sepulveda 2003), or geo-statistical and GIS methods for hydraulic properties over a large scale (Pinder 2002).

2.2.3 Hydrogeologic research on the Middle Platte River

The braided reaches of the Middle Platte River were typified as the classic "Platte-type" braided model by Miall (1996) based mainly on N.D. Smith's work (Smith 1970, 1971,1972). Complexity of surface water and groundwater interactions in broad and braided rivers like the Middle Platte River is profound and unique. Hydrogeological research tasks have been conducted mainly on the river valley to basin scale over the last century (Bentall 1975; Hurr 1983; Eschner et al. 1983; Landon et al. 2001; Lugn and Wenzel 1938; Lyons and Randle 1988; Peckenpaugh and Dugan 1983). Recently, a cooperative program, the Cooperative Hydrology Study (COHYST), has been carried out at the basin scale in order to develop scientifically supportable hydrologic databases, analyses, and modeling on the Platte Basin in Nebraska (COHYST 2002). However, there were only a few hydrogeologic studies done at a reach scale (Hurr 1983; Henszey and Wesche 1993; Wesche et al. 1994).

One challenge for hydrogeologists is to determine the spatial distributions of hydraulic conductivity (K) over a broad and braided river floodplain. The Middle Platte River is a shallow, wide (about 2 km), perennial, sand-bed braided river that partially penetrates (1.8 to 2.4 m) a relatively permeable alluvial aquifer, and may have many flow-through or parallel-flow reaches (Eschner et al. 1983; Landon et al. 2001; Woessner 2000; Miall 1996). As a part of the COHYST, Landon and others (2001) compared multiple instream methods for measuring hydraulic conductivity in the sandy and gravel streambeds of the Platte River. They reported hydraulic conductivity values of 50 to 150 m/day in the main channel and 15 to 55 m/day in the tributaries by using different instream test methods. They also determined that the streambed interface is not a low K layer relative to underlying deposits on any of the streams investigated (Landon et al. 2001).

Hurr (1983) provided a detail hydrogeological study report for a wet meadow habitat of the Mormon Island Wildlife Preserve Areas of the Middle Platte River in Hall County (one of my study areas). He estimated a hydraulic conductivity of 45 m/day and a specific-yield value of 0.10 for the alluvium in the wet meadow and the vicinity of the island (Hurr 1983). Henszey also estimated same specific-yield value based on groundwater flux in response to precipitation in the wet meadow (Wesche et al. 1994).

The alluvial substratum of the Platte River floodplain is generally thick and uniform with saturated thickness ranging from 46 to 70 m (150 to 250 ft) along the broad river valley, as reported in previous hydrogeological surveys (Bentall 1975; Hurr 1983; Lugn and Wenzel 1938). For instance, Hurr (1983) reported a test hole showed an alluvial sand/gravel aquifer beneath the Mormon Island wet meadow area to be 41 m (135 ft) thick. Below is a layer of silt and clay, which does not contribute to the short-term groundwater responses measured in the upper part of the aquifer (Hurr 1983).

A number of aquifer-test determinations of transmissivity (T) and coefficient of storage (S) for the river valley were reported. They are summarized as: T = 720-2900 m^2/day, S = 0.01-0.18 for the portion of the river valley in the Hall County; and T = 2400 m^2/day, S = 0.07 for that in the Buffalo County (Bentall 1975). There are no reported T and S values for the region in or near the river main channel on the floodplains.

Another hydrogeological challenge is to determine patterns of SW-GW interaction across the floodplains in the Middle Platte River, which is dominated by braided streams and other types of riverine water bodies. Previous investigations (Henszey and Wesche 1993; Hurr 1983; Lugn and Wenzel 1938; Stanton 2000) suggested that the Platte River main channel interacts with adjacent aquifers as both a gaining stream and losing stream depending on longitudinal locations of the reach and dynamic of the instream flow. Lugn and Wenzel (1938) stated “the slope of the water table near the Platte River is almost parallel to the stream, thus indicating that fluctuations of the water table or changes in discharge of the river may cause the Platte to become either a losing or a gaining stream”.

A number of studies address the influence of river discharge on the hydrology of wet meadow habitats in the Middle Platte River (Hurr 1983, Henszey and Wesche 1993, Wesche et al. 1994). The results suggested that the main channel river stage, precipitation, and evapotranspiration drive the groundwater hydrology in wet meadows. Hurr (1983) stated that “the change of groundwater level will occur within approximately 24 hours in areas along the river’s edge as much as 762 m (2,500 ft) wide.” However, the response of wet meadow sloughs to changing hydrologic conditions has not been well understood. The recognition of the geomorphology and groundwater flow relationship is important for studying the sloughs and other riverine water bodies in the floodplain fluvial systems.

2.3 The riverine landscape -- a holistic perspective

Paralleling the GW-SW ecotone studies in the last 15 years, some stream biologists and ecologists adapted the concept of patch dynamics from the discipline of landscape ecology to address basic questions in lotic system ecology (Malard et al. 2002; Malanson 1993; Pringle et al. 1988; Townsend 1989). In the past seven years, tools and techniques of landscape ecology have been pervasive in publications on lotic system ecology

(Hunsaker and Levine 1995; Johnson and Gage 1997; Wiens 2002), promoting a unique perspective of riverine landscape (Tockner et al. 1998, 2002; Ward 1998; Wiens 2002), and a brand-new interdisciplinary field – fluvial landscape ecology (Poole 2002) has emerged.

2.3.1 Concept of the riverine landscape

The term riverine landscape, as defined by Ward (1998), implies a holistic geomorphic perspective of the biotic communities, their habitats, and environmental gradients associated with the floodplain, as well as the entire river valley. As a river channel migrates laterally across its floodplain, the fluvial processes form a variety of lotic, semi-lotic, and lentic habitats. The morphology and hydrology of these riverine habitats are very dynamic depending upon time scale concerned. Interactive pathways or hydrological connectivity are also established in riverine reaches with fringing floodplains (Junk et al. 1989). These are especially pronounced on an extensive floodplain in a braided river valley such as the Middle Platte River.

A distinctive character of the braided river ecosystem is high landscape heterogeneity of diverse lotic and lentic habitats, successional stages, and floodplain dynamics across a range of spatial-temporal scales. The riverine habitats addressed here refer to the patches of water body existing on the alluvial floodplain that fish, wildlife, or other organisms use as their habitats. Examples of such aquatic habitats on the floodplain of the Middle Platte River are backwater areas, abandoned or intermittent braided channels aside the main channel, riverine sloughs in wet meadow, and small ponds in riparian and wet meadows.

Sand and borrow pits adjacent to river channels are examples of human-made riverine aquatic habitats. I refer to these broad scale patterns and processes associated with the braided river system as "riverine landscape" (Wu 1999a, 2001a, 2001b), or, as it was sometime called "riverscape" (Ward 1998).

2.3.2 Diversity of riverine habitats

The holistic concept of riverine landscapes provides a new perspective of biodiversity in braided rivers across different spatial and temporal scales -- the riverine habitat diversity. A braided river ecosystem consists of extensive interconnected biotic communities, their habitats, and environmental gradients. The floodplain and groundwater is recognized as integral components of the river (Ward 1998). The stream channels are only part of the river ecosystem that is featured as the lotic ecosystem, and links the extensive interactive aquatic and non-aquatic habitats associated with the fluvial system. As Ward (1998) states, "much of the biodiversity associated with riverine landscape is attributable to heterogeneity at the habitat scale"

In the Middle Platte River, the riverine landscape is comprised of diverse permanent and temporary aquatic habitat patches, such as backwaters, abandoned channels (or stream braids), seasonal active channels (or intermittent braided channels), wet meadow sloughs, wetland and floodplain ponds, etc. Management or restoration of biodiversity on the floodplain should be based on a quantitative understanding of the hydrological interactions among these riverine habitats, as well as spatial-temporal changes in the riverine landscape on the floodplain. However, the hydrological regimes and structural patterns of these riverine habitats have not been well understood. One limitation for quantitatively examining the hydrological interaction and linkage among these water bodies in the Middle Platte River was a lack of systematic and comparative data collected from the riverine habitats.

2.4 Research design

2.4.1 The hierarchical patch dynamic research framework

The conceptual foundation for studying riverine landscape in a braided river is based on the theory of landscape heterogeneity, hierarchical patch dynamics (Wu and Loucks 1995), and methodology from the fluvial geomorphology. The landscape of a river is a mosaic of flowing water corridors, and patches of various aquatic habitats on the matrix of the floodplain. Definition of a patch in landscape ecology is relevant to the organism or ecological phenomenon under consideration. The area of a patch, from an ecological perspective, represents a relatively discrete spatial domain of relatively homogeneous environmental conditions. Patch boundaries may be distinguished by discontinuities in environmental characteristics from their surroundings.

In the view of landscape ecology, river channels are elements of a landscape mosaic, and are linked with their surroundings by boundary (or ecotone) dynamics (Wiens 2002). Spatial distribution of the landscape mosaic is usually heterogeneous and hierarchical with the scale ranging from watershed fluvial network, river segment, reach, and down to habitat patches, as a nested geomorphic hierarchy of riverine landscapes (Ward 1998; Frissell et al. 1986):

Catchment or watershed
↓
Longitudinal drainage network
↓
Segment patterns (channel-river valley)
↓
Reach patterns (channel-floodplain)
↓
Riverine macrohabitat patch patterns
↓
Microhabitat patch patterns

Spatial scale of the landscape approach in this study is from the riverine macrohabitat up to the reach channel pattern. Channel pattern in alluvial rivers is primarily dependent on discharge, sediment load, and slope. On the floodplain or river valley scale, vegetation cover is another factor affecting channel geomorphology (Miall 1996).

2.4.2 The conceptual model of the braided riverine landscape

The alluvial braided river is unique among river and stream channel patterns. A braided river system may be characterized by multiple interactive channels (connectivity) flowing around alluvial islands and sandbars (patches) on its floodplain (matrix). From a geomorphologic perspective, a braided river on its floodplain consists of a complex hydrological network that links flowing water of main channels with active braided stream channels (side channels), while maintaining hydrologic connectivity with other

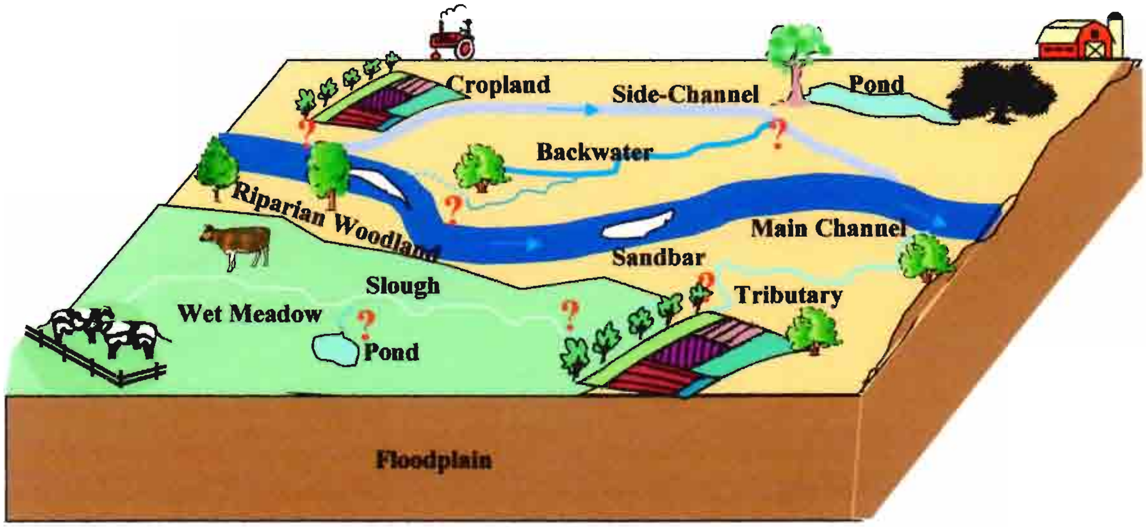


Figure 2-1. Conceptual model of a braided riverine landscape. The question symbols indicate those “hot spots” for studying the hydrological connectivity.

On a geological time scale, these diverse geomorphologic types and their spatial configurations on the floodplain represent different geological process stages of the braided river, and reflect a series in fluvial geomorphic succession. The general trend of the fluvial succession, as results from the processes of fluvial erosion and sedimentation, is: main channel →active braided channels → backwater or abandoned braided channel → slough or pond. However, natural disturbance such as an extremely high flood-pulse may rapidly shift the sequence or invert the order.

My study of the river system focused on the ecological time scale and habitat and landscape spatial scales. During my study period, the relative spatial locations and geomorphic characteristics of the riverine habitats may be seen in dynamic equilibriums, and may not change significantly, except those directly connected with the main channels.

My study of the river system focused on the ecological time scale and habitat and landscape spatial scales. During my study period, the relative spatial locations and geomorphic characteristics of the riverine habitats may be seen in dynamic equilibriums, and may not change significantly, except those directly connected with the main channels.

Riverine aquatic habitats on the floodplain are diverse and dynamic in their hydrological conditions: standing or low flowing water may be present perennially or seasonally; surface water of a riverine habitat may or may not connect directly to a stream channel. However, a patch of riverine habitat usually connects with a stream channel indirectly through shallow groundwater, because it forms on highly permeable sandy to silty-sandy alluvial sediments adjacent to the stream channel where the shallow groundwater table is usually very close to the surface (Henszey and Wesche 1993). Thus, both surface and subsurface hydrologic linkages should be considered when studying a riverine aquatic patch.

Patch size, or a real horizontal riverine aquatic habitat is study dependent. For the purposes of this hydrologic linkage study, only the wetted area was considered for area calculations. The boundaries of a riverine aquatic habitat are determined by edges of the wetted surface area of the habitat, surface water elevation, and the groundwater table. Edges and area of the wetted surface water may be identified by direct measurement in the field and integrating survey information of topography, vegetation and soil types surrounding the riverine habitat. The groundwater table is assigned as the subsurface boundary of a riverine aquatic habitat, since it responds to the hydrologic fluctuation of adjacent stream channel(s) and may be used as a dependent variable of subsurface hydrologic linkage. The groundwater table also represents the vertical position of the surface-water/groundwater ecotone, an important component of a river ecosystem.

2.4.3 Hydro-geomorphological approaches to the riverine landscape

In this research, I address hydrologic linkage of the riverine landscape by studying the hydrological connectivity of riverine habitats on the floodplain of the Middle Platte River. The hydrological connectivity is an essential attribute of the riverine habitats. This may be studied by: (a) analyzing and mapping the hydrological connections (landscape structures) between the main channel and associated riverine habitats, and (b) calculating and evaluating the strength of hydrological interactions (functions) between them.

The structure, or spatial pattern of the hydrologic connectivity is a very important component of riverine landscape. The hydrological interactions between the riverine habitats and main channel affect other ecological functions, such as flux of nutrients and movement of aquatic organisms across the riverine landscape. Therefore, study of the hydrological connectivity is fundamental to understanding the degree to which the riverine landscape facilitates or impedes movement among resource patches, i.e., the landscape connectivity, as defined by Taylor et al. (1993).

To clarify explanation and facilitate the study of field survey, hydraulic monitoring, and statistical analysis, I introduced the following denotation:

H_r -- Height of water level in a river channel, usually read from a staff gauge;

H_s -- Height of surface water level in a nearby riverine habitat, read from gauges installed in the studied habitats;

H_g -- Height of water level in a piezometer that was installed in a stream or a nearby riverine habitat, where the hydraulic head underneath the stream bottom, or groundwater table beneath the riverine habitat was measured.

The first step of my research project was monitoring how the riverine habitats respond to discharge fluctuations in main channel(s). Networks of hydrological monitoring wells and transects were established to measure surface and subsurface water fluctuations in both the main channels and riverine habitats simultaneously. Figure 2-1 shows a detailed illustration of such monitoring network. The interactions of the main channel and the riverine habitats with groundwater may be determined from water table contour maps (Winter et al. 1998), or by comparing water levels of a piezometer (H_g) with a stream gauge (H_r) near the piezometer (Hudak 2000).

The second step was sampling surface water, analyzing field physicochemical conditions, survey topography, land cover and land use, and soil/sediment properties.

The third step was analyzing spatial patterns of the riverine landscape with geographical information systems (GIS), remote sensing images, and spatial statistical techniques at different spatial scales. A series of digital map-based spatial explicit models (SEM) may be generated to locate the habitat patches, superimpose the groundwater table distribution maps, and incorporate changes of riverine habitats with the given hydrological regime.

The fourth step was classifying the riverine habitats based on the hydrological and geomorphological information collected during the first three steps. The grouped riverine habitat types may be used for assessing their hydrological and ecological functions.

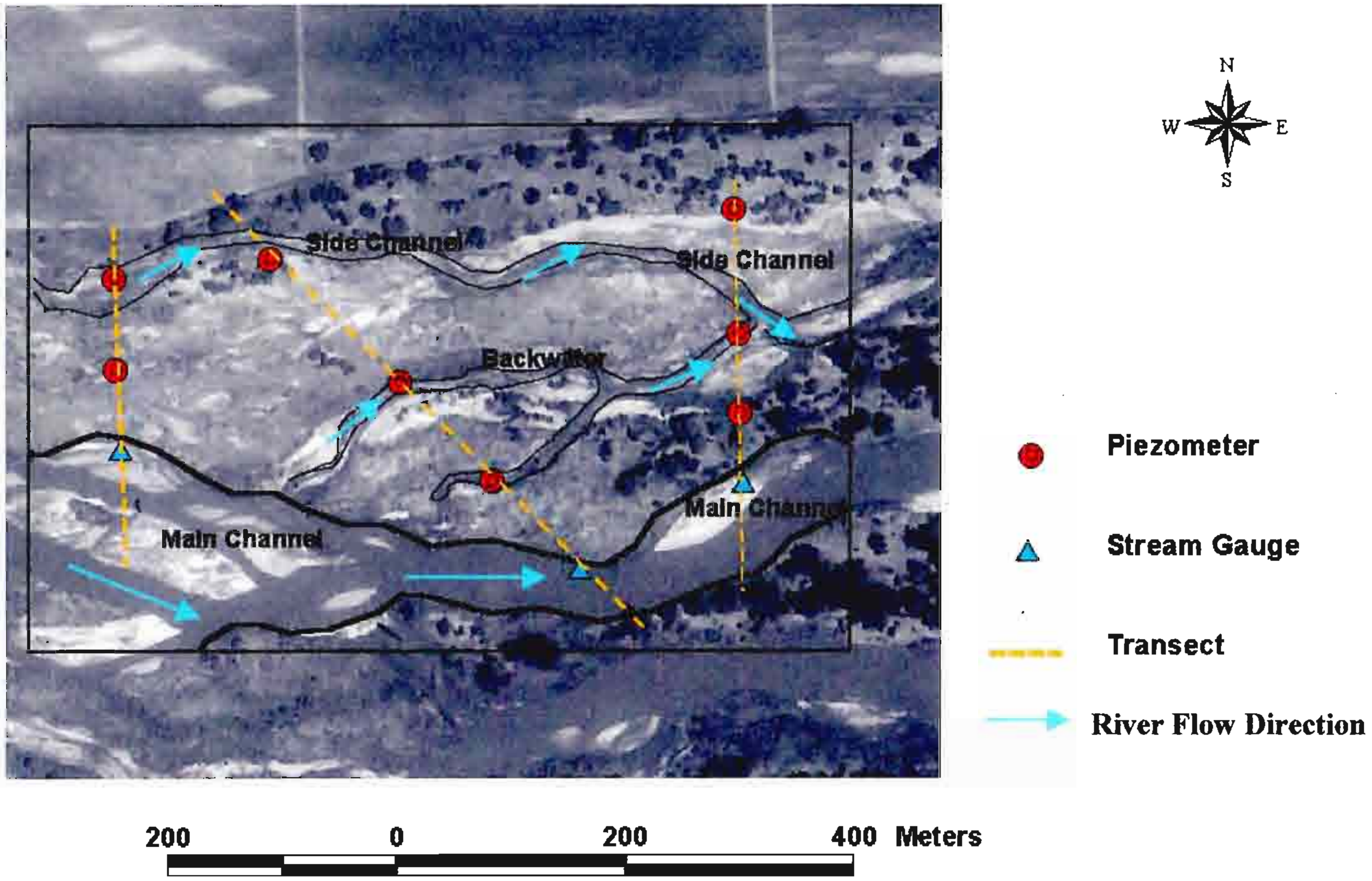


Figure 2-2. Design of hydrologic monitoring network at study area 13, about 4.5 km southeast of Kearney, Nebraska.

The fifth step was quantitatively examining hydrological interactions between river discharge and water levels in the riverine habitats. This is necessary for studying the spatial diversity of the hydrology and its influence on patterns of biodiversity. Multiple statistical techniques such as Correlation Examination and Multiple Regression Analysis (Helsel and Hirsch 1992) were applied to examine the complex hydrologic relationship between main channels and various riverine habitats.

The sixth step was evaluating effects of natural and human disturbance on the riverine habitats and uncertainty of the analyses. By comparing results of the statistical models, I evaluated differences of morphological and ecological characteristics among the diverse riverine habitats.

2.4.4 Physical principles of the riverine hydrologic processes

Based on the continuity equation of water mass conservation (Chow et al. 1988), the water budget of a riverine surface water body, with an unsteady, constant density flow at time t, is derived by considering the mechanisms by which water may flow in ($I(t)$), flow out ($O(t)$), and be stored in this predefined "wetted" patch area of the riverine habitat (S). The net flow (total inflow minus total outflow) must be equal to the change in surface water stored in the patch area of the riverine habitat (dS) over a time interval (dt):

$$dS/dt = I(t) - O(t) \qquad (2\text{-}2a)$$

$I(t)$ and $O(t)$ are flow rates, having dimensions $[L^3T^{-1}]$, while S is a volume, having dimension $[L^3]$, and t is time, with dimension $[T]$.

The following factors of water balance in a riverine aquatic system need to be considered as major components in a conceptual model for studying hydrologic linkages of a riverine habitat with an adjacent river channel: precipitation (P), surface inflow (Q_s), recharge to river from river bank (Q_b), evaporation (E), transpiration (T), surface outflow (Q_o), and discharge to river bank (R_r). Thus, continuity Equation 2-1a can be expressed as

$$dS/dt = (P + Q_s + Q_b) - (E + T + Q_o + R_r). \qquad (2\text{-}2b)$$

In practice, "the evaporation and transpiration are often combined as evapotranspiration (ET) since it is both difficult and unnecessary to separate these two processes" (Stephens 1996). Thus, one may write Equation 2-1b as

$$dS/dt = (P - ET) + (Q_s - Q_o) + (Q_b - R_r) \qquad (2\text{-}2c)$$

All variables on the right-hand size of the equations have units of $[L^3T^{-1}]$. Dividing both sides of the above equations by the area of riverine habitat patch (A), the water budget components can be expressed with dimensions $[LT^{-1}]$ (Stephens 1996).

Most hydrologic data are available only at discrete time intervals. On a discrete time basis with an interval of time length Δt, indexed by j, the Equation 2-1a can be rewritten as

$$dS = I(t)\,dt - O(t)\,dt \qquad (2\text{-}3)$$

and integrated over the j^{th} time interval to output

$$\int_{S_{j-1}}^{S_j} dS = \int_{(j-1)\Delta t}^{j\Delta t} I(t)dt - \int_{(j-1)\Delta t}^{j\Delta t} Q(t)dt \qquad (2\text{-}4a)$$

or

$$S_j - S_{j-1} = I_j - Q_j \qquad j = 1, 2, 3, \ldots \qquad (2\text{-}4b)$$

where I_j *and* Q_j are volumes of inflow and outflow in the j^{th} time interval with dimensions $[L^3]$, or volumes of inflow and outflow for a unit patch area (in plane view) with dimensions [L]. Denoting the incremental change in water storage over time interval Δt as ΔS_j

$$\Delta S_j = I_j - Q_j \text{ , and } \quad S_j = S_{j-1} + \Delta S_j \, . \tag{2-5}$$

Suppose that the initial storage in a riverine water body at time $t = 0$ is S_0, then,

$$S_j = S_0 + \sum_{i=1}^{j} (I_i - Q_i) \tag{2-6}$$

which is the discrete-time continuity equation, described by Chow et al. (1988). Thus, the discrete-time continuity equation for a water body of the riverine aquatic habitat can be written as:

$$S_j = S_0 + \sum_{i=1}^{j} \left[(P_i + Q_{s,i} + Q_{b,i}) - (ET_i + Q_{o,i} + R_{r,i}) \right] \tag{2-7}$$

having dimensions $[L^3]$ or [L].

The right-hand side of Equation 2-1c and Equation 2-6 represents three major water exchange processes occurring in a riverine aquatic patch: vertical water exchange between the atmosphere and surface water, horizontal surface water exchange, and shallow groundwater exchange. For the purposes of this study, the vertical water exchange between the atmosphere and surface water may be quantified by using available data of precipitation and evapotranspiration from local weather stations. The horizontal surface water exchange may be considered when a channel connection with the patch exists, and Q_s equals zero if there is no surface connection between the patch of water body and a stream channel or any other nearby surface water body. The portion of shallow groundwater exchange underneath the riverine habitat, (Q_b - R_r), should include: (a) riverbank storage to the riverine water body; (b) river recharge from the surface water body (i.e. seepage of water from and into the stream bank), (c) soil-water stored in the unsaturated subsurface of the riverine area when there is no surface water in riverine habitats (this often occurs in a dry summer event), and (d) shallow groundwater moving in the saturated alluvium beneath the riverbed and the riverine aquatic habitat.

2.4.5 Research assumptions

The following assumptions and discussions consider a patch of riverine habitat as a spatial scale, and a unit of day for the temporal scale.

First, it was assumed that surface water appears only when the lower unsaturated layer becomes saturated. Therefore, any surface water input to a riverine habitat patch (rainfall, or stream flow, etc.) is either channeled or ponded. This assumption is based on the fact that (a) the groundwater table in a riverine zone is very shallow, usually less than 2 m below surface; (b) surface water accumulated on the floodplain of the river by a rapid rainfall event either quickly infiltrates into the shallow saturated groundwater layer, or is removed into stream channels by horizontal runoff (Voinov et al. 1999); and (c) riverine habitats adjacent to a river channel are mostly on porous media such as coarse sand, sand, and silty-sandy alluvium. These sediments have a relatively higher hydraulic conductivity ($K=10^{-1}$-10^{2}m/d) (Freeze and Cherry 1979; Heath 1983; Stephens 1996);

infiltration rates vary with similar magnitudes as that of the hydrologic conductivity (0.048-21m/d) (Skaggs and Khaleel 1982).

With this assumption, infiltration processes and unsaturated subsurface flow are not considered separately from saturated groundwater processes, because the water level data used in this study were collected during relative longer periods of time (2-3 day interval in summer, and 7 day in spring and fall).

Second, sections of the saturated layer beneath channeled and ponded surface water bodies are assumed to be connected hydrologically, more or less, depending on their relative distances and the properties of the riverine alluvium media (such as a fine sand sediment clogging the bottom of a riverine water body). This is the precondition of correlation and regression analyses. The assumption is reasonable for this study because of the general permeable properties of the fluvial sediment. Although silty and loamy soils or a sandy sediment layer are predominant in most of the riverine habitats, there was no clay layer found underneath any of the studied sites, nor was there a concrete structure, such as ditch, canal, or levee in the study areas.

Third, it was further assumed that any loss of surface water or output from the stream channels and riverine habitat patches would lead to replenishing or discharging of water from the underlying saturated layer, and from another surface water body if there is any surface hydrologic connection between them.

Fourth, it was also assumed that within the same travel distance of water flow, the horizontal flow rate of groundwater in the saturated layer is slower than that of surface water movement through stream channels, if a surface hydrological connection existed.

This is based on Darcy's Law and characteristics of a porous alluvium. When the surface hydrological connection is "cut-off" (i.e. the flow rate of surface water equals zero), however, the contribution of groundwater becomes significant.

Assumptions regarding the floodplain alluvial sediments as are to follow: (a) the main channel and riverine stream channels over the study areas are shallow, only partially penetrating the alluvial aquifer; (b) the thickness of the floodplain alluvial aquifer is significant comparing with the channel penetration, and relatively constant along the riverine areas, based on reports from previous hydrogeological investigations (Bentall 1975); (c) there is no low hydraulic conductivity streambed clogging of the main channel according to the in-channel hydraulic conductivity measurement results of Landon et al. (2001) and visual inspections of streambed sediment profiles in the studied reaches; and (d) the aquifer hydraulic heterogeneity at the reach and riverine landscape scales may be represented by relatively discrete spatial domains or patches, in which, relatively homogeneous hydraulic properties may be observed. The boundaries of the domains may be distinguished by discontinuities in the riverine habitat characteristics from their surroundings. Soil survey maps and my in-field soil/sediment inspection results helped the estimation of the aquifer hydraulic heterogeneity.

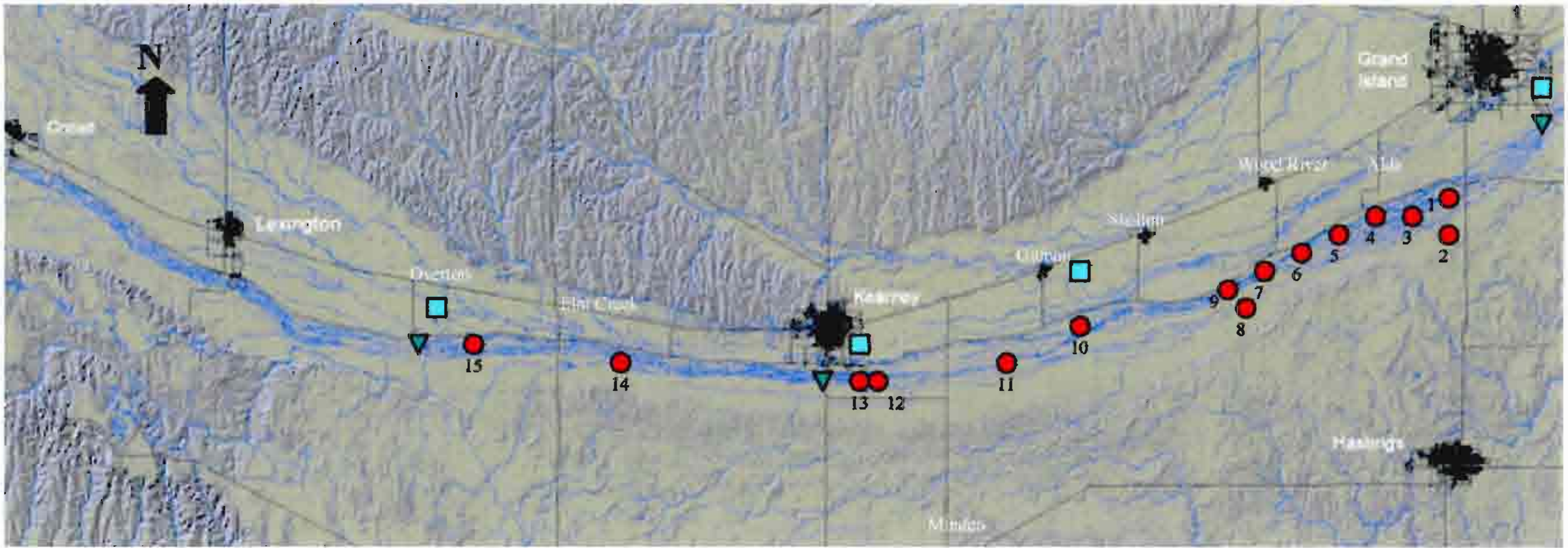
Chapter 3. Methodology

3.1 Study areas

The riverine aquatic habitat addressed here refers to a patch of water body existing on the alluvial floodplain of a river that fish, wildlife, or other organisms use as their habitat. Fieldwork for this study was conducted from summer 1996 to fall 1998. A total of 50 sites in 15 study areas were selected along the reach of the Middle Platte River between the Highway 281 (Exit 312 of I-80) at Grand Island and three kilometers east of the Exit 248 of I-80 at Overton (Figure 3-1). The studied habitats covered about 26 km (16 miles) of river segments along this 109 km (68 miles) reach between Overton and Grand Island.

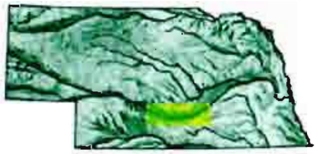
The study sites were located in 42 individual stream channels, backwaters, ponds and wet meadow sloughs. The width, depth, and wetted perimeter of the studied water bodies were surveyed along each transect. Black/white and color-infra-red (CIR) digital orthophoto (quarter) quadrangles (DOQ) (NDNR 1999; USGS 2000b) were used for mapping the study areas and identifying land cover and surface hydrological connectivity. Land cover and other landscape characteristics of major aquatic habitat types in the Middle Platte River floodplain are summarized in Table 3-1, based on analysis results and field surveys of this study. Figure 3-2 shows an example of land cover image map at study area 13, about 4.5 km southeast of Kearney, Nebraska.

In general, the Middle Platte River has one or two broad, braiding main channels in upstream of Kearney, Nebraska, and multiple main channels downstream from Kearney. The main channels link numerous braided side-channels on the



Source of the base map: The Platte River Program, USGS (USGS, 2000b)

Legend



● Study Area

▼ USGS Gauging Station

▢ Weather Station

Scale

10 km 0 10 20 km

List of the Study Areas

1. Mormon Island
2. Wolback
3. Crane Meadows
4. Brown Tract
5. Caveney Tract
6. Wood River Sand Pits
7. Dahms Tract
8. Uridil
9. Martin's Ranch
10. Dipple
11. West Rowe Sanctuary
12. Speidell Tract
13. Wyoming's Property
14. The John's Property
15. Cottonwood Ranch

Figure 3-1. Location of the study areas, USGS' stream gauging stations, and weather stations along the Middle Platte River.

Table 3-1. Characteristics of major aquatic habitat types in the Middle Platte River floodplain, summarized based on analysis results and field surveys of this study.

Habitat type	Main Channel	Side-channel	Backwater	Wet Meadow Slough	Pond
Aquatic condition	Lotic; open space;	Most time lotic; woodland riparian belts	Most time lentic; surrounding with riparian and hydrophytes	Most time lentic	Stagnant
Main source of inflow	Upstream channel flow; Rainfall	Main channel; groundwater; overbank flow	Side-channel or main channel; groundwater; overbank flow	Groundwater; precipitation; overbank flow	Groundwater; overbank flow; rainfall
Main source of outflow	Downstream channel flow; discharging to side-channel and backwater	Downstream channel; backwater; wet meadow	Downstream channel; wet meadow;	Downstream backwater; Side-channel; pond	Infiltration, and overflow when flooding
Water dynamic	Fast flow	Medium-slow flow	Slow flow; sometime stilling in summer	Very slow or stilling	Standing water
Current velocity (cm/s)	> 30	15-30	10 - 15	< 10	0
Water depth (cm)	30 - 120	20 - 50	5 - 40	5 - 20	> 50
Substratum	Coarse sand and gravel	Sand and gravel	Fine gravel, sand and silt	Sandy silt and clay loam	Clay loam, silt or sand
Geomorphology	Wide open braided channels with sandbars	Opened or riparian channel with pool-riffle sequence	Small channel or pond with riparian belts	Flat wet meadow or elevated sand ridges with swales	Varied lowland or oxbow
Dominant plant communities	Sandbar willows	Willows and cottonwood	Bulrush, cattail, dogwood, willow shrubs;	Sedges, giant reed, buried, bulrush, cattail	Bulrush, cattail, sedges
Landscape geometry	Wider corridor with patches of sandbars; braided network	Narrow corridor	Small linear patch connected or near river channel	Long linear patch in wet meadow matrix	Small patch mosaic in wet meadow or backwater
Land use	Water transportation; crane's habitat; recreation	Channel network; irrigation runoff; grazing; hunting	Grazing; hunting; recreation	Grazing; haying; wildlife conservation; hunting	Grazing; fishing; hunting

floodplain. In some places, there are multiple braided branches of main channels in the wide riverbed where the stream flow is shallow. The main channel is a broad but shallow (range from 0.5-1.5 m), sand bedded channel during high discharge periods. It becomes braided at low stages of discharge when the tops of in-channel sandbars were exposed. The inner characteristics of the main channels were not the focus of this study.

Distinctions between a side-channel and a main channel are the degree of difference in their geomorphological features (such as length, width, and shape) and their hydrological characteristics (such as flow depth, velocity, and hydraulic linkage). A typical side-channel is a reach of braided stream fully connected with a main channel of the river. It is usually several hundred meters long, less than 15 m wide, with shallow water and a lower flow rate than the main channel. It is a lotic habitat at most times of a year. Water velocity in a side-channel is usually 0.15-0.30 m/s. During the low flow season, side-channels may be embedded in a wide main channel, as so called "secondary channels" (Petts and Amoros 1996).

Backwaters usually connect with main channels and active braided channels. A backwater does not change in size, depth or flow velocity as much as a side-channel. Thus, a backwater habitat has relatively stable hydrophyte communities and higher percent cover of vegetation than in a side-channel. A backwater habitat is also more lentic than a side-channel. During most of the year, the velocity of backwater flow is usually less than 0.15 m/s. The length of backwater bodies varies from less than 100 meter to several hundred meters.

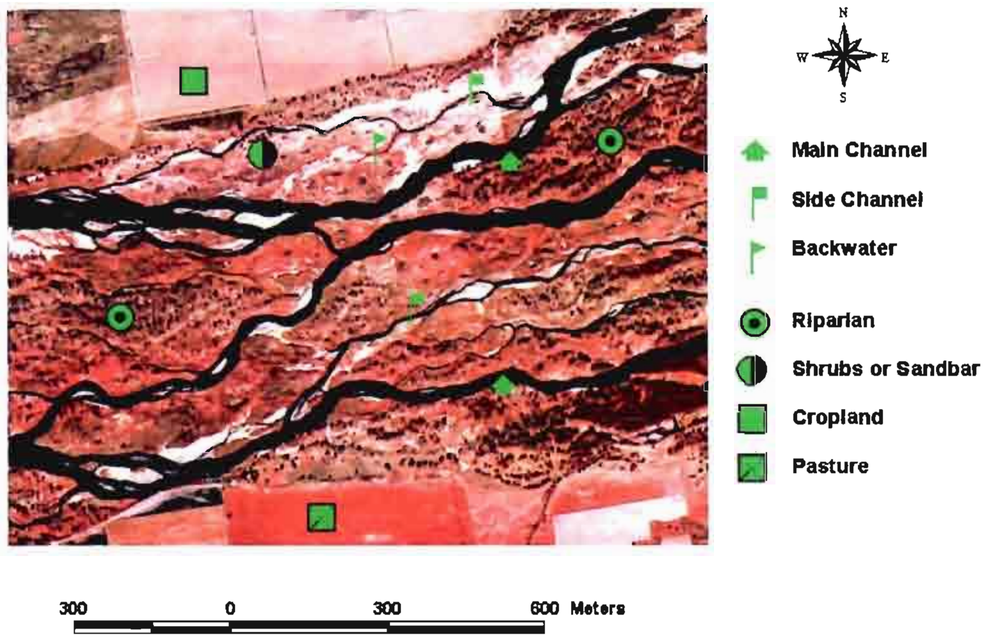


Figure 3-2. Land cover of a reach of Middle Platte River floodplain, about 4.5 km southeast of Kearney, Nebraska

Sloughs are linear shape, shallow water bodies in wet meadows and in transitional zones of wet meadow and riparian habitats. Sloughs are usually located relatively far from a main channel, and hydrologically in semi-lentic and lentic status. Sloughs are formed geomorphologically in former side-channels during evolution of the floodplain. Woody vegetation presents along the sloughs, except those managed wet meadow areas.

There are also non-linear shape, isolated, small shallow water habitats in wet meadows and riparian woodlands, which are normally called ponds. A pond, as defined by Franti et al. (1998) is:

> "a small body of standing fresh water, either natural or artificial, usually with negligible current and having more or less continuous vegetation from the marginal land into the water" (Franti et al. 1998).

Pond depth varies from less than 1 meter (shallow lowland ponds) to several meter (deep gravel pits). Some shallow ponds (with mean depth less than 2 m, and hydric soils and hydrophytic vegetation along edges) qualified as wetlands by definition (Mitsch and Gosselink 2000); while many deeper ponds have abrupt edges, and lack hydric soils and hydrophytic vegetation.

3.2 Data sets

3.2.1 Hydrological data

Hydrological parameters measured were: stream water stage and water current velocity in the river channel (either main channel or side-channel) adjacent to a study site; surface water stage, depth and current velocity in riverine aquatic habitats; and groundwater table measured with a mini-piezometer at the same point where surface water level was measured in an aquatic habitat.

River discharge data were collected from three USGS gauging stations at Overton, Kearney, and Grand Island. Daily river discharge and long-term peak flow data were downloaded from the USGS' on-line stream flow data service (USGS 2000a). Data of monthly and annual discharges at the USGS' Kearney, and Grand Island stations were collected from USGS publications (Boohar et al. 1996,1997, 1998; Boohar 1999, 2000).

3.2.2 Weather and climate data

Weather and climate data used in this study were provided by the High Plains Regional Climate Center, University of Nebraska-Lincoln. The data were collected from five weather stations located within 3 to 16 km (2-10 mi.) of each study area, namely Overton, Kearney, Shelton, Wood River, and Grand Island (Figure1). Data used included daily average air temperature (T, °C), total daily precipitation (P, mm), and daily potential evapotranspiration (ET, mm). The potential ET values were calculated from the Penman combination equation (Rosenberg et al. 1983) with a Nebraska wind function (Hubbard 1992; Robinson and Hubbard 1990). The climate data from 1996 to 1998 indicated a close to "normal" condition of mean monthly temperature during the study period, with some deviation from normal in the amount of rainfall received by the study region (HPRCC-UNL 2000; National Weather Center, USA, 1999).

3.2.3 Soil/sediment and land cover data

Soil/sediment characteristics were taken from publications of the U.S. Department of Agriculture, Soil Conservation Service (USDA-SCS 1962, 1973, 1974, 1984), and augmented by observations of soil profiles taken on-site and soil texture analyses for some study sites. Streambed sediment profile visual inspections (Morris and Johnson 1967) were conducted in the studied reaches.

Land cover of riverine habitats was surveyed on-site in May and August 1998. Species composition, richness, average height, and cover areas were measured and compared over the growing season. Distribution of the vegetation was identified based on the Normalized Difference Vegetation Index (NDVI) using spatial analysis technique in ArcView GIS (ESRI, Inc. 1999). Results of the soil and vegetation surveys were used for land cover types and landscape pattern analyses. Previous vegetation and land cover studied results (Currier 1982, 1995, 1999; Currier et al. 1985; O'Brien and Currier 1987) were considered in the surveys. Landscape features of the studied aquatic habitats were summarized in Table 3-1.

3.2.4 Surface water physicochemical data

Surface water samples were collected for chemical analysis bimonthly during the growing seasons (Table 3-2). Physicochemical parameters measured in field were: water temperature, pH, dissolved oxygen, conductivity, and salinity. Analyzed chemical parameters include: (a) dissolved nutrients: Nitrogen (NO_3^--N, NO_2^--N, and NH_4^+-N) and Phosphate (PO_4^{-3}-P); (b) major dissolved ions: Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^+), Sodium (Na^+), Sulfate (SO_4^{2-}), and Chloride (Cl^{1-}); (c) dissolved trace elements: Aluminum (Al), Arsenic (As), Bismuth (Bi), Boron (B), Cadmium (Cd), Chromium (Cr), Cobalt (Co), Copper (Cu), Iron (Fe), Lead (Pb), Manganese (Mn), Molybdenum (Mo), Nickel (Ni), Titanium (Ti), Vanadium (V), and Zinc (Zn).

Table 3-2. Water sampling periods and corresponding main channel flow conditions.

Sampling Period	**Group ID**	**Seasonal Hydrological Condition**	**Range of Discharge in Main channel**
May 23-27, 1996	9605	Spring, normal water level	42.46-70.79 m^3/s (1,500 - 2,500 cfs)
Aug. 06-09, 1996	9608	Summer, normal water level	56.63-70.79 m^3/s (2,000 - 2,500 cfs)
Apr. 17-20,1997	9704	Spring, normal water level	48.14-73.62 m^3/s (1,700 - 2,600 cfs)
Jun. 14-17, 1997	9706	Summer, high water level	99.11-212.38 m^3/s (3,500 - 7,500 cfs)
Aug. 14-20, 1997	9708	Summer, high water level	82.12-121.8 m^3/s (2,900 - 4,300 cfs)
Oct. 19-22, 1997	9710	Autumn, normal water level	59.46-82.12 m^3/s (2,100 - 2,900 cfs)
Jun. 9-12, 1998	9806	Summer, normal water level	67.96-82.12 m^3/s (2,400 - 2,900 cfs)
Oct. 31-Nov. 19, 1998	9810	Autumn, normal water level	56.63-70.79 m^3/s (2,000 - 2,500 cfs)

3.2.5 Spatial imagery data

Several sources of imagery data were utilized in this study.

(1) Digital orthophoto quadrangle (DOQ) images of the study region, products of the National Aerial Photography Program. Two types of these computer-compatible representations of aerial photographs were used as base-map layers for creating and referencing other geo-spatial data in the study region: (a) black-and-white color images acquired for the summers of 1993, mapped to 1:12,000 scale accuracy specifications (NDNR 1999); and (b) color infra-red images acquired for the summers of 1998 at scale of 1:40,000 (USGS 2000b). The images were digitized and geo-referenced with 1-meter ground resolution and stored in 256 gray levels of spectrum and projected in the Universal Transverse Mercator (UTM) coordinates based on the North American Datum of 1983 (NAD 83) (NDNR 1999; USBR 1999).

(2) One infrared aerial photo (achieved in 1995), provided by U.S. Fish and Wildlife Service at Grand Island, Nebraska, was scanned as a TIFF-formatted image file. It covers one of the study sites near Kearney, Nebraska. The scanned image was then rectified with reference to the DOQ images using the Polynomial Geometric Model of Raster Image Rectification in the ERDAS IMAGINE 8.4 (ERDAS Inc., 1999).

(3) Three series of true color aerial photos (acquired for summer 1996, 1997, and 1998) purchased from the Farm Service Administration (USDA) in Buffalo County, Dawson County, and Hall County, Nebraska were also used as reference images to compare and identify changes of riverine aquatic habitats in the study areas.

3.3 Methods

3.3.1 Hydro-geomorphological classification of the aquatic habitats

The aquatic habitats in the Middle Platte River floodplain were classified by integrating their environmental features (Table 3-1) characterized according to my landscape survey and hydrological monitoring data from the 50 study sites located in 42 riverine habitats and main channel reaches in15 study areas (Figure 3-1). The habitat classification is based on the fluvial geomorphological features (shape, width, depth, and surface connection with the main channel, etc.), surface water hydrologic dynamics (lotic or lentic, permanent or intermittent), and land covers (riparian, wet meadow). Hydrographs and scatter plots of the main channel discharge-habitat water level for each of the study sites were compared to analyze discharge changes and variations of water levels in the main channel, surface water levels, and groundwater tables in each associated riverine water body. The classification system is shown in Table 3-3. Comparing with Table 3-1, several subtypes of riverine habitats were identified in this study as discussed below:

Table 3-3. Hydro-geomorphological classification system of aquatic habitats used in this study.

Habitat Class Level		**Criteria of Classification** *			
Habitat Type	**Habitat Subtype**	**Fluvial Geomorphology**	**Surface Water Connection**	**Surface Water Dynamics**	**Land Cover**
Main channel (MC)	Sandbar; braided stream	Wide and braided, open, linear, with large sandbars	Link with SC, TB, and BW	Lotic, permanent	Water and large sandbar and islands
Side-channel (SC)	Side-channel (SC)	Medium width, linear, semi-open or canopied, shallow water	Fully-connected to MC	Lotic, permanent	Small sandbars and riparian
	Tributary (TB)	Medium width, linear, semi-open or canopied, shallow water	Partially-connected to MC; surface inflow from upland	Lotic, permanent	Riparian, rangeland
Backwater (BW)	Connected Backwater (CB)	Very shallow, hydrophyte present; medium width, linear, Most canopied	Partially-connected to MC in most of a year	Semi-lotic; permanent	Small sandbars and riparian
	Disconnected Backwater (DB)	Very shallow, hydrophyte present; Medium width, linear, Most canopied	Disconnect from MC in most of a year	Semi-lentic; permanent or intermittent	Riparian
Slough (SL)	Permanent Slough (PS)	Very shallow, hydrophyte present; narrow width, linear, Most canopied	Disconnect from MC; some link to BW or SC	Semi-lotic; permanent	Wet meadow; riparian
	Intermittent Slough (IS)	Very shallow, hydrophyte present; narrow width, linear, Most canopied	Disconnect from MC; some link to BW or SC	Semi-lentic; intermittent	Wet meadow;
Pond (PN)	Riparian Pond (RP)	Non-linear, canopied, hydrophyte present or absent;	No direct surface water connection with other habitats	Lentic; most permanent	Riparian
	Wet Meadow Pond (WP)	Non-linear, non-canopied, hydrophyte present or absent;	No direct surface water connection with other habitats	Lentic; intermittent or permanent	Wet meadow

* Criteria of classification refer to that presents in "normal" conditions (i.e. excluding flood and extremely drought periods), as quantitatively defined as: (1) Average channel bankfill/water width (m): wide (> 50/35), medium (15/10 - 50/35), narrow (< 15/10); (2) Surface water depth (m): shallow (0.3-0.5), very shallow (< 0.3); Canopy cover area (%): canopied (60-80), semi-open (20-59), open (<20); (3) Hydrophyte present: > 10% of surface area; (4) Surface water connection: fully-connected: connected at both upstream and downstream ends; partially connected: either upstream or downstream end.

Some tributaries of the Middle Platte River are termed "side-channels" in general, but they are much longer, paralleling a main channel for several kilometers before they merge with the main channel. Tributary streams usually connect with a side-channel or directly flow into the main channels. They may also link with sand and gravel pits, irrigation canals, ditches, or small tributaries from uplands, and receive water from upland runoff, groundwater recharge, irrigation return flow, and overbank flow from main channels when they are flooded. These longer side-streams appear to belong to side-channels morphologically; however, they have different hydrological patterns. Thus, I sub-classified them as "tributary", a subtype under the category of side-channel for this study.

A backwater represents a habitat intermediate between lentic and lotic systems. Flood scouring and alluvial aggradation are two fluvial geomorphologic processes that alter the morphology of backwater habitats and their hydrological connectivity with the main channels. The backwater habitats are divided into two subtypes based on their surface hydrological connections with the main channels. Hydrological characteristics of backwater habitats in the braided river system depend upon their locations in the floodplain and the habitat geomorphologic features.

It needs to mention that the connected backwater subtype includes backwaters located within the broad main channels and those in braided channels adjacent to the main channels. The backwater habitats located inside the broad and braided main channel may be called as "instream backwater", or "intermittent backwater" because they appear during low-river-flow seasons, and are submerged during high flow seasons. Thus, the instream backwater habitats are highly dynamic and unstable. Peters et al. (1989) described distribution of the instream backwater in the Lower Platte River as a water body located either at the downstream end of a large sandbar in a broad channel, or presents at the interface of a main stream channel, i.e. an area between a large sandbar and the adjacent riverbank (Peters et al. 1989). These distribution patterns are similar in the main channels of the Middle Platte River.

Other connected backwater habitats are found in some inactive channels, or small stream braids adjacent to a main channel. From a geomorphological point of view, those inactive channels appear to be former side-channels. These backwater bodies are disconnected from the stream channel at their upstream entries, and are connected to active stream channels, either main channels or side-channels, at their outlets; thus, the backwater channels are fed by subsurface shallow groundwater or bank seepage from the main channels during normal stream flows. Surface backflow from main streams input the backwater habitat through their downstream outlets during high stream flows, and overbank flow when flooding. During high flow periods, part or entire areas of backwater channels may be submerged, and backwater channels may become active streams.

Unlike the connected backwaters mentioned above, the disconnected backwater is a type of "isolated backwater" in a "cut-off channel" (Bornette et. al.1998) or a so-called "abandoned-channel" (Nanson and Croke 1992, Carson 1984). This refers to backwater areas that have been partially or fully separated from the main stream at both ends of their channel, or have been disconnected from stream channels by bank stabilization or beaver dams. Compared with the first kind of backwater bodies, this type of backwaters is a lentic aquatic environment with relatively stable surface water levels. It is fed by bank seepage, overbank flow, and groundwater discharge. There is no surface water connection with the main channel for this type of backwater habitat.

Slough habitat type is subdivided into two subtypes: permanent slough and intermittent slough. Wet meadow sloughs have more lentic hydrological characteristics than backwaters. In contrast to a backwater body, it does not directly connect to a main stream via surface flow. Instead, a wet meadow slough usually links to a side-channel or a backwater body. On the floodplains of the Middle Platte River, wet meadow sloughs may be separated from main stream channels by natural sand levees or other aggradational alluvium or debris deposits (Petts and Amoros 1996), beaver dams, or man-made constructions for irrigation, drainage, bank stabilization, highways, recreation, etc.

A pond is a small, non-linear patch of standing water in riparian or wet meadow that is surficially isolated, and distant from any stream. Stewart and Kantrud (1971) classified natural ponds and lakes in the glaciated prairie region as ephemeral, temporary, seasonal, semi-permanent, permanent, etc. According to this classification, most of the riverine ponds in the Middle Platte River floodplain are semi-permanent or permanent ponds. For purposes of this study, ponds were classified into two sub-types according to their land cover composition and geomorphologic location: “riparian ponds” in riparian woodland habitats, and “wet meadow ponds” in wet meadow habitats. In general, grain sizes of the wet meadow ponds subsurface sediments are smaller than that of riparian ponds, although it can been seen in both of the subtypes that there is a very thin silt or clay-sand layer covering the bottom.

3.3.2 Correlation analysis on the main channel-riverine habitat interactions

Correlation analysis was conducted to identify strength of the hydrological interactions between discharge, precipitation, temperature, evapotranspiration and water level changes in different types of the riverine habitats. The Kendall's Tau (τ) measurement was used for the evaluation of correlation of the paired monitoring data. The τ measures the strength of all monotonic (linear and nonlinear) relationships between x and y, and is based on ranks, so the procedure is resistant to the effects of outliers (Helsel and Hirsch 1992). "The τ coefficients are based on the number of concordant and discordant pairs. A pair of rows for two variables is concordant if they agree in which is greater. Otherwise they are discordant, or tied" (SAS Institute Inc. 1995).

The time delay of riverine habitat water levels in response to the river stages adjacent to the habitats was less than an hour for those riverine habitats connected with the main channel, and within several hours for those disconnected riverine habitats according to my field water level measuring results and previous reports (Henszey and Wesche 1993; Hurr 1983; Lugn and Wenzel 1938; Wesche et al. 1994). The correlation of the paired water levels between the main channel and the adjacent habitats was examined based on the monitoring data collected at time-intervals of 2-3 day in summer and 7 day in spring and fall seasons. Since the Kendall's τ coefficient correlation is calculated based only on the number of concordant and discordant pairs, the effect of the time delay of the water level response on the correlation analysis is not significant, and it was treated as an random error in the statistic analyses.

The time delay of wet meadow slough habitat water levels in response to precipitation is similar as that to the main channel water stages. Based on continual groundwater monitoring data collected from water level recorders at three observation sites in wet meadow along the Middle Platte River (Henszey, unpublished data, 1995-1998), a local rainfall event and associated surface runoff in sloughs may cause a maximum rise in the groundwater table within an hour or so. But it often takes 5-7 days for the elevated water table to reach a new equilibrium with the river stage and evapotranspiration (Henzey 2000). Hurr (1983) also indicated the similar pattern of the time delay for the water levels in the wet meadow habitat. Because we usually measured the water level and groundwater table changes 12-24 hours after a rainfall event, the time delay of the water level in response to precipitation was also considered as "noise" during the water level fluctuation at the multi-day time scale used in this study.

At each of the study sites, the following paired or grouped river stage data and habitat surface water level and groundwater table data were used for the correlation analysis:

Riverine Habitat Surface Water Level vs. River Stage Level (H_s vs. H_r);

Riverine Habitat Groundwater Table vs. River Stage Level (H_g vs. H_r); and,

Riverine Habitat Surface Water Level vs. Groundwater Table (H_s vs. H_g).

The riverine habitat water level and groundwater table data were also correlated to the river discharges reported from the closest USGS' gauging station to check riverine habitats in response to the instream flow change (H_s vs. Q and H_g vs. Q) at the landscape scale. The average travel time of the river flow in the main channel was estimated about 80 km/day (50 mi/day) based on the discharge data collected from three gauging stations (USGS 2000a). Most of my study sites were located within 30 km from the closest the gauging station (Figure 3-1). Thus, the daily average discharge was used for the statistic analyses in this study to reduce the time delay effect between the study sites and the closed gauging stations.

3.3.3 Cluster analysis on spatial pattern of the riverine habitat types

Cluster analysis of characteristic hydrological data was undertaken to develop groupings based on the degree of similarity (Johnson and Gage 1997). I used τ correlation coefficient as a parameter for clustering pairs of hydrologic linkages at the study sites. Classified data groups were used to examine the spatial patterns of riverine habitats and their hydrological connectivity with the main channels according to their spatial distributions. To incorporate both the channel width (w) and the distance between the main channel bank and a riverine habitat (d) in analysis, a location parameter (L_r) for the riverine habitats was introduced as:

$$L_r = (d + w/2)/w \qquad \text{(dimensionless)} \tag{3.1}$$

i.e., a ratio of the distance between the center of the main channel and a riverine habitat to the main channel width.

3.3.4 Regression analyses of the main channel discharges-riverine water levels

Regression analysis and curve fitting techniques were applied to the data from riverine habitat water levels (as response variables), and main channel discharges and local area climatic data (as explanatory variables) to estimate or predict the hydrological changes between the main channels (represented by daily mean discharges) and the various riverine habitats (represented by their surface water and groundwater levels). The general form of the multiple linear regression (Helsel and Hirsch, 1992) for modeling of the stream-riverine habitat interaction is denoted as:

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots + b_kx_k + \varepsilon \qquad (3.2)$$

where y is the response variable, such as surface water level (H_s, m) or groundwater table (H_g, m) of the riverine habitat; b_0 is the intercept; b_1, b_2 , ..., b_k are a set of coefficients for the explanatory variables: x_1, x_2, ... x_k; x_k is an explanatory variable. It may be the discharge (Q, m^3/s), temperatures (T, °C), precipitation (P, mm), and/or evapotranspiration (ET, mm). ε is the error and represents the remaining unexplained variability in the data. Observed significance probability was set as 0.05 for all regression analyses. Analyses were conducted by: (1) Bivariate regression models of riverine habitat water levels (H_s and H_g) by main channel discharges (Q); (2) Stepwise multivariate regression models of riverine habitat water levels using main channel discharges (Q) and climate data, including temperatures (T), precipitation (P), and potential evapotranspiration (ET).

I also transformed the T, P, and ET data to moving average values at intervals of three, four, and seven days, using a moving average method introduced by Gomez and Gomez (1984, pp. 480-483), and Hoshmand (1998, pp. 366-368), in order to match the temporal scales of hydrological observation to eliminate daily weather variation from the time series. These transformed variables are denoted as T_3, P_3, ET_3, T_4, P_4, ET_4, T_7, P_7, and ET_7, respectively. They are correlated with the original T, P, and ET data. Thus, as candidates for the stepwise regression analysis, they cannot be added simultaneously into the process of modeling; instead, a combination of discharge with one of the grouped three-day, four-day, or seven-day variables was used each time. The candidates for explanatory variables for the regression modeling were first examined for their correlation, and their significance on the hydrological interaction of the stream-riverine habitats. For example, the temperature and the potential ET variables were correlated. Thus, they were used separately with other independent variables for the stepwise regression. The moving average method was also applied to the discharge data, but the regression outcomes using this type of transformation showed no improvement in the models.

Three types of residuals plots from each of the regression models were produced and examined for adherence to the assumptions of the regression models (Helsel and Hirsch 1992), including: residuals vs. predicted values, residuals vs. time, and residuals vs. normality of residuals displayed by normal probability plot, histogram, boxplot, etc.

3.3.5 Analysis of variances on heterogeneity of physicochemical data

For analyses of the physicochemical data, temporal changes were incorporated into the statistical analyses and discussion as: (a) the entire study period, and (b) eight levels of the sample seasons. The sample seasons were grouped and notated as the month and the year when the samples were collected, as described in Table 2.

Normality distribution tests and homogeneity of variance tests (SAS Institute Inc. 1995) were first performed to detect whether the data violated any assumptions of further statistical analysis. Analysis of Variance (ANOVA) was conducted to test if the level means of season or habitat were all equal. For those data sets with non-normal distributions, several nonparametric statistics methods were applied. When the homogeneity of variance assumption required by ANOVA was found to be violated, Welch's ANOVA (SAS Institute Inc. 1995) was conducted. Other multiple comparison techniques, such as Multiple Comparisons for All pairs (MCA), Multiple Comparisons with the Best (MCB), and Multiple Comparisons with Control (MCC) (SAS Institute Inc. 1995) were also applied to the data analyses. Other influences such as land-use and cover, and management processes were also considered in interpreting the chemical analysis data. Boxplots and bar charts were used to illustrate the statistical results and compare the differences in parameters due to both seasonal change and spatial heterogeneity described by the habitat category.

3.3.6 Spatially explicit models of the riverine landscape

The spatially explicit model (SEM) developed in this study is a GIS-based, digitized map of actual or simulated phenomena superimposed on a landscape (Withers and Meentemeyer 1999). The SEMs are used to transform raw photographic image data into land cover and riverine habitat maps, and visually identify the channel connectivity and interpret landscape features. Distribution and change of habitat patches and the effect of other landscape features on the dynamics of the habitats may be studied with such digitized maps.

A case study site was selected in a wildlife management area of the Middle Platte River near Kearney. I achieved two "simultaneous" remote sensing images within my study period to match a recommended flow rate (USGS 2000b; U.S. FWS 1994). Spatial analysis and geo-statistical modeling processes supported by ArcView GIS (v. 3.2a) were used to develop a series of spatially explicit, map-based surface water distribution models based on my field topography survey and hydrological monitoring data. By coupling groundwater table distribution in the riverine habitats with the land cover spatial data on the study sites, I analyzed the spatial patterns of the riverine landscape (McGarigal and Mars. 1995) for this targeted riverine conservation site managed by the U.S. Fish and Wildlife Service.

The methods used in this research were expected to identify:

(a) The surface hydrological connections between the braided main channel and its associated riverine habitats in landscape scale by conducting on-site geomorphological survey, soil and sediment grain sizes analyses, and interpreting braided stream network with high-resolution digital images;

(b) The riverine habitat spatial patterns and configurations by extracting landscape indices from a suite of riverine landscape theme maps generated from GIS-based spatially explicit models;

(c) The physical processes influencing hydrological interaction between the main channel and its associated riverine habitats by developing a series of regression-based models to examine the hydrological and climatic factors influencing hydrological interaction between the main channel and the riverine habitats at the habitat scale; and,

(d) The diversity of the riverine habitats by analyzing and comparing the hydrological connections, the strength of hydrological interactions with the main channels, the physicochemical data at habitat and landscape scales and at the bimonthly seasonal scale, and integrating information of environmental components within the riverine landscape.

Chapter 4. Results and Discussions (I): Hydrological Connectivity

4.1 Surface hydrological connection and classification of the aquatic habitats

Aquatic habitats in the study areas are quite diverse. Table 3-1 summarizes some of the significant differences between these commonly recognized habitat types based on image interpretation and a literature review. According to the detailed information gained from my on-site fluvial geomorphological surveys, I further classified the riverine habitats according to quantitative classification criteria on the dynamics of the habitat hydrology, land cover, and the surface hydrological linkage between the main channel and the riverine habitats. The criteria and results of the classification system are listed in Table 3-3 and Figure 4-1. The aquatic habitat type class was organized in two levels. The first level, habitat type, was classified by the degree of hydrological linkage with the main channel and morphology of the habitats. The second level, habitat subtype, was identified based on their hydrographs and land covers. There are nine habitat subtypes: main channel (MC), side-channel (SC), tributary (TB), connected backwater (CB), disconnected backwater (DB), permanent slough (PS), intermittent slough (IS), wet meadow pond (WP), and riparian pond (RP). Each of the subtype habitats has relatively unique hydrological conditions, land cover, geomorphology, and alluvial features. Most importantly, habitats within a subtype are identical in terms of their hydrological connectivity and dynamics in this complex fluvial channel system. Figure 4-1 illustrates the hierarchical network and hydrological dynamics among the aquatic habitats. Using the riverine habitat subtypes for analysis allows the properties of landscape components (i.e. land cover, fluvial geomorphology, soil type, and substratum grain sizes, thickness, etc.) be held in a relatively identical manner inside each of the habitat patches. It may also maximize the hydrological and geomorphological differences across the subtypes, which, consequently, facilitate spatial pattern analyses in the riverine landscape (Wu 1999b, 1998a, 1998b).

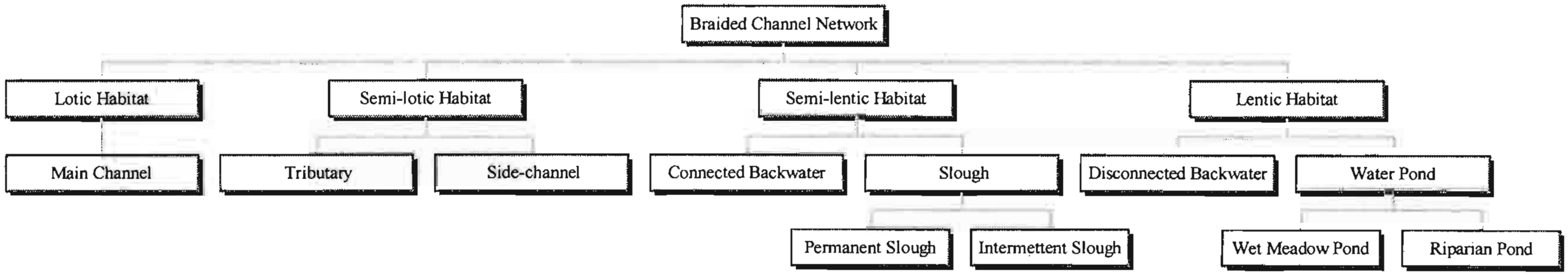


Figure 4-1. Hierarchy of the aquatic habitat classification in the Middle Platte River floodplain

4.2 Correlation between the main channel and the riverine habitats

The results of τ-values from the correlation analysis are summarized in Table 4-1, and the mean τ-values are compared by the habitat subtypes and illustrated in Figure 4-2. All of the correlation analysis results are listed in Table D-1 of Appendix D. The results show significant differences in surface water levels and groundwater tables versus river stages (Hs vs. Hr, and Hg vs. Hr) among the habitat subtypes. By comparing the correlation results across the subtypes (Figure 4-2, Table 4-1), one may see that the degree of correlation may be depended upon the level of hydrological connectivity between the main channel (s) and the associated aquatic habitats.

Among the 50 sites analyzed, side-channels (n = 9) have the strongest hydrological correlations with adjacent main channels in terms of water level change. Mean τ-values were over 0.80 ($p < 0.0001$) for both the surface water levels and groundwater tables beneath the riverbed. The mean τ-values for the tributary type, in sharp contrast, were less than 0.40 ($p \leq 0.0343$) for surface water, and less than 0.50 ($p \leq 0.0110$) for groundwater (Figure 4-2). These patterns of correlation suggest a significant distinction in hydrological interaction between the main channel and the side-channel, and the main channel and the tributary.

The different flow regime in the tributary is a result of inflow from upland, because the upstream of the tributaries usually link ditches and sloughs. Local intensive rainfall events and return flow from irrigation may contribute to the tributary flow variation that is different from the instream flow change in the main channel.

Backwater's surface water change, in response to the main channel, was slightly less active than the side-channel, with mean τ-values ranging from about 0.70 to 0.85 ($p \leq 0.0009$). Between the two subtypes of backwater habitat, however, there are differences in the degree of interaction. In average, the disconnected backwater habitats have a stronger hydrological correlation with the main channels than the connected backwater habitats. The mean τ-values of the surface water correlations are 0.6985 ($p \leq 0.0009$) and 0.7602 ($p < 0.0001$) for connected backwater and disconnected backwater, respectively. The groundwater mean τ values are 0.7891 ($p < 0.0001$) and 0.8493 ($p \leq 0.0000$) for connected backwater and disconnected backwater, respectively. The water body area, shape and fluvial geomorphological features between the two backwater subtypes may explain their differences in the hydrological interactions. Connected backwaters generally have longer surface water flow paths and more open surface areas than those in the disconnected backwaters. Consequently, they may be more adjusted to influences from the surrounding environment conditions that are less dependent on water flow changes in the main channel. The disconnected backwaters are found near the main channel, and have relative smaller patch sizes than the connected backwater channels. Although they are disconnected from the main channel in surface, the disconnected backwaters usually are located on highly permeable alluvial substratum, and have a good subsurface hydrological connection with the main channel.

All other riverine habitats in wet meadow and riparian areas have lower average τ-values, less than 0.55 ($p \leq 0.0445$) for their surface water correlations with the main channels. This suggests a weak hydrological connection to the main channel. This is due to their surface disconnection from the main channel, and relative finer subsurface sediment layer they have. Intermittent slough type in wet meadows has the lowest average τ-value (0.2779, $p \leq 0.0445$) (Figure 4-2, Table 4-1).

Statistical results show that 20% of the studied permanent wet meadow sloughs and 50% of the intermittent wet meadow sloughs and riparian ponds have no significant correlation to the main channels ($p > 0.0500$).

Hydrological connectivity with the main channel seems to play a key role in characterizing riverine habitat properties. The strength of hydrological response of a riverine habitat to the main channel instream flow change is directly related to the degree of its surface water connection with the main channel, as illustrated in Figure 4-3. Fully surface-connected riverine habitats (side channels) have identical hydrographs with that of the main channel. Partially surface-connected backwaters have similar hydrographs to the main channel during high stream flow periods, but maintain relatively stable and shallow water levels when the main channel has low flow rates. The tributaries have distinct hydrological patterns from the main channel hydrograph because of their connections with upland runoff and return flows from irrigation. Wet meadow sloughs generally are not directly connected to the main channel. Subsurface groundwater discharge and rainfall are the sources of the water supply. They usually drain to backwaters or side-channels. Disconnected backwaters, ponds in riparian and wet meadows normally do not have any surface linkage with other aquatic habitats, except they may receive surface water input from overbank flow occurring during a flood event (Figure 4-3).

After excluding five riverine habitats that were either ephemeral and had non-significant correlation with the main channel, or were profoundly altered by beaver dams, a total of 40 surface water study sites and 45 groundwater sites were used for further analyses on the effects of physical environmental factors.

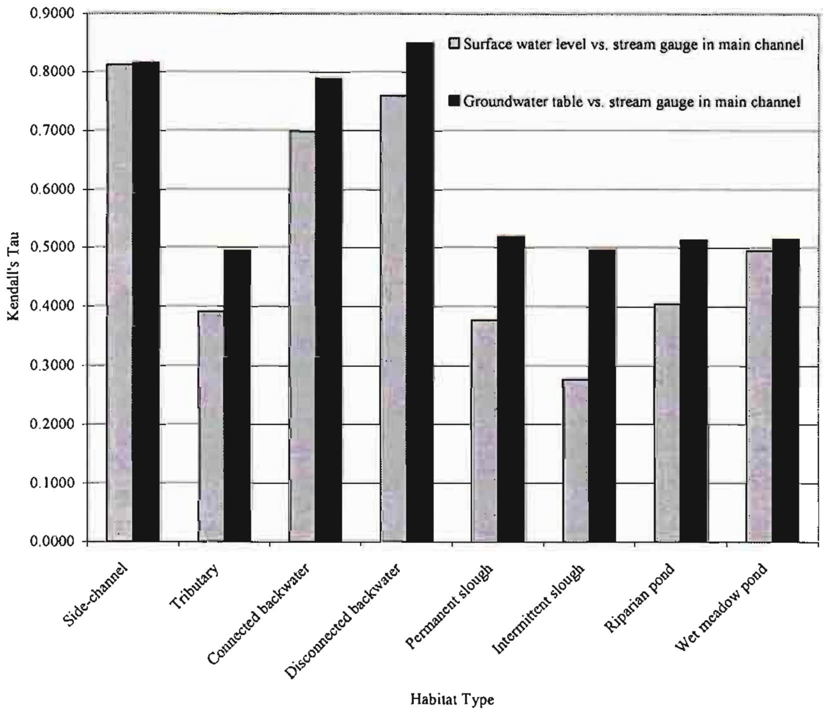


Figure 4-2. Comparison of the mean correlation coefficients (Kendall's τ-values, $\alpha = 0.05$) for water level changes between the main channel and the riverine habitat subtypes.

Table 4-1. Summary of correlation coefficients (Kendall's τ) ($\alpha = 0.05$) for correlation analysis on water level changes between the main channel and riverine habitats

Habitat Type	Habitat Sub-type	n	*Kendall's t*							
			Surface Water vs. Main Channel (H_s-H_r)				Groundwater vs. Main Channel (H_g-H_r)			
			Mean	Max	Min	Prob > | t |	Mean	Max	Min	Prob > | t |
Side channel	Side channel	9	0.8127	0.9212	0.6626	< 0.0001	0.8152	0.9511	0.6682	< 0.0001
	Tributary	5 (2 *)	0.3918	0.7522	0.1658	<= 0.0343	0.4945	0.7703	0.2046	<= 0.0110
Backwater	Connected backwater	12	0.6985	0.8640	0.3814	<= 0.0009	0.7891	0.9344	0.6698	< 0.0001
	Disconnected backwater	8	0.7602	0.8561	0.6274	< 0.0001	0.8493	0.9104	0.7484	0.0000
Slough	Permanent slough	6 (1 *)	0.3773	0.5482	0.1871	<= 0.0194	0.5183	0.6761	0.3054	< 0.0001
	Intermittent slough	5 (2 *)	0.2779	0.4021	0.0741	<= 0.0445	0.4964	0.5856	0.3588	<= 0.0046
Pond	Riparian pond	4 (1 *)	0.4046	0.5609	0.2471	<= 0.0370	0.5132	0.7893	0.3075	<= 0.0080
	Wet meadow pond	4 (1 *)	0.4949	0.5742	0.4156	<= 0.0002	0.5149	0.5811	0.4486	< 0.0001

Notes: * number of sites where $p > 0.05$ for the correlation analysis

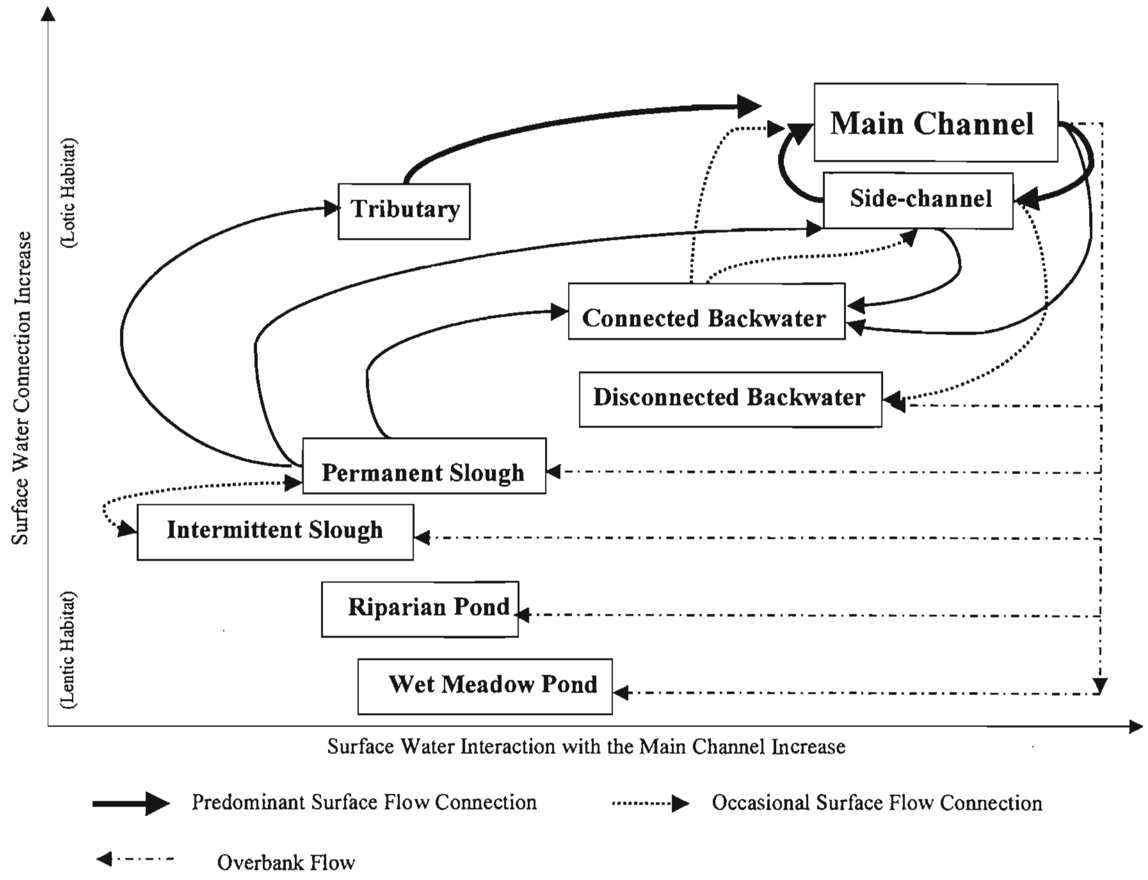


Figure 4-3. Illustration of the riverine habitat hydrological connectivity with the main channel in the Middle Platte River. The hydrological connectivity is determined by both the surface water connection and interaction with the main channel instream flow. The size and length of the arrow lines represent the relative magnitude of the surface flows and the lengths of the surface flowpath in the riverine landscape.

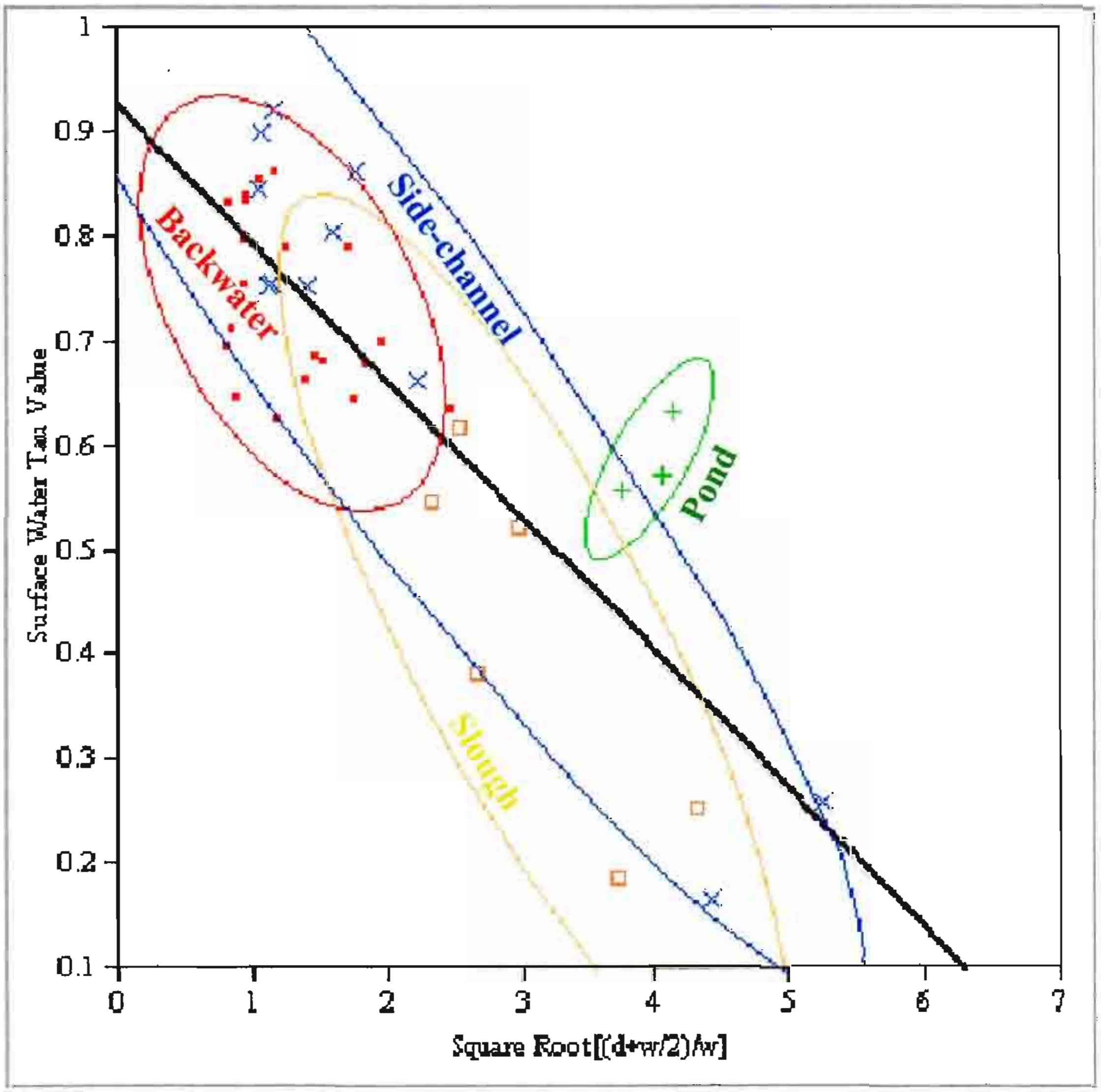
4.3 Stream widths and habitat locations on the stream-riverine habitat correlations

In addition to the surface hydrological connectivity, a stream channel width and distance between the stream and associated riverine habitats are among those environmental factors considered to have an effect on the stream-habitat hydrological interaction. Zlotnik and Huang (1999) proposed an analytical model of stream-aquifer interaction that explicitly accounts for the stream width for a partially penetrating stream with streambed clogging. Given a fixed distance between a stream bank and a groundwater monitoring well, Zlotnik and Huang's modeling results show that the impact of stream width on head changes in the monitoring well is significant if the stream width varies in a range that is less than the distance between the stream bank and the well. The effect of the stream width on the head change in the well becomes less significant if the stream width increases to equal the distance, or wider than the distance between the stream bank and the observation site (Zlotnik and Huang 1999, Huang 2000). This model provides an insight for the riverine landscape study, although the stream width parameter is not well defined for dynamic braided streams in a floodplain river system. The main channel of the Middle Platte River is a wide, active, braided channel. Sandbars and vegetated islands are commonly distributed in the broad stream channel, and their sizes and shapes change season by season. Thus, measuring the actual stream width is difficult in practice.

In this study, I measured the actual main channel width at two instream flow conditions: high flow rate ($Q = 56.6\ m^3$, or 2,000 cfs) and low flow rate ($Q = 11.5\ m^3$, or 405 cfs). Average stream widths for each of the studied sites was calculated based on multiple transect measurement data collected in the field across the studied reaches, and from high resolution digital maps. The overall average main channel width from 45 studied reach sites is 64 m (SD = 56 m) with a range from 8 to 230 m. The distances from the main channel stream bank to the studied riverine habitats varied from 7 to 670 m with an overall average distance as 178 m (n=45, SD = 172 m).

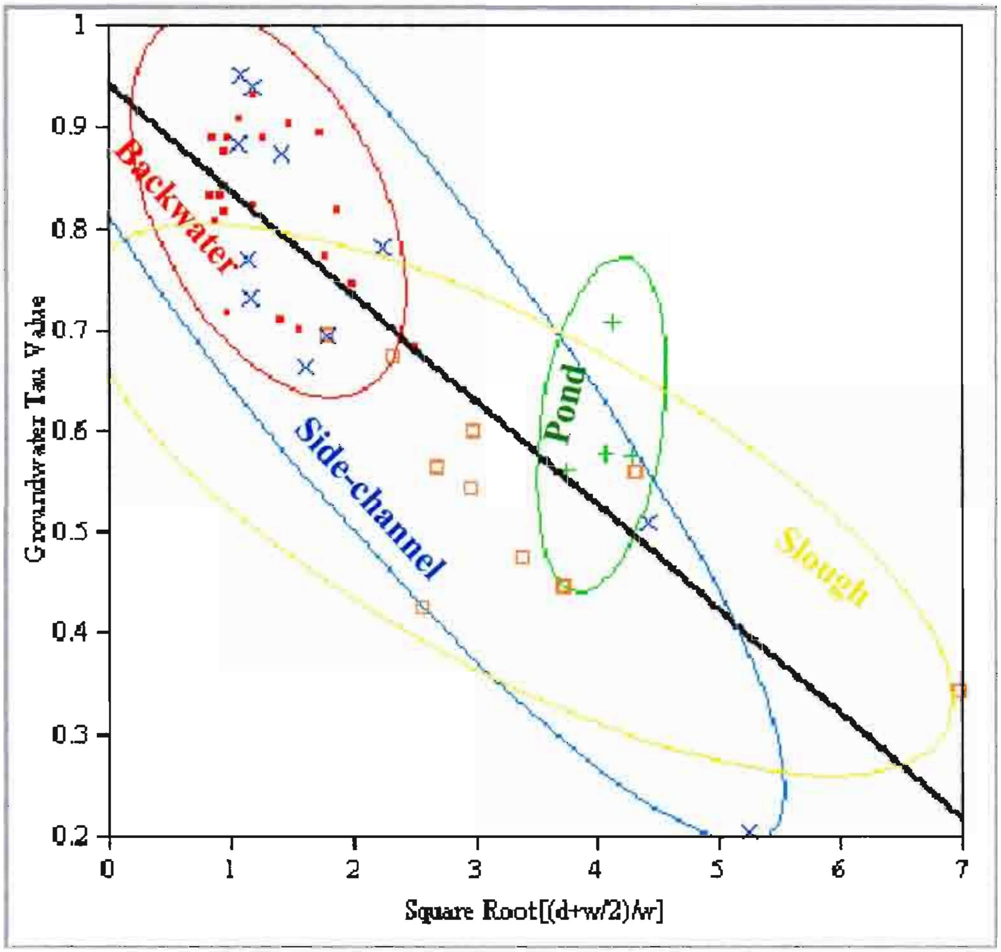
In order to exam effect of the riverine habitat location on the strength of the main channel-riverine habitat interaction, the surface water level τ-values were plotted by the location parameter (L_r). Then, the τ-values were fitted with the normal ellipses ($p = 0.950$) (SAS Institute Inc. 1995) by the habitat types. The results are superimposed in Figure 4-4. The same procedure was used for the groundwater table τ-values, and plotted as a L_r-τ scatter diagram in Figure 4-5. The statistical results are listed in the Table 4-2.

The Figure 4-4 and Figure 4-5 show a similar negative linear relationship between the τ-values and the location parameters for both the surface water ($R^2 = 0.68$, $p < 0.0001$) and the groundwater ($R^2 = 0.71$, $p < 0.0001$). The analysis results and the figures illustrate two clear spatial patterns: a geographical location pattern of the riverine habitat types, and a hydrological interaction pattern between the riverine habitats and the main channel as a function of the location parameter.



(Data symbols: ▪ Backwater; + Pond; × Side-channel; and □ Slough).

Figure 4-4. Clustered riverine habitats by the habitat types, and the habitat surface water τ values fit by the square root of the location parameter [$L_r = (d+w/2)/w$].



(Data symbols: ▪ Backwater; + Pond; × Side-channel; and □ Slough).

Figure 4-5. Clustered riverine habitats by the habitat types, and the habitat groundwater τ values fit by the square root of the location parameter [$L_r = (d+w/2)/w$].

Table 4-2. Statistics of the habitat surface water and groundwater τ values fitting by the square root of the location parameter (L_r), clustered by the habitat types

Cluster Group	n	R^2	p
		Surface Water	
All sites	40	0.68	< 0.0001
Side-channel	11	0.89	< 0.0001
Backwater	20	0.22	< 0.036
Slough	6	0.69	< 0.040
Pond	3	n/a	n/a
		Groundwater	
All sites	45	0.71	< 0.0001
Side-channel	11	0.82	< 0.0001
Backwater	20	0.21	< 0.044
Slough	10	0.53	< 0.017
Pond	4	n/a	n/a

These results suggest that:

(a) The lateral distributions of the riverine habitat types exhibit different spatial patterns at the riverine landscape scale, as a function of integrating effect of the main channel widths and the distances of the habitat geographic positions from the river banks. The backwater habitat type is positioned close to the main channel, while wet meadow slough and pond habitat types are located relatively far from the main channel. The side-channel is a widely distributed habitat type over the riverine landscape. By closely examining the location of the side-channel type, one may notice that the sites located far from the main channels are those of the tributary subtype, and that located near the main channel belong to the side-channel subtype. This indicates a general fact that no matter the size of the associated main channel, tributary subtype habitats are usually located far from the main channels. So does the pond type, as shown in Figure 4-4 and Figure 4-5.

(b) The geographical location (L_r) affects negatively on the strength of the main channel-riverine habitat interaction at the landscape scale. The strength of the hydrological interaction decreases linearly with increasing square root of the location parameter.

(c) This effect appears differently at the habitat scale. As shown in Table 4-2, Figure 4-4 and 4-5, it is clearly demonstrate that the location of the side-channels affects their hydrological linkage with the main channel. The habitat τ values of the side-channel habitats decrease significantly along with increasing of the square root of the L_r ($R^2 = 0.89$ and 0.82 for surface water and groundwater, respectively, $n = 11$, $p < 0.0001$). The pattern is similar to the slough habitat type ($R^2 = 0.69$, $n = 6$, $p < 0.04$ for surface water, and $R^2 = 0.53$, $n = 10$, $p < 0.02$ for groundwater). However, there is no significant L_r- τ relationship for the backwater habitat type ($R^2 = 0.22$, $n = 20$, $p < 0.04$ for surface water, and $R^2 = 0.21$, $n = 20$, $p < 0.04$ for groundwater). This is because the backwaters locate within similar distances to the main channel ($\sqrt{Lr} = 1 - 2$), and have relatively the same, strong hydrological interactions with the main channel ($\tau = 0.7$-0.9). This effect is not clear for the pond type due to the lack of enough site data for the statistical analysis.

In the case that there was no surface hydrological connectivity to the main channel, the groundwater linkage seems to be the primary cause determining the strength of hydrological interaction between the stream channel and the adjacent habitats. Other climatic and land cover factors may also influence the stream-riverine habitat interaction.

4.4 Statistical modeling of the stream-riverine habitat interaction

Simple linear regression models were built to fit water levels in adjacent habitats (Hs and Hg, m) with main channel discharge (Q, m^3/s) for all of the habitats studied, to evaluate the effects of the main channel regime on water level changes in the adjacent habitats. The parameters and detailed modeling results are listed in Table D-2 of Appendix D.

Stepwise multiple regression modeling procedures were used to consider the contributions of other selected environmental parameters on the stream-riverine hydrological interaction. The full sets of parameters in the multiple regression models and the detail results can be found in Table D-3 of Appendix D.

4.4.1 Modeling water level change by the main channel discharge

Table 4-3 summarizes the adjusted coefficient of determination, or Adjusted R-square (Adj. R^2), and p-values by riverine habitat subtypes. The Adj. R^2 quantifies the proportion of variation explained by the regression model on the change of riverine habitat water level by discharge of a main channel. These Q-H models illustrate that: (1) the main channel discharge has a significant hydrological impact on side-channel and backwater habitats ($p < 0.0001$); most of the permanent wet meadow sloughs ($p <= 0.0002$), wet meadow ponds ($p <= 0.0003$), and tributaries ($p <= 0.0001$); (2) discharge has no statistically significant impact on surface water level change in intermittent wet meadow sloughs, or isolated water ponds in riparian areas ($p > 0.0500$), but the correlation of groundwater and discharge is significant in intermittent wet meadow sloughs and riparian ponds ($p < 0.0001$).

Both the surface water regression (Q-Hs) models and the groundwater regression (Q-Hg) models reveal an identical trend in the significant influence of main channel discharge on adjacent habitats, i.e. side-channel > connected backwater > disconnected backwater > tributary > wet meadow pond and permanent slough > intermittent wet meadow slough > isolated riparian water pond (Table 4-3). This trend is similar to the results of the correlation analysis between water level elevations from main channel stream gauges and water levels monitored in the riverine habitats. Here it can be examined by comparing the Adj. R^2 values of the models for different riverine habitat types, and by contrasting that to the surface water models and the groundwater models.

It is not surprising that both of the surface water-discharge (Q-Hs) model and the groundwater-main channel discharge (Q-Hg) model in the side-channel habitats explained more than 90% of the variation in adjacent habitats by main channel discharge alone, because the side-channel subtype habitats are the most closely tied hydrologically with the main channel. On other hand, applying the regression model on the tributary subtype, the main channel discharge alone could only explain about one-third of the water level variation in the tributary habitats. These results indicate quantitatively the hydrological differences between the tributary and the side-channel subtypes. Thus, it is necessary to separate the tributary habitat from the side-channel habitat type, and classify it as a separate type.

The regression models also perform well (the mean Adj. R^2 varies from 68.2% to 88.3%) for two subtypes of backwater habitat (Table 4-3). The Q-H models predict water level variation in the connected backwater habitat better than in the disconnected backwater subtype. This reflects the hydrological connectivity as a cause to the hydrological interaction between the habitats and the main channel. The fact that the backwater habitats' adj. R^2 value are generally lower than those for the side-channel habitats may imply a declining strength in the hydrological interaction between the main channel and the backwater habitats as compared to the side-channel habitats.

Table 4-3. Summary of the Adj. R^2 and p-values of the simple linear regression models by riverine aquatic habitat subtype.

Habitat Type	Habitat Sub-type	Adj. R^2									
		Discharge-Surface Water (Q-H_s) model					Discharge-Groundwater (Q-H_g) model				
		n	Mean	Max	Min	p-value	n	Mean	Max	Min	p-value
Side channel	Side channel	6	0.9125	0.9585	0.8237	<.0001	5	0.9225	0.9590	0.8416	<.0001
	Tributary	5 (2*)	0.3384	0.4482	0.2212	<.0001	3 (1*)	0.3525	0.4341	0.2710	<.0001
Backwater	Connected backwater	15	0.8614	0.9528	0.7378	<.0001	15	0.8831	0.9514	0.6838	<.0001
	Disconnected backwater	6	0.6822	0.7524	0.6070	<.0001	6	0.8038	0.8919	0.6538	<.0001
Slough	Permanent slough	6 (1*)	0.1673	0.3313	0.1012	<=.0002	6 (1*)	0.3179	0.4749	0.1474	<.0001
	Intermittent slough	3*				>.0500	3	0.2200	0.2834	0.1632	<.0001
Pond	Riparian pond	2*				>.0500	2	0.1710	0.2030	0.1390	<.0001
	Wet meadow pond	4 (2*)	0.2425	0.4098	0.0126	<=.0003	3 (1*)	0.5810	0.8611	0.3010	<.0001

Notes: * Indicated number of site on which the regression model's $p > 0.05$.

The Q-Hs models of the slough and pond habitats have very low Adj. R^2values. More than half of the studied wet meadow slough and pond habitats (8 of 15 study sites) did not have a statistically significant relationship ($p > 0.0500$) between their surface water changes and the main channel discharge changes. The Q-Hg models of the slough and pond habitats show significant relations between the main channel discharge and the groundwater table changes (Table 4-3).

The regression models explain more of the variation in the groundwater table than surface water level changes (Table 4-3). This modeling feature suggests that there is a stronger relative hydrologic response of riverine habitats through the groundwater flow paths between the main channel and the riverine habitats than that through surficial flow. Degree of difference varies among the habitats, and it seems to have been negatively associated with the surficial hydrological connectivity between main channel and adjacent habitats. For instance, for those types of habitats maintaining surficial hydrological linkage with main channels, such as the side-channel, tributary, and connected backwater habitats, there was only a 1.0 to 2.2 % difference in Adj. R^2 values between the surface water and groundwater regression models (Table 4-3). This means that the Q-Hg regression models work slightly better than the Q-Hs models in explaining hydrological variations associated with the main channel discharge.

The hydrological characteristics of the sloughs contrast with the hydrological features of other subtypes that surficially separated from the main channel, such as disconnected backwater, sloughs, and ponds. For these 'non-surficially linked' habitats, the differences in mean Adj. R^2 values between surface water regression models and groundwater regression models are significant. The calculations for these differences yield 12.2 %, 15.1 %, 22.0 %, 17.1 %, and 33.9 % for disconnected backwater, permanent slough, intermittent slough, riparian pond, and wet meadow pond, respectively). These results suggest the relative importance of the main channel discharge to groundwater in diverse riverine habitats.

The simple discharge-water level regression model poorly describes the hydrological response in a wet meadow habitat. This suggests that other environmental factors, such as temperature, precipitation, and evapotranspiration may be responsible for variations in water level in wet meadows. A multiple regression modeling is needed to consider other possible factors.

4.4.2 Stepwise multivariate regression models

The series of multiple linear regression models generalized from the stepwise regression identified eleven combinations of the four primary environmental variables (Q, T, P, and ET) (Table 4-4). The models identify the main hydro-climatic factor(s) that control the hydrological process in each of the riverine habitats. These combinations for modeling hydrology of the riverine habitats may also reflect the landscape heterogeneity in habitat scale, and the complexity of hydrological processes within the riverine landscape.

A summary of the Adj. R^2 values of the models by habitat subtypes is given in Table 4-5. By comparing the Adj. R^2 values in Table 4-3 and Table 4-5, one may find that the multiple regression models in general provide: (a) only a slight improvement (0.6- 5.6 %) over the simple linear regression models in explaining water level variations in side-channel and backwater habitats; (b) an 11- 32 % improvement in the interpretation of the variation for ponds in riparian and wet meadow slough habitats; (c) little advantage for ponds in wet meadows; and, (d) The climate variables contribute differently to the habitat subtype of in explaining variation in water level changes. It shows that the temperature factor contributes more than the ET factor does. This is most likely due to the process of direct evaporation from the open surface water of the riverine habitats, which is strongly related to the temperature factor. No direct on-site ET measurement was conducted. The ET data used in this study were calculated values based on weather observation data collected in areas with dominant agricultural land cover and located several kilometers from the river floodplain (Hubbard 1992; Robinson and Hubbard 1990). This maybe another reason for the relatively weak correlationship between the ET and the water level change in the riverine habitats. Furthermore, the linear regression model cannot model water level change at several study sites due to significant natural or human disturbances and other biological impacts such as beaver damming.

Table 4-4. Combinations of explanatory variables in the linear regression models generalized by the stepwise multiple regression processes, and numbers of modeled riverine habitats by each of the associated models.

Variables in model	Number of sites modeled	Type and landscape features of the modeled riverine habitats
Q	14	(1) Most of side-channels and some of backwaters immediately adjacent to main channels, and have surface water connection with the main channels; (2) A few of wet meadow ponds near the main channel.
Q and T	12	Some of small side-channels and most of backwater and wet meadow habitats close to the main channel with large open space and bare ground, such as sandbars.
Q and P	7	Longer side-channels, tributaries, backwaters, and wet meadow sloughs that have relative large catchments, and closed canopy of riparian belts or woodland along these riverine aquatic habitat channels.
Q and ET	1	A beaver pond built in a tributary reach with open area and shrubs cover.
Q, T, and P	4	Longer backwaters and wet meadow sloughs with relatively large catchments, and no closed riparian canopy.
Q, P, and ET	1	A long side-channels that have relative large catchments, and shrubs dominant riparian, no closed canopy.
T	2	Ponds far from main channels with open space and bareground, no canopy.
T and P	2	Longer wet meadow sloughs that have relative large catchments, far from main channel, and no closed riparian canopy for most of the habitats.
P	1	A small lowland pond in riparian far from main channel.
No suitable variable	6	Tributary and wet meadow pond far from main channel, with silt, or sandy clay stratum.

Table 4-5. Summary of the Adj. R^2 and the p-values of the multiple linear regression models by the subtypes of the riverine habitats

Habitat Type	**Habitat Sub-type**	**Adj. R^2**									
		Surface water multiple linear models					**Groundwater multiple linear models**				
		n	**Mean**	**Max**	**Min**	**p-value**	**n**	**Mean**	**Max**	**Min**	**p-value**
Side channel	**Side channel**	**6**	**0.9186**	**0.9644**	**0.8545**	**<.0001**	**5**	**0.9287**	**0.9590**	**0.8722**	**<.0001**
	Tributary	**5 (2*)**	**0.3939**	**0.5615**	**0.2747**	**<.0001**	**3 (1*)**	**0.3757**	**0.4341**	**0.3173**	**<.0001**
Backwater	**Connected backwater**	**15**	**0.8813**	**0.9528**	**0.7775**	**<.0001**	**15**	**0.8954**	**0.9514**	**0.7158**	**<.0001**
	Disconnected backwater	**6**	**0.7194**	**0.7909**	**0.6625**	**<.0001**	**6**	**0.8267**	**0.9116**	**0.6735**	**<.0001**
Slough	**Permanent slough**	**6 (1*)**	**0.3218**	**0.4760**	**0.1012**	**<=.0002**	**6 (1*)**	**0.4270**	**0.6371**	**0.2611**	**<.0001**
	Intermittent slough	**3 (2*)**	**0.3185**	**0.3185**	**0.3185**	**<=.0001**	**3**	**0.3716**	**0.5474**	**0.2505**	**<.0001**
Pond	**Riparian pond**	**2 (1*)**	**0.3013**	**0.3013**	**0.3013**	**0.0004**	**2**	**0.3104**	**0.3695**	**0.2512**	**<.0001**
	Wet meadow pond	**4 (2*)**	**0.2425**	**0.4098**	**0.0126**	**<=.0003**	**3 (1*)**	**0.5888**	**0.8765**	**0.3010**	**<.0001**

Notes: * Indicated number of site on which the regression model's $p > 0.05$.

4.5 Spatial patterns of the riverine landscape as response to hydrological changes

4.5.1 Components of the riverine landscape

Landscape ecology considers spatial and temporal attributes of landscapes and links spatial patterns to processes when addressing ecosystem integrity (Fortin 1999; Pickett and Cadenasso 1995; Wiens 2002; Wiens et al. 1993). Landscape attributes refer to patch quantity and quality, patch structure, and patch dynamics (Leuven and Poudevigne 2002). Figure 4-6 and Figure 4-7 are land-cover maps exported from my GIS-based spatial explicit models (SEMs) generated based on two digital images. They were achieved on the dates when there were distinct river discharges. One image was taken in October 1995 when discharge was 56.6 m^3/s (2,000 cfs), and represented a high instream flow management scenario (Bowman 1994; Bowman and Carlson.1994; CNPPID 1998, 1999; CPNRD 1990, 1992; Farrar 1992; Hill et al. 1991; NDWR 1992, 1998; NGPC 1993b, 1997). Another image was taken in August 1998, when discharge was 11.5 m^3/s (405 cfs), and represented a low instream flow scenario. They cover one of the management properties of the U.S. FWS and adjacent areas.

Land cover was classified into six categories, based on digital values of the land cover spectral data. Landscape components were recognized based on the land cover classification and field surveys. In the present study area they include hierarchically linked aquatic habitat patches (such as main channel deep water patch and shallow water patch, instream sandbar patch, side channel patch, riverine backwater patch, riparian pond patch) and mosaics of terrestrial patches of riparian woodland, grassland, cropland, etc. The habitat attributes were measured and quantified at 1 and 2-meter resolution, and aggregated to the habitat scale.

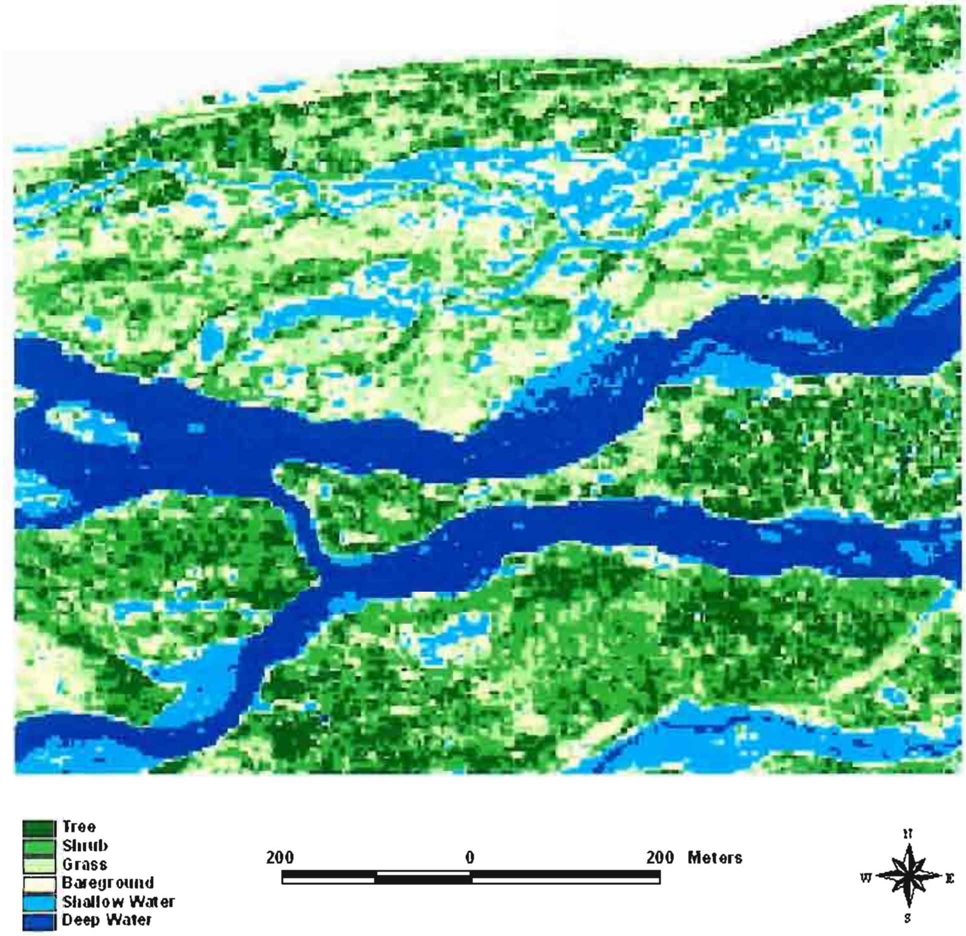


Figure 4-6. Land cover map exported from a GIS based digital riverine landscape classification model that covers a management property and adjacent areas at a reach of the Middle Platte River, 4 km southeast of Kearney, Nebraska. Original color infrared photograph was taken by U.S. FWS (1995) on October 25, 1995, when Q = 56.6 m^3/s (2,000 cfs), representing a high instream flow management scenario.

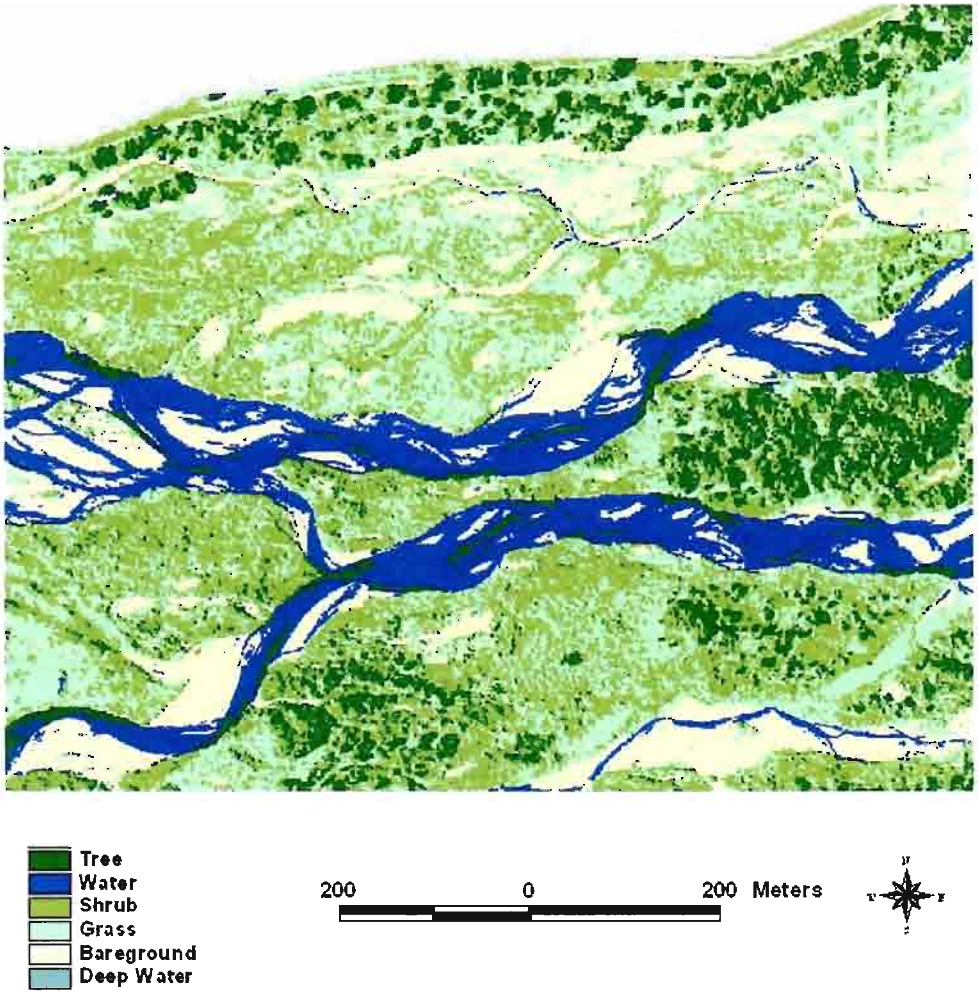


Figure 4-7. Land cover map exported from a GIS based digital riverine landscape classification model that covers a management property and adjacent areas at a reach of the Middle Platte River, 4 km southeast of Kearney, Nebraska. The original color infrared photograph was taken by U.S.G.S. (1998) on August 1998, when Q = 11.5 m^3/s (405 cfs), representing a low instream flow scenario.

4.5.2 Spatial analysis of the riverine hydrological patterns

Aquatic habitat patches and hydrological networks were extracted from the GIS models to make new aquatic patch theme maps as shown in Figure 4-8 (a) and (b), and Figure 4-9 (a) and (b). My analyses were focused on one side-channel and one backwater channel on the north bank of a branch of the main channel.

Groundwater table contour lines were generated based on the water-table monitoring data in eight piezometers and a detailed field topographical survey carried out along three transects and the stream banks. They were superimposed on the aquatic patch theme maps as displayed in Figure 4-8 (b), and Figure 4-9 (b). The arrows on the maps indicate the groundwater flow paths.

Figure 4-8 (b) shows that during the high instream flow period, the river main channel discharged to the riverine aquifer laterally, and the groundwater flow paths went toward to the backwater and the side-channel habitats. Figure 4-9 (b) shows a relatively opposite groundwater flow path pattern during the base flow period. The lateral groundwater flowed paralleled the main channel flow direction and recharged the river at the downstream side of the study area. Parts of the groundwater flow went through the side-channel. No groundwater discharged to the side-channel due to the lower water tables in the riverine aquifer.

The riverine surface water and groundwater hydraulic gradients in the riverine aquifer may be determined using the calculation method presented by Heath (1983), by measuring: (a) the differences of surface water levels between the stream channel (H_r)

and the adjacent riverine backwater or the side-channel habitats (H_s) that connects with the stream; and (b) the difference between the stream gauge heights (H_r) and the groundwater tables underneath the adjacent riverine habitat (H_g), that may or may not have direct surface hydrologic connection with the stream; and (c) the water flow distance from the stream to the studied riverine habitats.

4.5.3 Spatial analysis of the riverine habitat patterns

Landscape indices were calculated using ArcView's Patch Analyst extension (Elkie et al. 1999) at both landscape and habitat scales. Results are summarized in Table 4-6. By comparing the landscape indices at the low instream flow condition with that at the high flow rate, one may calculate the dynamics of the habitat patches and explore patterns. In the study area, the total area of the aquatic habitats, expressed as patch class area in the patch analysis, declined by 34 %, while the number of patches increased by 135 %. These changes indicate a more fragmented landscape with reduced aquatic habitat areas appeared under the low discharge condition. Mean habitat patch size decreased by 72 %, from 234 m^2 down to 65.7 m^2. The smaller patch size standard deviation in the low flow conditions as shown in Table 4-6 suggests that the sizes of the aquatic habitat patches was more similar under low flow conditions than at a high rate of flow. Corresponding to the habitat fragmentation, total patch edges and patch edge density increased 59 % and 141 %, respectively. Due to increasing numbers of patches, the mean patch edges decreased about 32 %. The mean patch shape index (MSI) is used to describe patch shape complexity. It is an averaged perimeter-area ratio for all patches in the landscape, i.e. the mean patch shape index compares a patch shape with a square, and it is greater than 1 (Elkie et al. 1999). The larger the MSI, the more complex a patch shape is. Thus, the MSI results in this area indicate that the shapes of the aquatic patches were less complex under dry conditions than when the instream flow rate was high. Another important spatial difference, found by comparing total cover areas on each type of habitat in Figure 4-8 and Figure 4-9, is that when flow rate in the main channel dropped to its base-flow level, more patches in side-channel and backwater habitats went dry than that in main channels. The consequence of reduction in habitat patch size and density in riverine habitats causes a decline of the riverine hydrological connectivity. Furthermore, lowering river water level led to change of the local groundwater flow paths. As the result, the riverine water was drained and discharged to the main channel until they went dry. These results, based on two hydrological scenarios (high and low instream flow rates), demonstrate that the landscape patterns and hydrological connectivity of riverine habitats are dynamic, and in response to the hydrologic regime in the main channel.

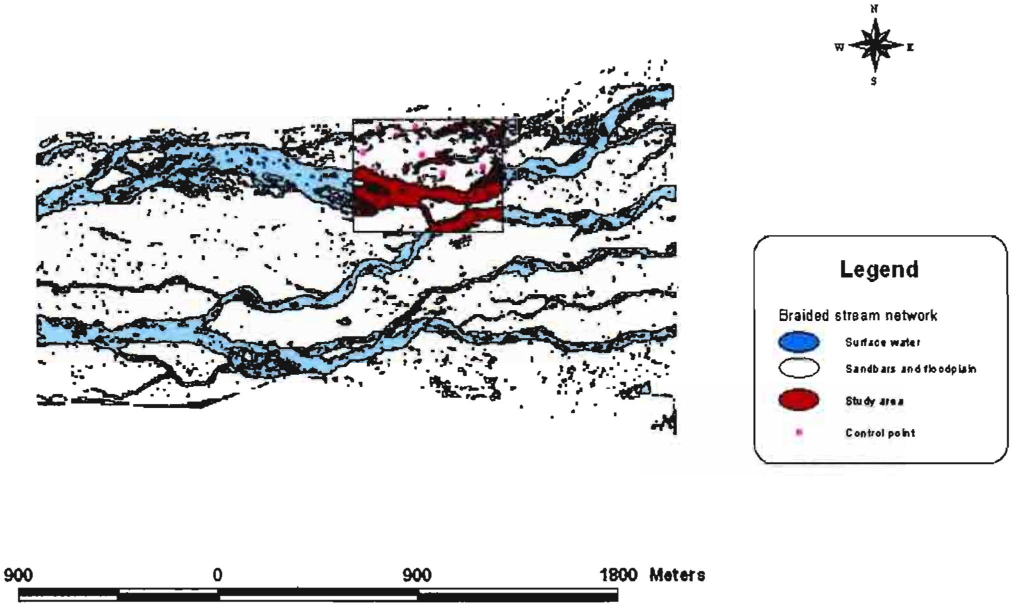


Figure 4-8 (a). A quatic habitat patches and braided stream networks under a high instream flow condition were extracted from GIS models to make this riverine landscape map at riverine landscape/reach scale. Rectangular area in center of the map, enlarged in figure (b), was detailed surveyed for topography. Red dots mark surveyed piezometers, stream gauges, and shorelines of the streams and banks. The river flows from west to east in the map.

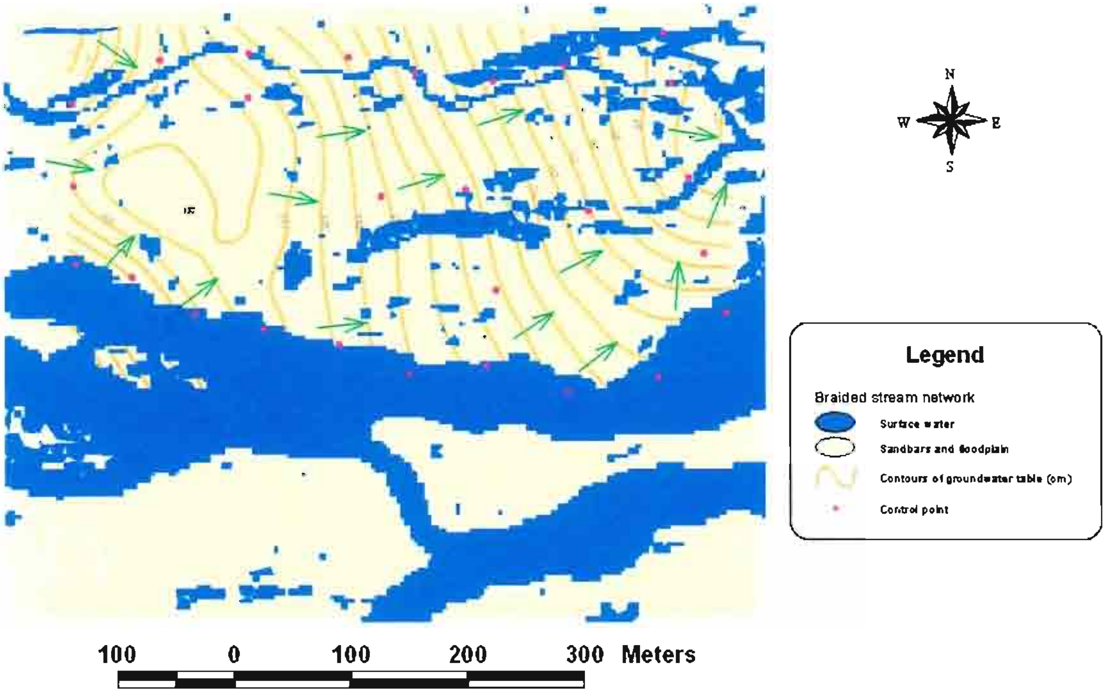


Figure 4-8 (b). Aquatic patch theme map at habitat patch scale, with groundwater table contour lines superimposed on the aquatic patch theme map. Arrows represent groundwater flow paths. This map represents a high instream flow condition (Q=56.6 m^3 or 2,000 cfs) in spring and fall. The river flows from west to east in the map.

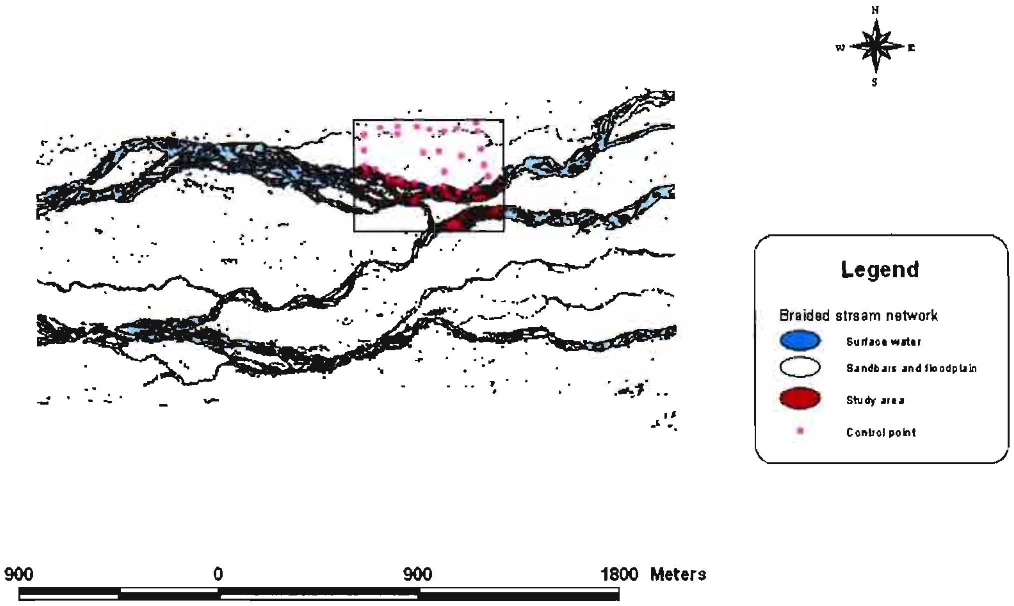


Figure 4-9 (a). Aquatic habitat patches and braided stream networks under a low instream flow condition extracted from GIS models to make this riverine landscape map at landscape/reach scale. Rectangular area in center of the map, enlarged in figure (b), was a detailed surveyed for topography. Red dots mark the surveyed piezometers, stream gauges, and shorelines of stream and banks. The river flows from west to east in the map.

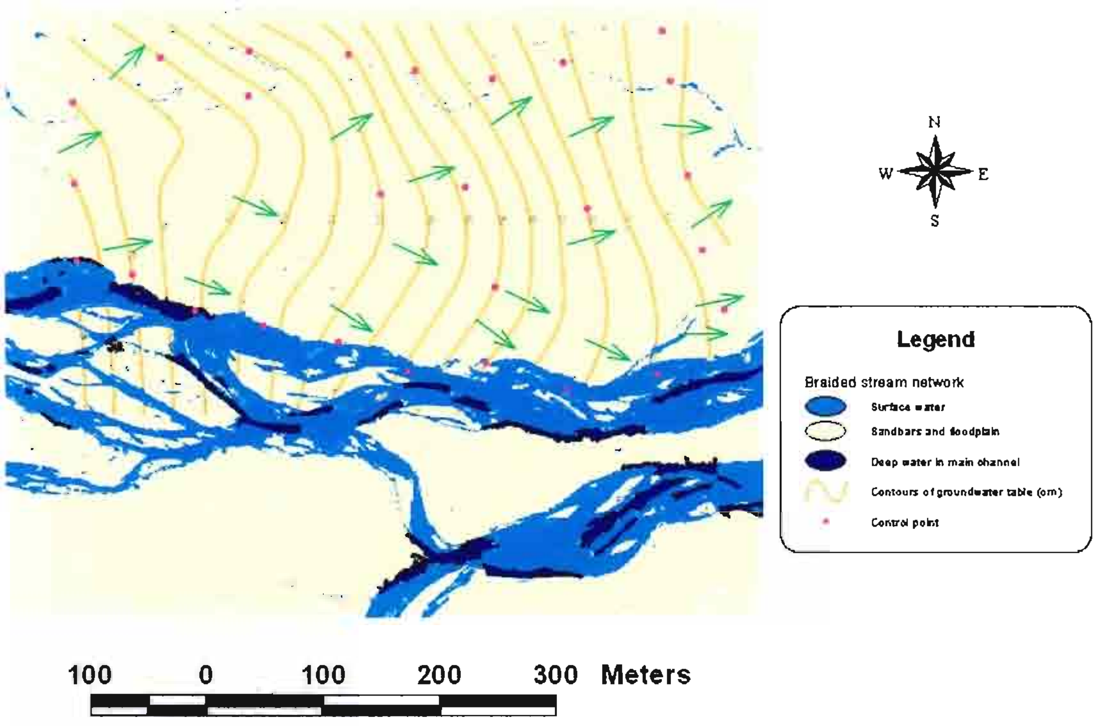


Figure 4-9 (b). Aquatic patch theme map at habitat patch scale, with groundwater table contour lines superimposed on the aquatic patch theme map. Arrows represent the groundwater flow paths. This map represents a low instream flow condition (Q=11.5 m^3 or 405 cfs) in a summer dry season. The river flows from west to east in the map.

Table 4-6. Comparison of landscape indices for riverine habitats changes under different hydrological processes at the landscape scale.

Landscape Indices (Elkie et al. 1999)	High Stream Flow (A)	Low Stream Flow (B)	Change (B - A)
Total patch class area (CA, m^2)	585,878	387,000	-34 %
Number of patches (NumP)	2504	5893	+135 %
Mean patch size (MPS, m^2)	234	65.7	-72 %
Patch size standard deviation (PSSD)	0.95276	0.25692	-73 %
Total patch edges (TE, m)	96912	154354	+59 %
Patch edge density (ED, $m/10^4m^2$)	1654.13	3988.44	+141 %
Mean patch edges (MPE, m/patch)	38.71	26.19	-32 %
Mean patch shape index (MSI)	1.3441	1.3218	- 2 %

Chapter 5. Results and Discussions (II): Physicochemical Heterogeneity

Understanding the distribution pattern of surface water physicochemical properties is very important for river ecology, and is critical for the ecological risk assessment of the river ecosystem. The landscape of the Middle Platte River floodplain is a diverse and dynamic mosaic of habitat patches. These patches have distinctive features of hydrology, geomorphology, land cover, and land use that may affect or determine physical and chemical characteristics of surface water. Thus, one may expect that the distribution of physico-chemical properties in surface water of the riverine habitats would reflect the habitat spatial heterogeneity. However, temporal variability of surface water in the riverine habitats is significant given their dynamic hydrological interactions with the main channel (Wu 1999c). The research questions are: (1) are the physicochemical properties of riverine aquatic habitat types significantly different from each other? And (2) what are the spatial and temporal patterns of physicochemical parameters across the habitat types? To investigate the heterogeneity of the river landscape from the physicochemical perspective, the spatial patterns of physicochemical heterogeneity were examined using the habitat types classified by the criteria listed in Table 3-3 in the chapter 3.

5.1 Physical and chemical properties of surface water in the riverine landscape

5.1.1 Daytime temperature

Temperature and water current are two of the major environmental factors that directly affect the activities of aquatic organisms (Allan 1995; Goldowitz 1996a, 1996b). Field measurements (n = 434) show that the mean daytime temperature of surface water in the Middle Platte River, including the main channel and adjacent habitats, was 18.8 °C (65.8 F) during the study period. The temperature varied from 15 to15.6 °C (59 to 60 F) in spring, 21.7 to 25.0 °C (71 to 77 F) in summer, and 9.3 to 10.9 °C (49 to 52 F) in the fall (Table 5-1, Fig 5-1). Analysis of variance (ANOVA) showed there was no significant difference in the mean daytime temperature among the nine subtypes of aquatic habitat ($F_{(8,\ 113.93)} = 1.65$, $p = 0.1191$. Table 5-2, Figure 5-2, Figure 5-3). Due to the direct connection of side-channels and backwaters with main channels, there were only slight mean temperature differences in these habitats. Temperatures in the tributary was more than 1 °C (2 F) higher than that of the main channel; by contrast, the mean daytime temperature in backwater was 0.6-1 °C (1 F) lower than in the main channels (Table 5-2). These differences may be the effect of different land cover, groundwater discharge, current velocity, and hydrological conditions. Permanent wet meadow sloughs, where groundwater is the main water source, had the lowest mean daytime water temperature among the nine habitat types, about 2.4 °C (4 F) lower than that of the main channels, which suggests groundwater as the dominant source of water input. Intermittent slough and shallow wet meadow ponds had higher mean temperatures than the main channel and other habitat subtypes due to their shallow and motionless water bodies (Table 5-2, Figure 5-2).

The spatial pattern of the distribution of mean daytime temperature in surface water across aquatic habitats of the Middle Platte River was illustrated by comparing the mean values of the habitat subtypes. This pattern changed with season (Figure 5-3). In spring, the distributions were nearly same in the nine habitat subtypes (F test, $p > 0.05$). The temperature in the main channel was about 1 °C to 3 °C lower than in the riparian habitats. In summer, a step-type distribution pattern occurred from the main channel (23-28 °C) to the wet meadow sloughs (20-24 °C), with the exception of intermittent wet meadow sloughs and riparian ponds, where in shallow, calm water mean temperatures rose to 28-32 °C. During high river flow periods in June and August 1997, water temperature in the main channel was no higher than that in the side channel (Figure 5-3). In the fall, the difference in mean water temperatures among the habitat subtypes was lessened, with those in the riparian pond and the backwater types being the highest and those in the sloughs being the lowest among the habitat subtypes.

Table 5-1. Temporal changes in physical and chemical properties (mean ± SD) of surface water in the Middle Platte River during the study period, 1996-1998 (n = 434). Note: no salinity measurement was conducted in May 1996.

Date	n	Temperature (°C)	pH	DO (mg/L)	Conductance (25°C, µs/cm)	Salinity (ppt)
May-96	33	15.1 ± 2.0	7.7 ± 0.4	7.57 ± 2.39	927 ± 158	.
Aug-96	63	25.1 ± 5.0	8.0 ± 0.6	7.54 ± 3.38	956 ± 236	0.5 ± 0.1
Apr-97	51	15.6 ± 2.9	8.4 ± 0.3	11.07 ± 3.33	984 ± 182	0.5 ± 0.1
Jun-97	61	23.1 ± 4.5	8.0 ± 0.4	8.21 ± 2.97	985 ± 140	0.5 ± 0.1
Aug-97	66	23.6 ± 3.5	7.9 ± 0.4	7.44 ± 2.91	1026 ± 289	0.5 ± 0.1
Oct-97	63	10.9 ± 2.1	7.8 ± 0.5	8.57 ± 2.94	1020 ± 213	0.5 ± 0.1
Jun-98	59	21.7 ± 2.7	8.1 ± 0.5	9.11 ± 3.42	950 ± 127	0.5 ± 0.1
Nov-98	40	9.3 ± 1.5	8.0 ± 0.7	9.12 ± 2.81	1054 ± 265	0.5 ± 0.1

Table 5-2. Spatial heterogeneity of physical and chemical properties (mean ± SD) of surface water in the Middle Platte River during the study period, 1996-1998 (n = 434), summarized by aquatic habitat subtype.

Habitat	n	Temperature (°C)	pH	DO (mg/L)	Conductance (25°C, μs/cm)	Salinity (ppt)
Main channel (MC)	112	18.7 ± 6.6	8.4 ± 0.3	9.50 ± 1.32	930 ± 58	0.5 ± 0.0
Side-channel (SC)	31	19.0 ± 6.3	8.3 ± 0.4	9.49 ± 1.56	933 ± 54	0.5 ± 0.0
Tributary (TB)	51	20.0 ± 7.1	8.1 ± 0.4	10.20 ± 3.59	973 ± 148	0.5 ± 0.1
Connected backwater (CB)	83	18.1 ± 6.0	7.9 ± 0.4	8.20 ± 3.35	1020 ± 148	0.5 ± 0.1
Disconnected backwater (DB)	41	17.4 ± 6.1	7.6 ± 0.4	5.73 ± 3.98	1052 ± 194	0.5 ± 0.1
Permanent slough (PS)	51	17.6 ± 5.7	7.7 ± 0.4	7.56 ± 3.22	1107 ± 288	0.6 ± 0.1
Intermittent slough (IS)	15	21.6 ± 9.3	7.5 ± 0.8	8.54 ± 3.97	774 ± 395	0.4 ± 0.2
Wet meadow pond (WP)	29	22.3 ± 8.4	8.0 ± 0.8	8.82 ± 3.58	1034 ± 422	0.5 ± 0.2
Riparian pond (RP)	23	17.6 ± 5.3	7.8 ± 0.7	6.87 ± 3.91	984 ± 228	0.5 ± 0.1

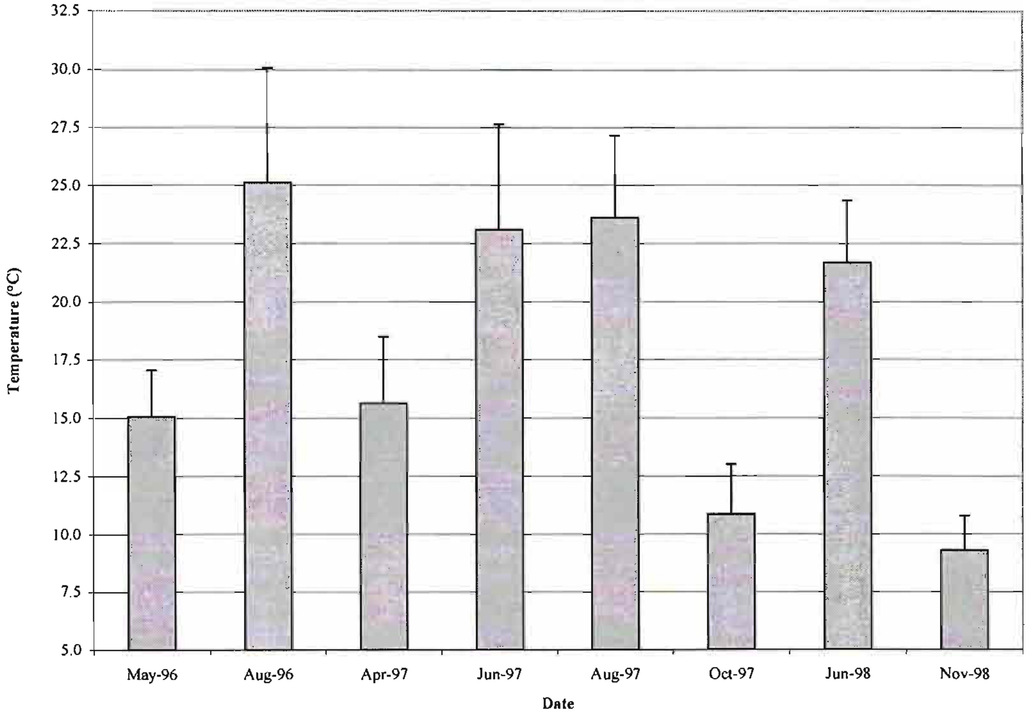


Figure 5-1. Seasonal change in surface water mean (+ SD) daytime temperature (°C) in the Middle Platte River during the study period, 1996-1998 (n = 434).

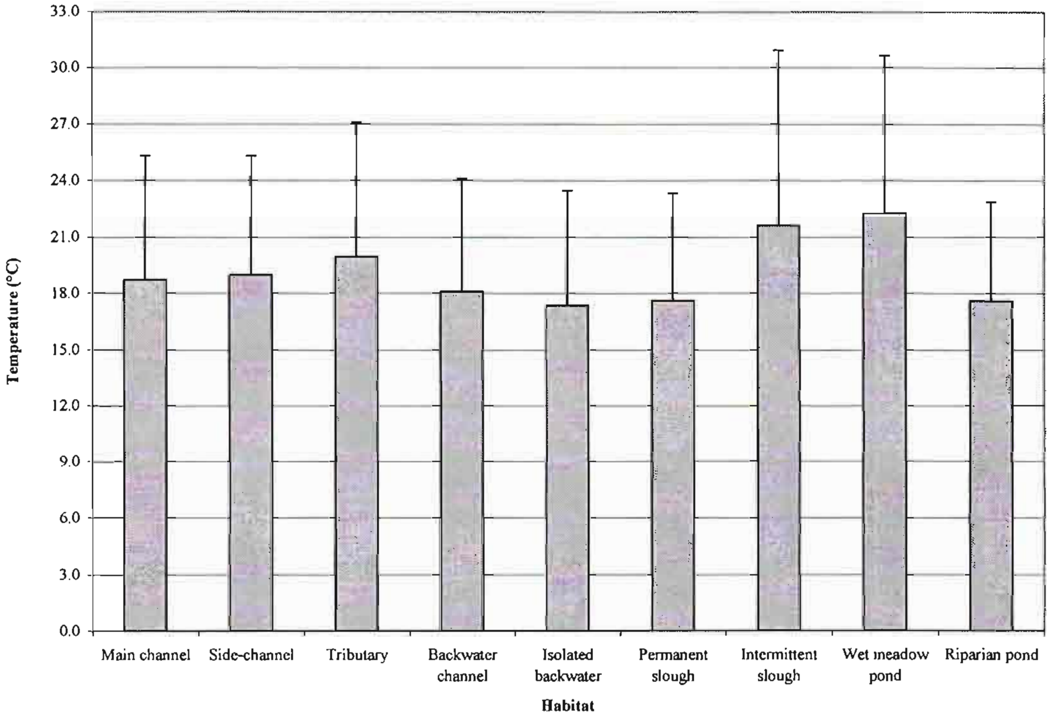


Figure 5-2. Surface water mean (+ SD) daytime temperature (°C) by habitat subtypes in the Middle Platte River during the study period, 1996-1998.

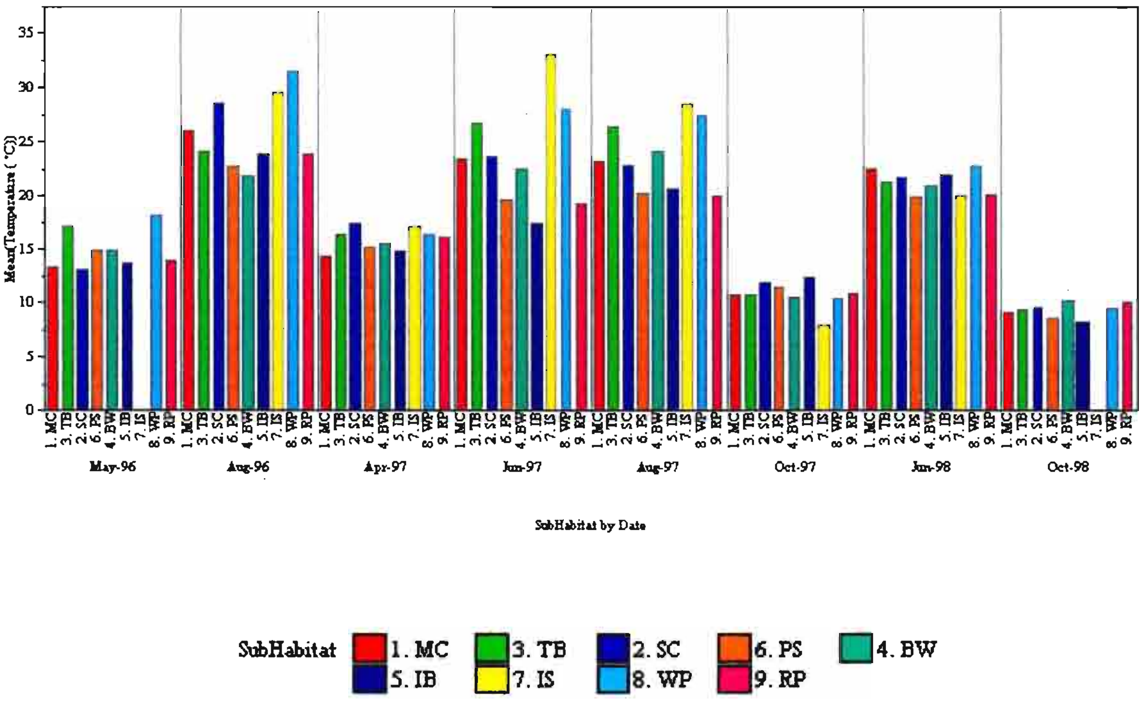


Figure 5-3. Spatial patterns of surface water mean daytime temperature (°C) in the habitat subtypes in the Middle Platte River, and their seasonal changes during the study period, 1996-1998.

Under similar weather condition, water depth, source of water input, and land cover of the riverine habitats play main roles in change of the temperature pattern. As my results showed, side-channel, tributary, and most backwater bodies were shallower (< 0.3 m) than the main channel (normally 0.30 to 0.80 m deep). Current velocity was typically

0.15-0.25 m/s in these habitats; while in the main channel it was usually over 0.30 m/s under normal flow conditions (Table 3-1). Side-channel and tributary channel habitats had narrow open channels with denuded or sparsely covered sandbars. The exposed sandy surface in the side-channel contributes to increasing the temperature of a side-channel faster than that in the main channel.

Most backwater bodies are disconnected from the main channel. Instead of direct inflow from surface channels, backwater bodies receive seepage from riverbanks, or recharge from subsurface groundwater. Cooler shallow groundwater recharge can reduce the surface water temperature of a backwater and wet meadow slough habitat. Also, in backwater habitat, vegetative cover was denser than that in the side-channel. Canopies of cottonwood, willow, and dogwood along the shoreline shaded most of the backwater areas, and probably reduced sun time in backwaters.

During a summer dry season, the river level in main channels dropped to about 30 cm or less, and large areas of sandbars appeared. The mean surface temperature was higher in this case than that in side channels.

5.1.2 Hydrogen ion concentration (pH)

Hydrogen ion concentration is one of the most important and frequently used chemical indicators in study of aquatic habitat, because many chemical phases and processes are pH-dependent (Eaton et al. 1995), for example, the bicarbonate buffer system of freshwater, which is critical to the maintenance of life (Allan 1995).

In this study, the ANOVA statistics (n = 436) revealed significant differences in average pH values by the habitat subtypes (ANOVA: $F_{(8, 110.74)} = 29.43$, $p < 0.0001$). The pH values were higher in lotic habitats (i.e. the main channel, tributaries, and side channel) than that in lentic habitats (i.e. backwater and wet meadow sloughs). A multiple comparison for all pairs (MCA) found no significant difference between main channel and side channel, or between backwater and sloughs. Average pH values in main channels and side-channels were 8.4 ± 0.3 (n = 112), and 8.3 ± 0.4 (n = 31), respectively (Table 5-2, Figure 5-4). By contrast, significant differences were found between lotic habitats (main channel and side channel) and lentic habitats (backwater and slough). The mean pH values in backwater and slough habitats ranged from 7.6 ± 0.4 to 7.9 ± 0.4 (Table 5-2, Figure 5-4). Intermittent wet meadow sloughs had the lowest mean pH of 7.5 (n = 38). This pattern of pH distribution among the four main habitat types did not change seasonally (Figure 5-5), although the magnitude of the mean pH values varied seasonally (Figure 5-6). ANOVA ($F_{(7, 354169.94)} = 15.33$, $p < 0.0001$, $r^2 = 0.29$) and MCA analyses of pH among the various types of habitats revealed that only mean pH in spring was significantly different from that in other seasons (Table 5-1, Figure 5-6). This seasonal trend in pH was similar in the aquatic habitat types except in the riparian pond habitat (Figure 5-7).

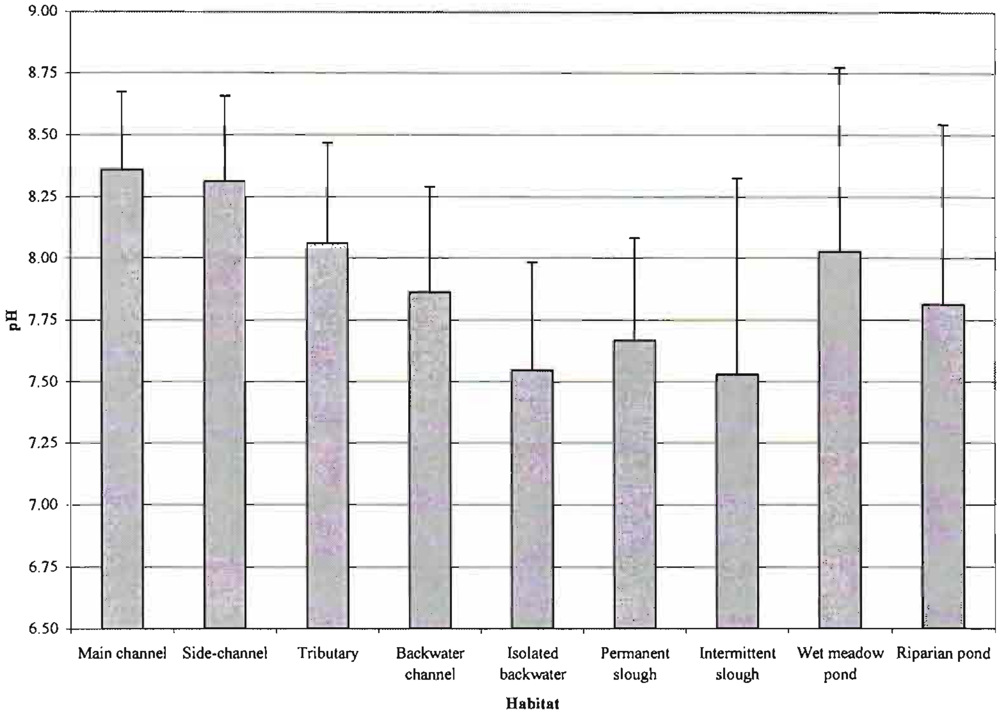


Figure 5-4. Mean (+ SD) pH value by habitat subtypes in the Middle Platte River floodplain during the study period, 1996-1998 (n = 436).

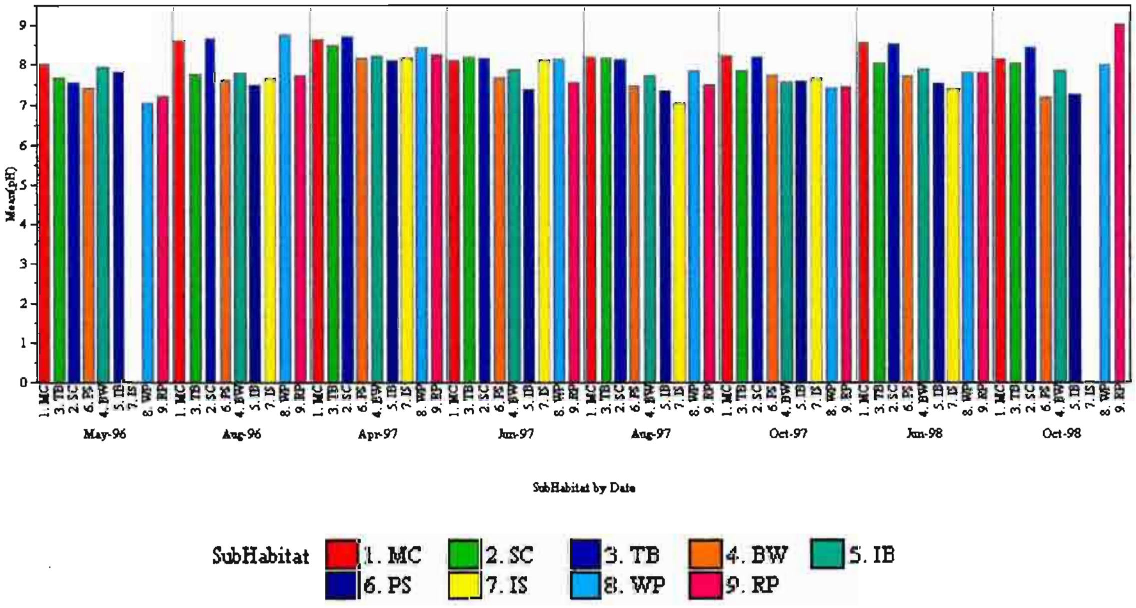


Figure 5-5. Spatial distribution patterns of mean pH by habitat subtypes in the Middle Platte River floodplain, and their changes during the study period, 1996-1998.

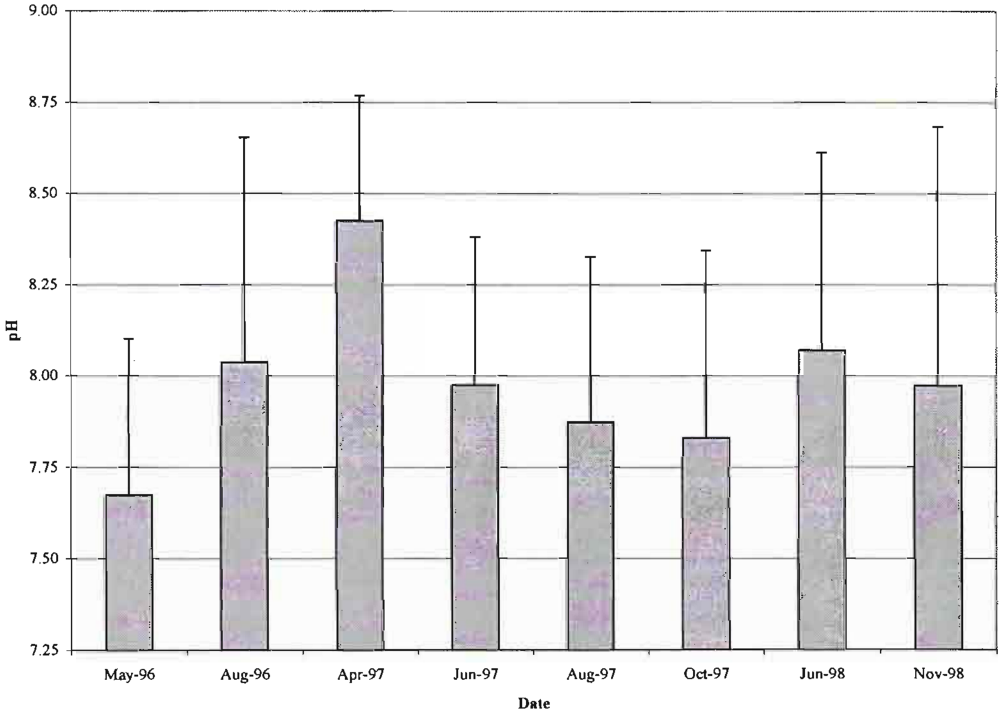


Figure 5-6. Seasonal change in mean (+ SD) pH in the Middle Platte River during the study period, 1996-1998 (n = 436).

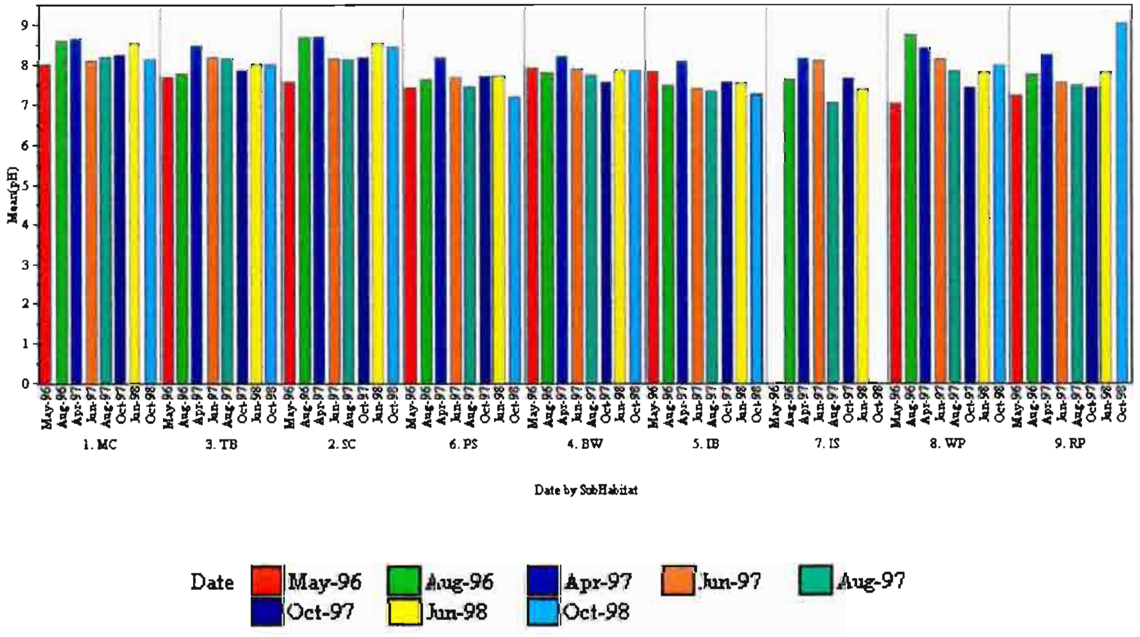


Figure 5-7. Seasonal change in mean pH within habitat subtypes in the Middle Platte River, during the study period, 1996-1998.

5.1.3 Dissolved Oxygen

Two important biological processes alter dissolved oxygen (DO) concentrations in water: photosynthesis and respiration of aquatic organisms. Since water temperature and current vary among the aquatic habitats and with season as shown in previous sections, it is not surprising that there was significant variation in DO concentrations in the study areas, due to changes in water temperature, depth, current velocity, and biological activity. The average concentration of surface water DO for all habitats studied was 8.5 mg/L during the study period ($n = 423$). ANOVA ($F_{(7, 160.73)} = 6.92$, $p < 0.0001$) and MCA analyses showed that mean DO in spring was significantly different compared to that in summer. The highest DO occurred in spring. Seasonal changes of mean DO in surface water varied from 10.9 mg/L in spring to 7.0-8.3 mg/L in summer, with up to 9.2 mg/L in fall (Table 5-1, Figure 5-8).

ANOVA ($F_{(8, 103.36)} = 8.3$, $p < 0.0001$), and MCA analyses suggested significant differences in the mean dissolved oxygen concentrations of surface water among the four habitat types, especially between the main channel and side channel group and the backwater and slough group. Statistical results (Table 5-2, Figure 5-9) indicated that mean DO concentrations in the main channel and side-channel with fast flowing water were 9.5-10.2 mg/L; in isolated backwater habitat, mean DO was 5.7 mg/L; sloughs in wet meadows had lower DO (7.6 mg/L), because of subsurface groundwater input and relatively static conditions of the water body (Table 5-2, Figure 5-9). Variation in DO concentrations was low in the main channel (SD= 1.32) relative to those in backwater (SD=3.98) and in wet meadow slough habitats (SD=3.97). This pattern probably results from abundant algae and macrophytes in the relatively calm environment of backwaters and wet meadow sloughs.

Spatial distribution patterns of mean dissolved oxygen concentrations in four main types of aquatic habitat changed seasonally during the study period. Three patterns of DO distribution in the four habitats repeatedly occurred during the study periods (Figure 5-10):

Pattern 1 (spring DO pattern): the side channel and tributary types had the highest DO levels, while the slough types had the lowest. This pattern happened in all of the three spring seasons studied (i.e. 1996 - 1998).

Pattern 2 (summer DO pattern): lotic habitats had the highest DO concentrations, while the slough had the lowest. This pattern occurred in summer (1996 - 1997).

Pattern 3 (fall DO pattern): backwater habitat had the lowest DO; other habitats had similar DO levels. This pattern happened in fall 1997 and 1998 (there was no water sampling in fall 1996).

DO variation in the intermittent slough and pond habitats was extremely high, with no evident pattern.

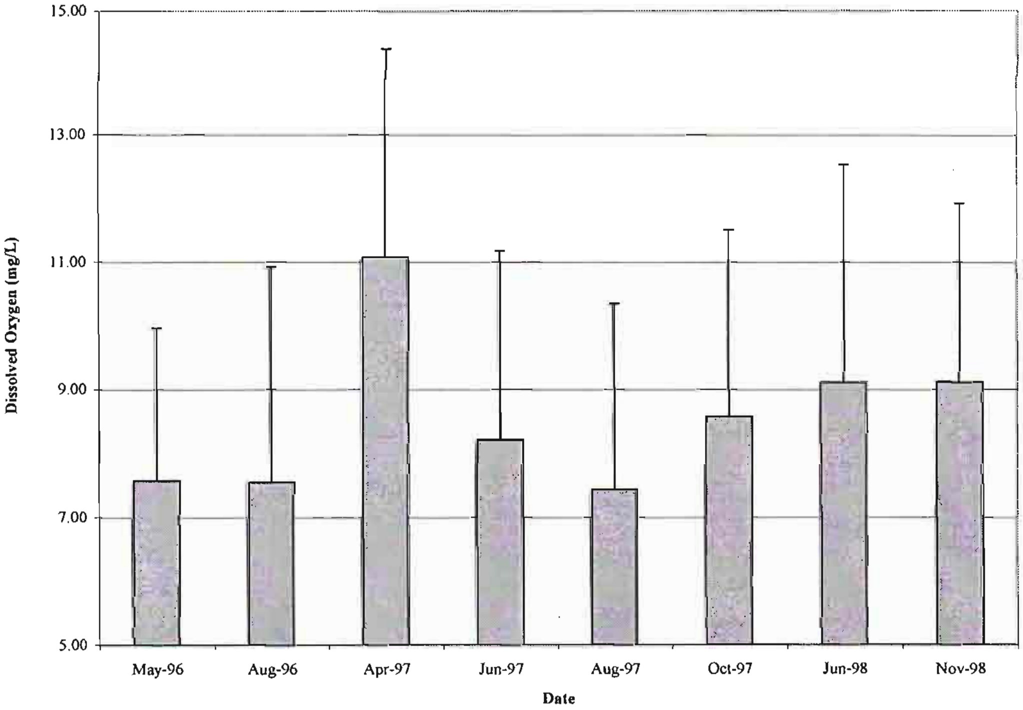


Figure 5-8. Seasonal change in mean (+ SD) dissolved oxygen concentration in the Middle Platte River during the study period, 1996-1998 (n = 423).

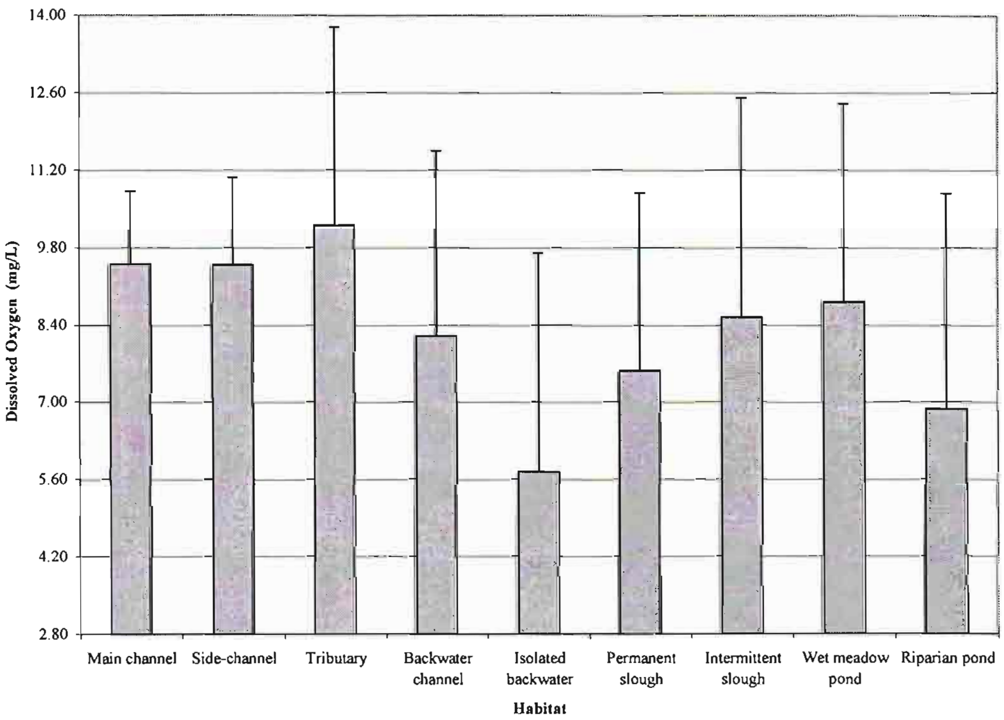


Figure 5-9. Mean (+ SD) dissolved oxygen concentration by habitat subtypes in the Middle Platte River during the study period, 1996-1998 (n = 423).

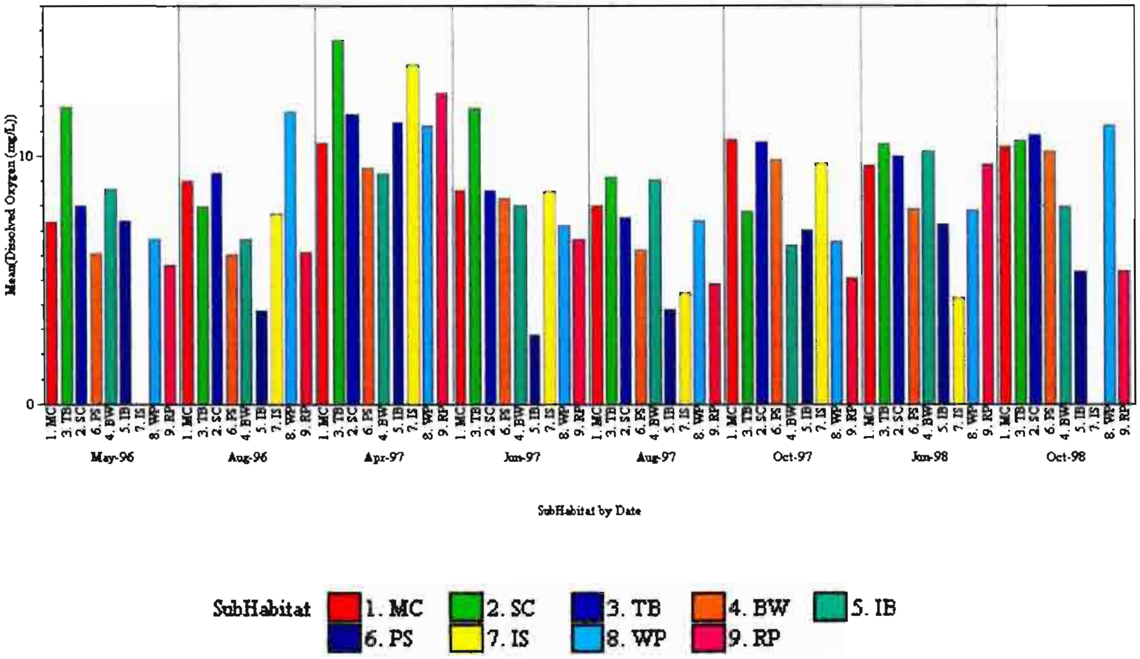


Figure 5-10. Spatial distribution patterns in dissolved oxygen concentration (mg/l) by habitat subtypes in the Middle Platte River, and their changes during the study period, 1996-1998.

5.1.4 Specific conductance

Conductivity is a measure of electrical conductance of water and is an approximate indicator of total dissolved ions (Allan 1995). Because conductivity is highly temperature dependent, a correction for this variable must be made to a standard temperature of 25 °C. In surface water at all sites in the Middle Platte River, mean specific conductance was 989.2 µs/cm during the study period (n = 430). Variation in conductance was higher in backwaters and sloughs than in the main and side channels (Table 5-2). ANOVA ($F_{(8, 107.5)} = 7.74$, $p < 0.0001$), and MCA analyses revealed significant differences in the mean specific conductance between lentic habitats and lotic habitats. Mean specific conductance ranged from 930 µs/cm in main channels to 1107 µs/cm in wet meadow sloughs (Table 5-2, Figure 5-11). There was no significant difference in mean specific conductance between side and main channels.

Seasonal changes in mean specific conductance for the entire river landscape were not significant (ANOVA: $F_{(7, 165.9)} = 2.03$, $p = 0.0542$). Most of the higher specific conductance values were observed during dryer periods in late summer and fall, and when surface water was shallow in lentic habitats (Figure 5-13). The mean specific conductance was relatively lower in early summer, and higher in late summer and fall (Table 5-1, Figure 5-12).

At the habitat scale, seasonal variation in specific conductance within each of the habitat types had clear spatial patterns (Figure 5-13). Variation was greater in backwater and wet meadow slough habitats than in main channel and side-channel habitats. In lentic habitats, surface water conductivity was higher in summer, with the maximum values in August. In contrast, it was lowest in spring, with the minimum value in April 1997 (Figure 5-13, 5-14).

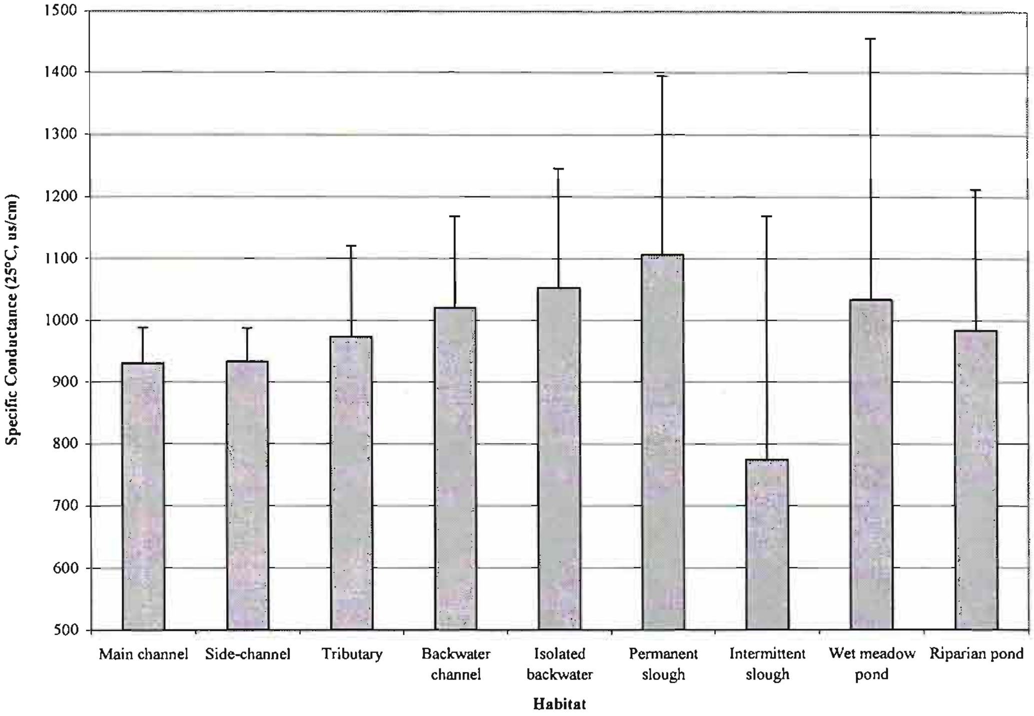


Figure 5-11. Mean (+ SD) specific conductance (25°C) by habitat subtypes in the Middle Platte River during the study period, 1996-1998 (n = 430).

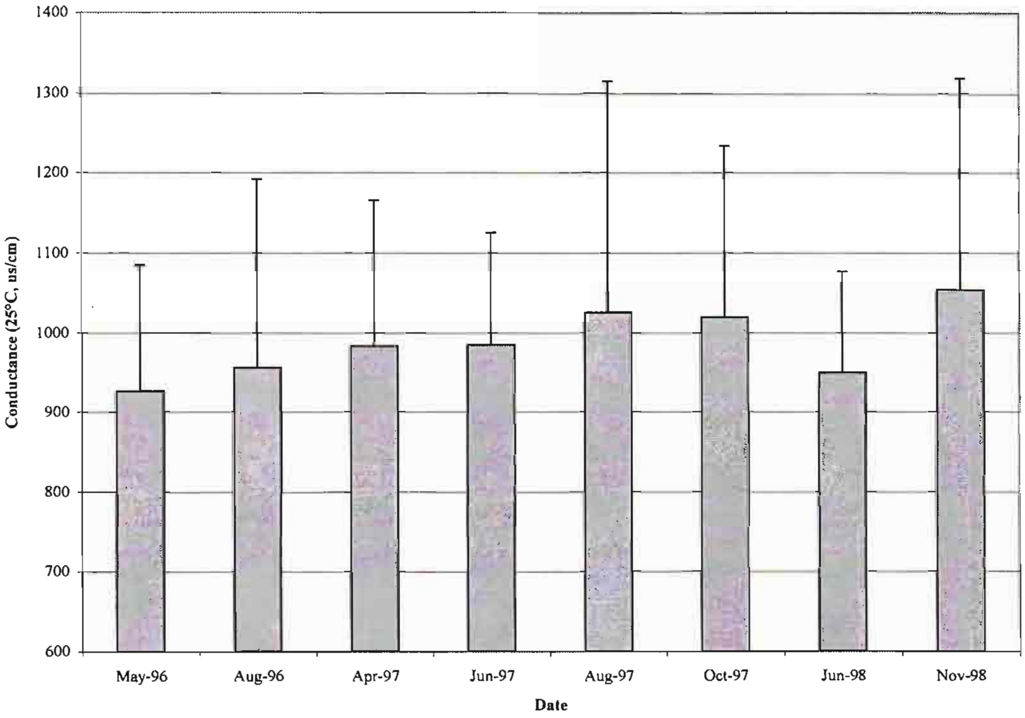


Figure 5-12. Seasonal change in mean (+ SD) specific conductance (25°C) in the Middle Platte River during the study period, 1996-1998 (n =430).

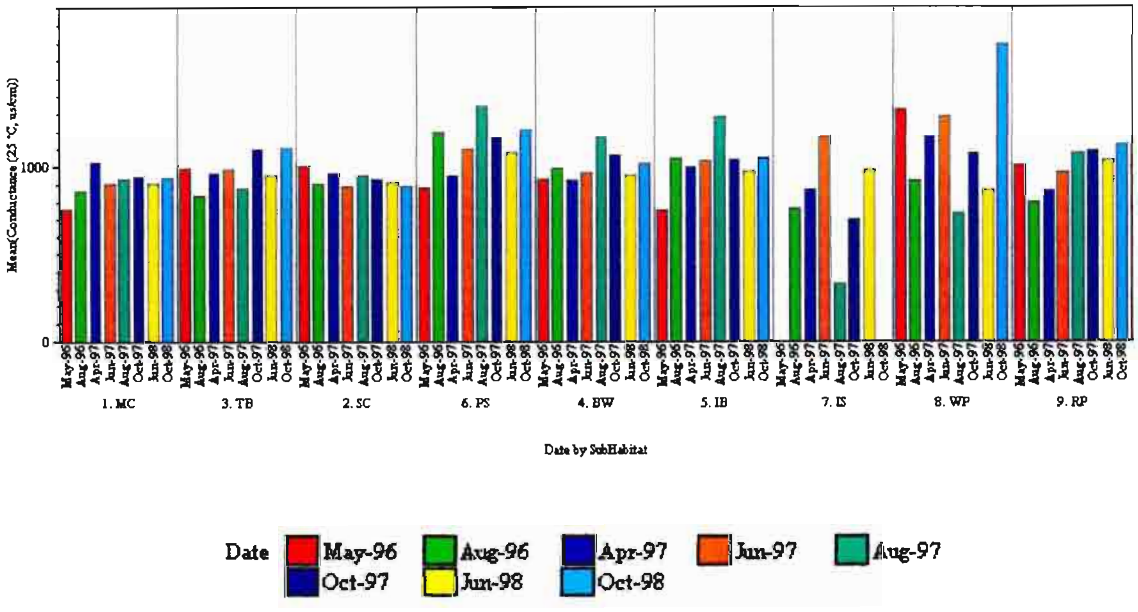


Figure 5-13. Changes in mean specific conductance (25°C) within habitat subtypes in the Middle Platte River, 1996-1998.

5.1.5 Salinity

Salinity, another indicator for total dissolved salts, showed the same trends as specific conductance. In the river floodplain, mean salinity of surface water was 0.5 ppt (n = 395) during the study period, with little change from spring to fall, and only slight differences among habitats (Table 5-2, Figure 5-15). Salinity in main channels and side-channels was 0.4-0.5 ppt, while in other lentic environments it was generally ≥ 0.5 ppt. ANOVA ($F_{(8, 99.62)} = 7.37$, $p < 0.0001$), and MCA analyses revealed significant differences in mean salinity (ppt) between backwater and slough and main and side channel, but no significant difference between main channel and side channel habitats. Some sites where salinity was as high as 0.8-1.1 ppt, were consistent with those with high conductivity (refer to Table 5-2, Figure 5-11).

Seasonal changes in mean salinity in the river valley were small (Table 5-1, Figure 5-16) although an ANOVA ($F_{(6, 162.9)} = 3.72$, $p = 0.0017$) suggested that there were significant differences between summer and fall. Comparing mean salinity among the four habitat types at the habitat scale, seasonal fluctuations in mean salinity in each of the four habitat types were significant for lentic habitats (Figure 5-17). Two distribution patterns in surface water mean salinity were found (Figure 5-18): a relatively flat spring pattern versus an abruptly changed summer-fall season pattern, reflecting a significant seasonal fluctuation in backwater and wet meadow habitats. These distribution patterns were very similar to patterns of specific conductance (Figure 5-14).

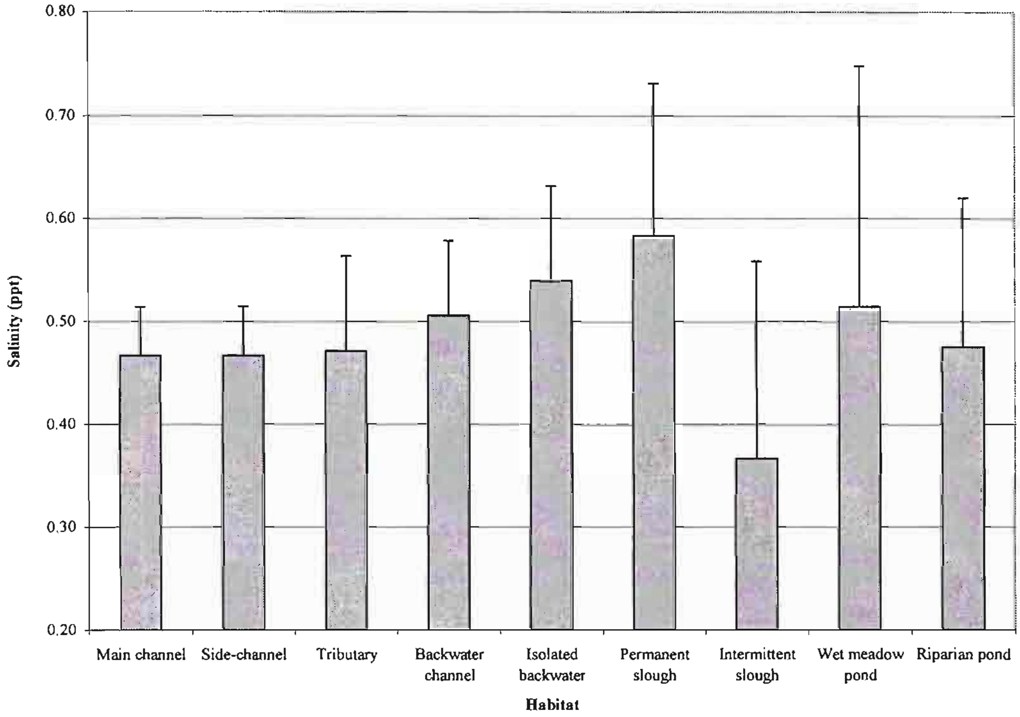


Figure 5-15. Mean (+ SD) salinity by habitat subtypes in the Middle Platte River during the study period, 1996-1998 (n = 395).

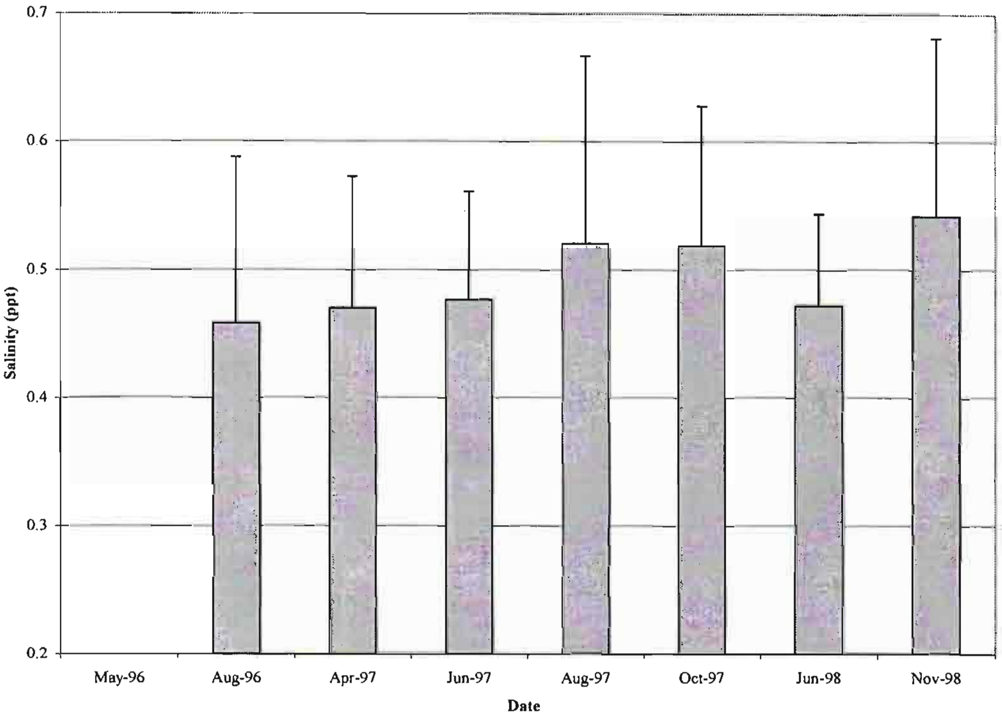


Figure 5-16. Seasonal change in mean (+ SD) salinity in the Middle Platte River during the study period, 1996-1998 (n = 395).

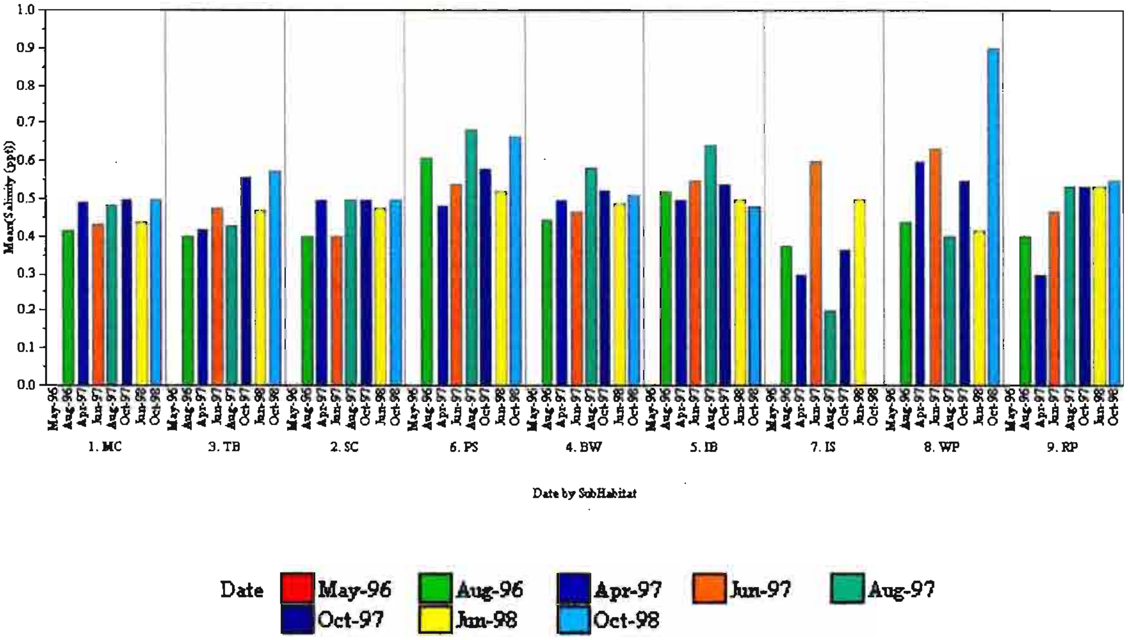


Figure 5-17. Seasonal changes in mean salinity by habitat subtypes in the middle Platte River, 1996-1998.

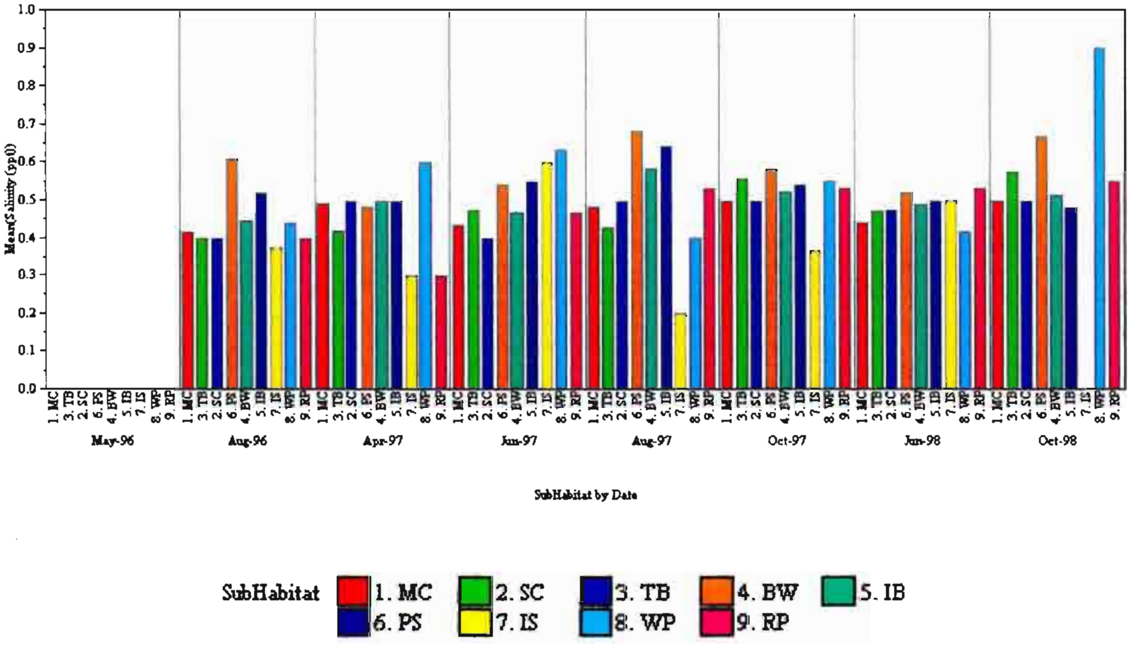


Figure 5-18. Spatial patterns of mean salinity by habitat subtypes and their seasonal changes during the study period, 1996-1998.

5.2 Nutrients of surface water in riverine habitats

5.2.1 Nitrogen (NO_3-N + NO_2-N)

Nitrogen was analyzed as nitrate + nitrite ($NO_3^- + NO_2^-$), and ammonium (NH_4^+). Nitrite was not detected or was below the limitation of detection in most samples.

The mean NO_3-N + NO_2-N concentration (n= 381) was 0.76 (± 1.14) mg/L for the study period. Ninety percent of the NO_3-N + NO_2-N values were below 2.35 mg/L, and about 2% of the samples had levels greater than 5 mg/L. These relatively high values of $NO_3^- + NO_2^-$ were found in tributary type habitats (Table 5-3, Figure 5-19) that linked with irrigation drainage ditches, or flow-through pastures. Higher nitrogen concentrations in tributary streams suggested that dissolved NO_3-N + NO_2-N were released mainly from agricultural runoff (irrigation drainage and grazing land surface and subsurface flow). The mean NO_3-N + NO_2-N concentration in the main channel was 1.07 (± 0.64) mg/L, while some sites with adjacent cropland had 2-3 mg/L nitrate + nitrite. Most of the backwater and wet meadow slough habitats had very low NO_3-N + NO_2-N concentrations (Table 5-3, Figure 5-19). ANOVA ($F(8, 100.43) = 58.0187$, $p < 0.0001$) and MCA analyses showed significant differences in mean NO_3-N + NO_2-N levels in surface water among the habitat subtypes (Figure 5-19). Specifically, there were significant differences between the lotic group (i.e. main channel and side-channel) and the lentic group (i.e. remaining habitat subtypes except intermittent sloughs and wet meadow ponds). Backwater, permanent slough, and riparian pond habitats had very low nitrogen concentrations, while the tributary had a very high nitrogen concentration. Spatial heterogeneity in NO_3-N + NO_2-N concentrations at the landscape scale was obvious and constant through all seasons (Figure 5-20).

ANOVA ($F_{(5,\ 152.8)} = 10759$, $p = 0.3740$, $\alpha = 0.05$) indicated no significant difference in mean concentrations of NO_3-N + NO_2-N among seasons in the Middle Platte River (Table 5-4, Figure 5-21). At the habitat level, however, the seasonal difference of the mean concentrations of NO_3-N + NO_2-N is noticeable for the types of main channel (ANOVA, $F_{(5,\ 9.719)} = 7.58$, $p= 0.0038$) and side-channel (ANOVA, $F_{(5,\ 6.2071)} = 13.27$, $p = 0.0030$), (Figure 5-22). The higher seasonal variation in NO_3-N + NO_2-N levels occurred in spring 1997 in the main channel, and in spring and summer 1997 in side-channel habitats. There were insufficient numbers of samples for statistical analysis on isolated backwater, intermittent slough, and riparian pond habitats, because most of these habitats were dry in summer.

Table 5-3. Spatial heterogeneity of nutrients and major dissolved ions (mean ± SD) in surface water of aquatic habitats in the Middle Platte River during the study period, 1996-1998 (n = 381), summarized by aquatic habitat subtype.

Habitat	n	NH_4-N (mg/L)	NO_3-N+NO_2-N (mg/L)	PO_4-P (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	K^+ mg/L)	Na^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)
Main channel (MC)	89	0.02 ± 0.04	1.07 ± 0.64	0.03 ± 0.03	37.2 ± 7.7	266.7 ± 40.3	10.2 ± 1.1	58.2 ± 16.7	47.1 ± 7.1	20.5 ± 1.8
Side-channel (SC)	26	0.01 ± 0.02	0.79 ± 0.38	0.02 ± 0.02	36.1 ± 4.6	264.6 ± 21.1	10.6 ± 1.2	60.4 ± 17.7	49.9 ± 9.3	21.0 ± 1.6
Tributary (TB)	43	0.09 ± 0.14	2.68 ± 1.88	0.10 ± 0.15	41.6 ± 13.1	234.5 ± 60.0	12.5 ± 2.0	56.6 ± 16.2	56.4 ± 12.9	21.7 ± 3.6
Connected backwater (CB)	79	0.02 ± 0.06	0.29 ± 0.51	0.03 ± 0.09	38.3 ± 8.7	288.4 ± 85.4	10.0 ± 1.4	61.7 ± 15.9	57.5 ± 11.7	22.1 ± 2.8
Disconnected backwater (DB)	36	0.03 ± 0.09	0.06 ± 0.22	0.04 ± 0.04	39.9 ± 10.6	315.4 ± 117.1	10.2 ± 2.2	62.5 ± 19.9	59.5 ± 13.6	22.8 ± 4.1
Permanent slough (PS)	47	0.03 ± 0.07	0.19 ± 0.41	0.03 ± 0.03	38.4 ± 10.7	314.9 ± 100.3	7.9 ± 2.7	67.5 ± 19.9	62.2 ± 14.4	22.1 ± 3.9
Intermittent slough (IS)	12	0.03 ± 0.08	0.75 ± 1.18	0.22 ± 0.33	24.7 ± 17.2	158.4 ± 157.1	14.0 ± 2.9	29.6 ± 21.4	39.5 ± 15.4	14.6 ± 7.6
Wet meadow pond (WP)	28	0.08 ± 0.23	0.58 ± 1.10	0.12 ± 0.21	38.5 ± 18.6	330.4 ± 184.4	10.6 ± 3.4	61.5 ± 25.2	57.0 ± 22.4	22.4 ± 6.6
Riparian pond (RP)	21	0.03 ± 0.07	0.01 ± 0.01	0.03 ± 0.08	40.6 ± 12.3	255.8 ± 77.6	10.0 ± 2.6	65.3 ± 22.0	59.6 ± 12.9	21.7 ± 4.5

Table 5-4. Temporal changes in nutrients and major dissolved ions (mean ± SD) in surface water of aquatic habitats in the Middle Platte River during the study period, 1996-1998 (n = 381).

Date	n	NH_4-N (mg/L)	NO_3-N+NO_2-N (mg/L)	PO_4-P (mg/L)	Cl^- (mg/L)	SO_4^{2-} (mg/L)	K^+ mg/L)	Na^+ (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)
May-96	33	0.02 ± 0.07	0.62 ± 1.33	0.07 ± 0.15	24.4 ± 7.5	206.7 ± 65.6	9.5 ± 2.8	68.3 ± 18.8	62.8 ± 11.7	19.8 ± 4.6
Aug-96	71	0.03 ± 0.11	0.63 ± 1.12	0.09 ± 0.11	29.5 ± 7.8	229.9 ± 95.8	10.2 ± 2.7	66.4 ± 19.8	56.5 ± 18.6	21.0 ± 4.8
Apr-97	62	0.02 ± 0.04	1.12 ± 1.49	0.01 ± 0.03	46.1 ± 7.8	302.6 ± 65.9	10.2 ± 2.6	32.2 ± 2.6	46.3 ± 5.6	21.2± 1.9
Jun-97	72	0.09 ± 0.17	0.68 ± 0.97	0.01 ± 0.03	40.2 ± 8.6	284.8 ± 50.2	9.9 ± 1.7	71.0 ± 8.3	52.6 ± 10.2	22.0 ± 2.5
Aug-97	71	0.03 ± 0.06	0.77 ± 0.85	0.09 ± 0.18	39.8 ± 9.8	323.7 ± 135.7	10.7 ± 2.4	55.4 ± 17.8	62.2 ± 14.0	21.4 ± 5.0
Oct-97	72	0.00 ± 0.01	0.72 ± 1.11	0.03 ± 0.11	42.8 ± 9.7	290.5 ± 87.0	10.8 ± 2.0	68.4 ± 10.8	51.0 ± 11.7	22.2 ± 3.6

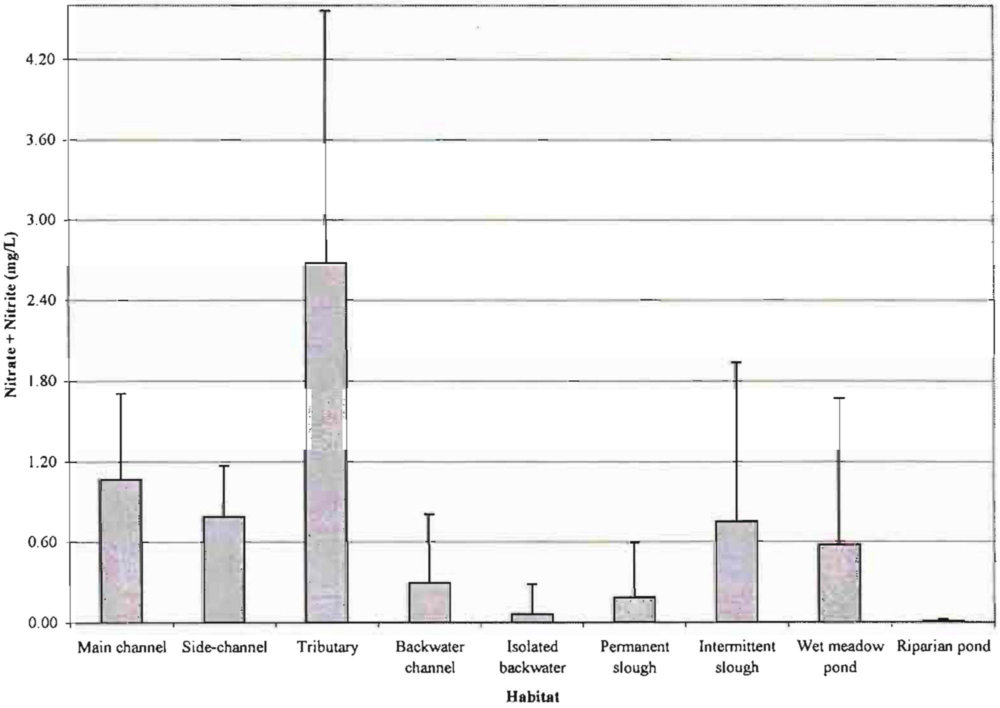


Figure 5-19. Mean (+ SD) concentrations of nitrogen (NO_3-N + NO_2-N) by habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 381).

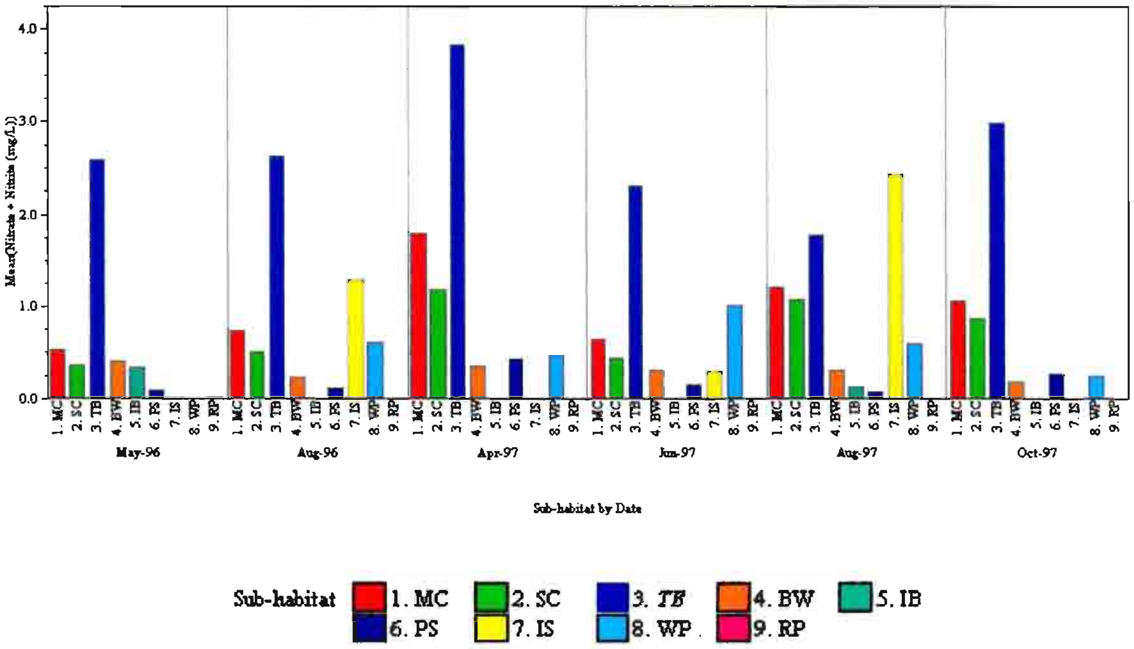


Figure 5-20. Spatial patterns of mean (+ SD) nitrogen (NO_3-N + NO_2-N) across habitat subtypes, and their seasonal changes during the study period, 1996-1997.

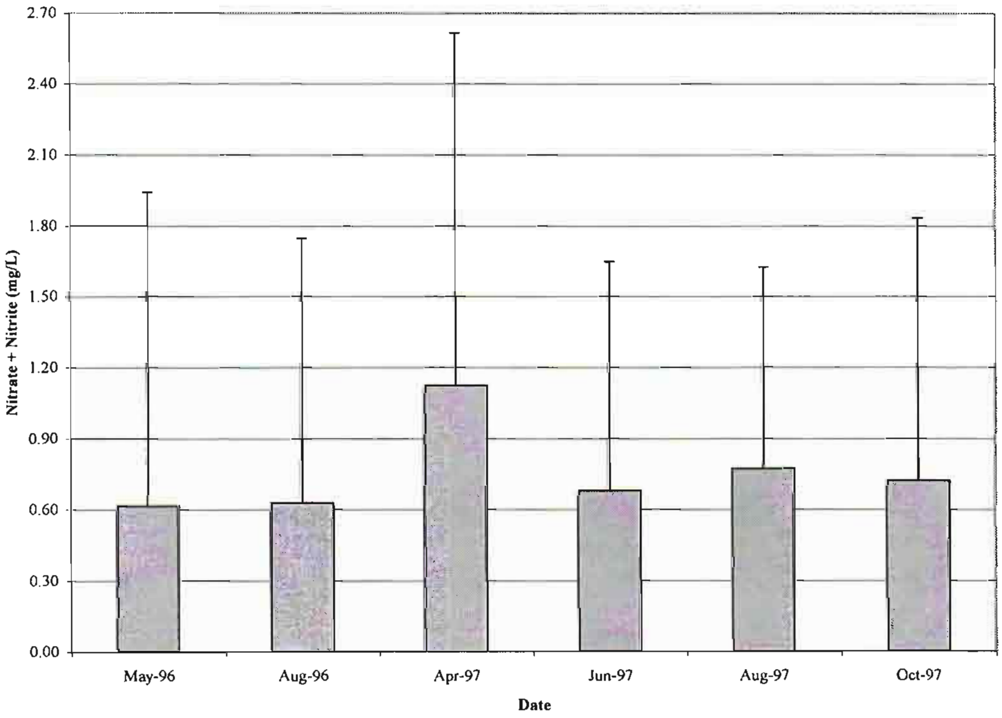


Figure 5-21. Seasonal change in mean (+ SD) nitrogen (NO_3-N + NO_2-N) concentration in the Middle Platte River during the study period, 1996-1997 (n =381).

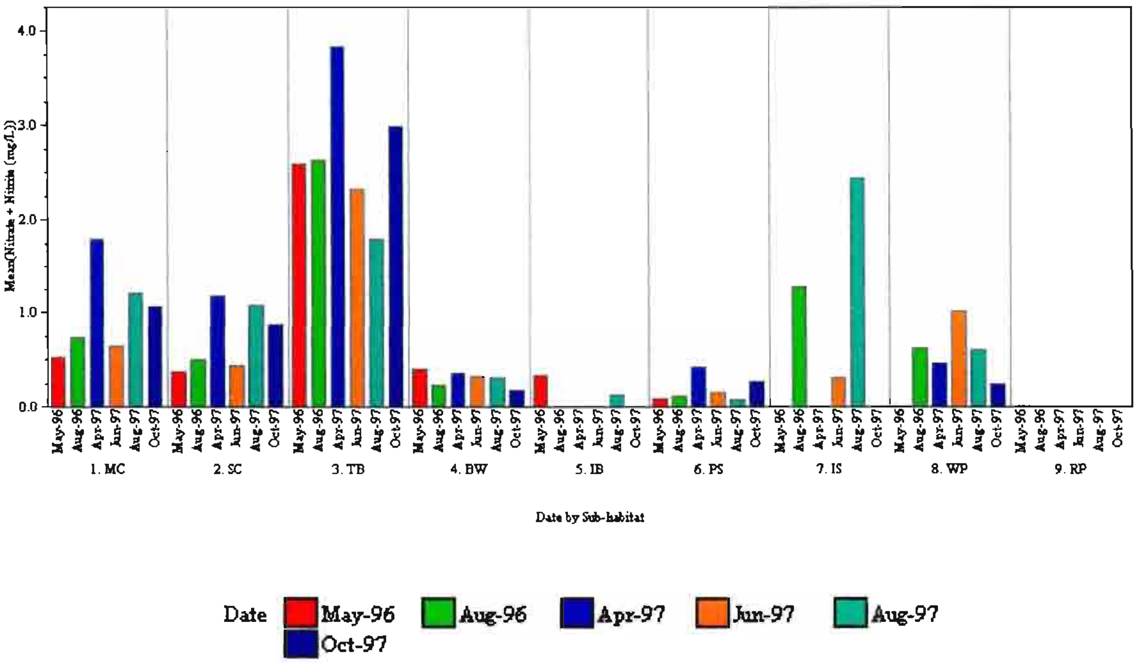


Figure 5-22 Seasonal changes in mean nitrogen (NO_3-N + NO_2-N) concentration in each of the habitat subtypes in the Middle Platte River, 1996-1997.

5.2.2 Ammonium (NH_4-N)

The overall mean concentration of ammonium (NH_4-N) in surface water during the study was 0.03 (± 0.10) mg/L (n = 379). Seventy-five percent of the water samples had NH_4-N concentrations or less than 0.01 mg/L (detection limit). Ammonium (NH_4-N) concentrations in tributary and wet meadow pond habitats were statistically different from the other seven habitat types (ANOVA: $F_{(8, 97.297)} = 2.26$, $p = 0.0290$). Mean concentrations of ammonium were 0.02 mg/L for main channel, 0.01 mg/L for side-channel, 0.09 mg/L for tributary, 0.02 mg/L for backwater, 0.03 mg/L for permanent slough, and 0.08 mg/L for wet meadow pond, respectively (Table 5-3, Figure 5-23). Similar to NO_3-N + NO_2-N, side-channels had higher ammonium concentration than other surface water habitats. Very high ammonium was found in wet meadow ponds where the land was used for seasonal grazing, which might be the results from decomposition of livestock wastes (Figure 5-25).

Statistical results for seasonal changes (ANOVA: $F_{(5, 133.55)} = 10.50$, $p < 0.0001$) also showed differences between summer and other seasons (Table 5-4, Figure 5-24). Higher NH_4-N values occurred in summer, especially in June, likely due to widely applied ammonia on cropland during summer growing seasons. Runoff in May to mid-June brought agricultural nutrients to riverine habitats. Distribution of higher NH_4-N concentration seemed to shift from the main channel type to associated habitats from spring to summer (Figure 5-25). The NH_4-N concentration was very low in spring and fall for all types of aquatic habitats (Figure 5-25, Figure 5-26).

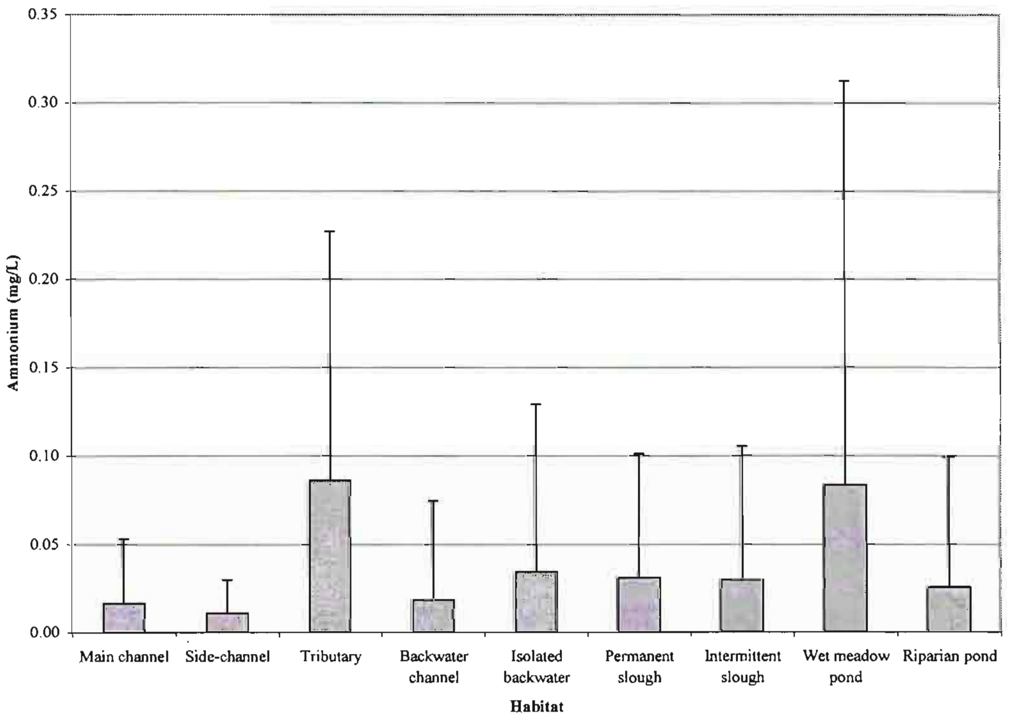


Figure 5-23. Mean (+ SD) concentration of ammonium (NH_4-N) by the habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 379).

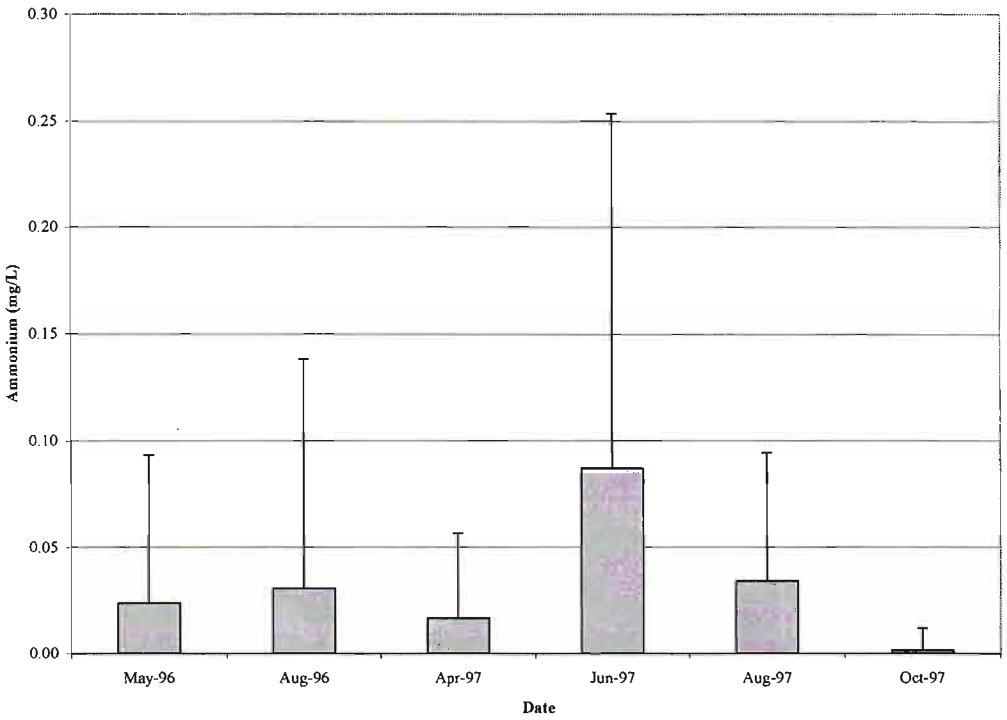


Figure 5-24. Seasonal change in mean (+ SD) ammonium (NH_4-N) concentration in the Middle Platte River floodplain during the study period, 1996-1997 (n =379).

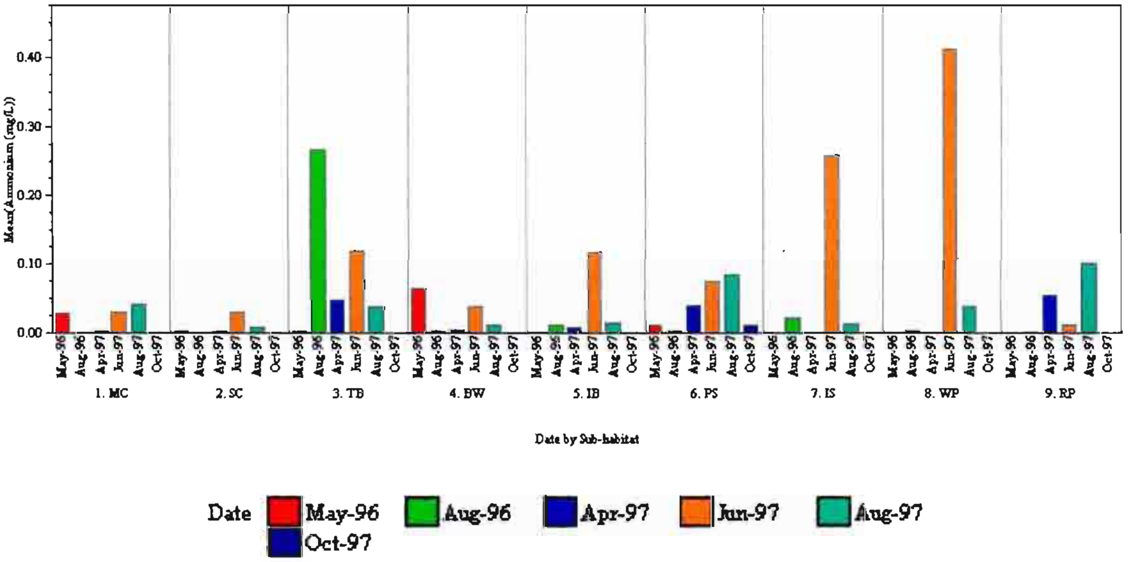


Figure 5-25. Changes of mean ammonium (NH_4-N) concentration in habitat subtypes in the Middle Platte River, 1996-1997.

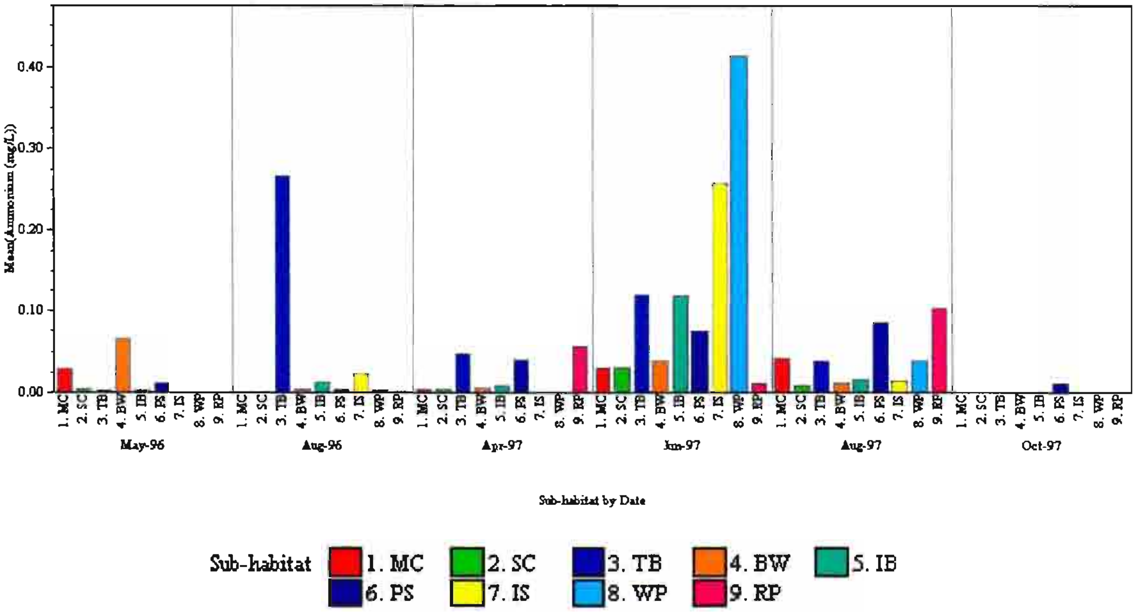


Figure 5-26. Spatial patterns of mean ammonium (NH_4-N) concentration in the habitat subtypes in the Middle Platte River, and their seasonal changes during the study period, 1996-1997.

5.2.3 Phosphorus (PO_4-P)

Most dissolved phosphorus concentrations (PO4-P) in the water samples were approximately 0.003 mg/L (the detection limit). Mean phosphorus concentrations of all water samples ($n = 381$) was 0.05 (± 0.12) mg/L. Difference of mean phosphorus concentration among the habitat subtypes is significant (ANOVA, $F_{(8, 96.641)} = 2.76$, $p = 0.0087$). Tributary, wet meadow pond, and intermittent slough habitats had higher mean concentrations ($\geq$ 0.10 mg/L) while phosphorus levels in other aquatic habitats were all lower than 0.04 mg/L (Table 5-3, Figure 5-27). The seasonal difference was also significant statistically (ANOVA, $F_{(5, 145.34)} = 12.8$, $p < 0.0001$) at the whole river ecosystem scale (Table 5-4, Figure 5-28). Higher phosphorus concentrations in surface water were detected mainly in samples collected during summer. These samples (> 0.20 mg/L) were not collected from the main channel, and only a few from grazed wet meadow habitats (Figure 5-29). The high phosphorus concentration values were likely related to agricultural activities on land adjacent to side channels, and associated to backwater areas. Seasonal variation in phosphorus concentrations was dramatic in the main channel and side-channel habitats. However, it was very low in both the backwater and wet meadow habitats. This temporal pattern of phosphorus variation across the aquatic habitat types was seen in all of the summers sampled. Phosphorus remained very low during other seasons, and there was no significant difference among these habitat types (Figure 5-29, 5-30).

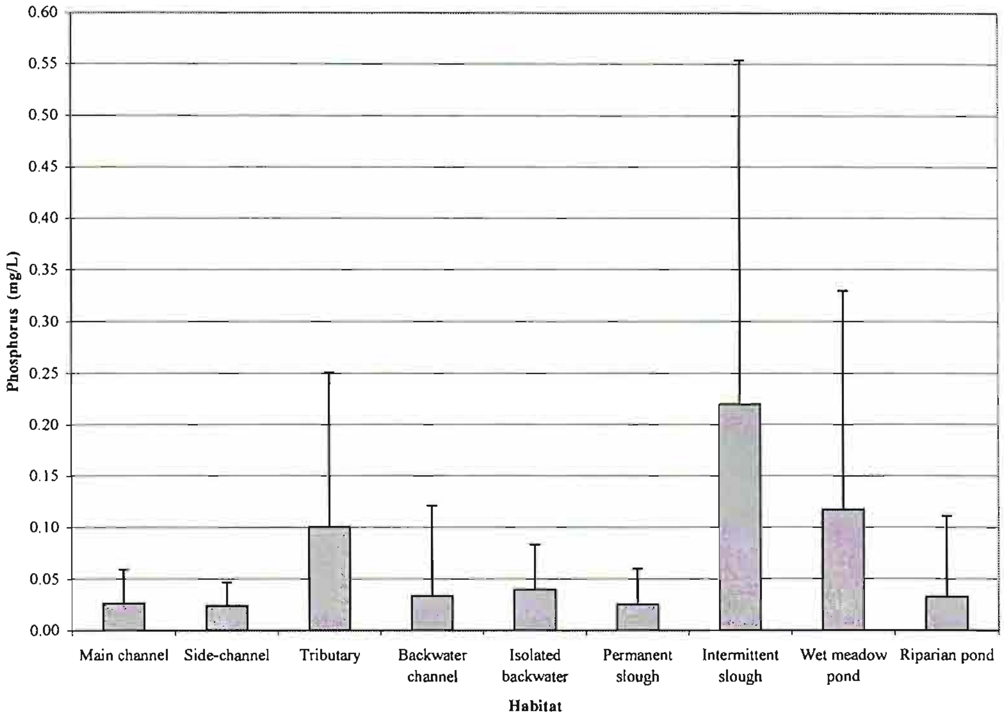


Figure 5-27. Mean (+ SD) phosphorus concentration by habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 381).

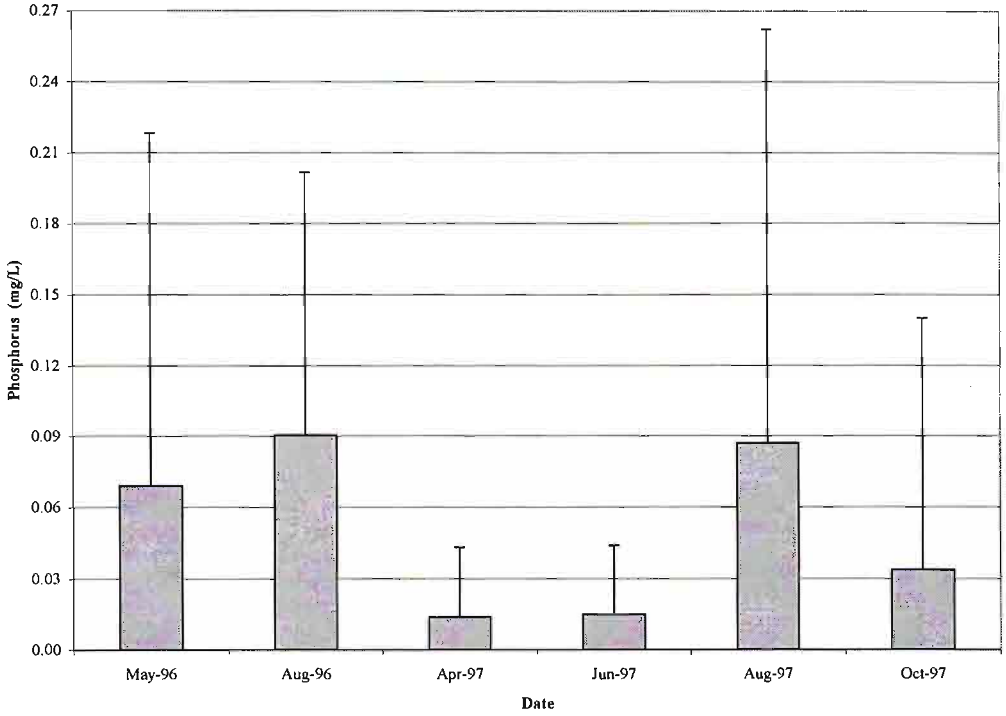


Figure 5-28. Seasonal changes in mean (+ SD) phosphorus concentration in the Middle Platte River during the study period, 1996-1997 (n =381).

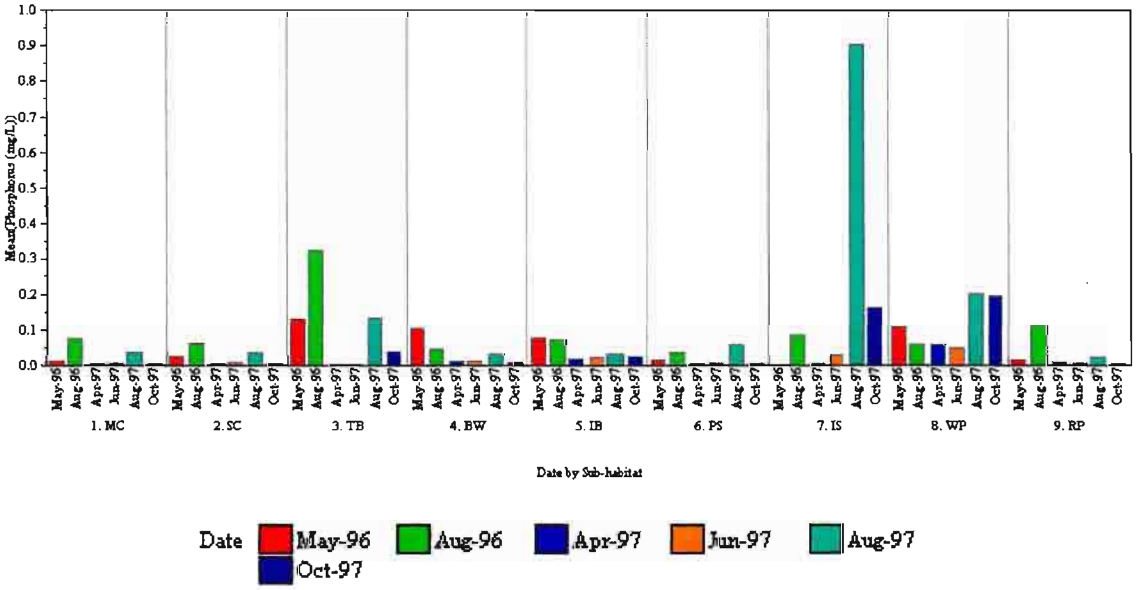


Figure 5-29. Seasonal changes in mean phosphorus concentration by habitat subtypes in the Middle Platte River, 1996-1997.

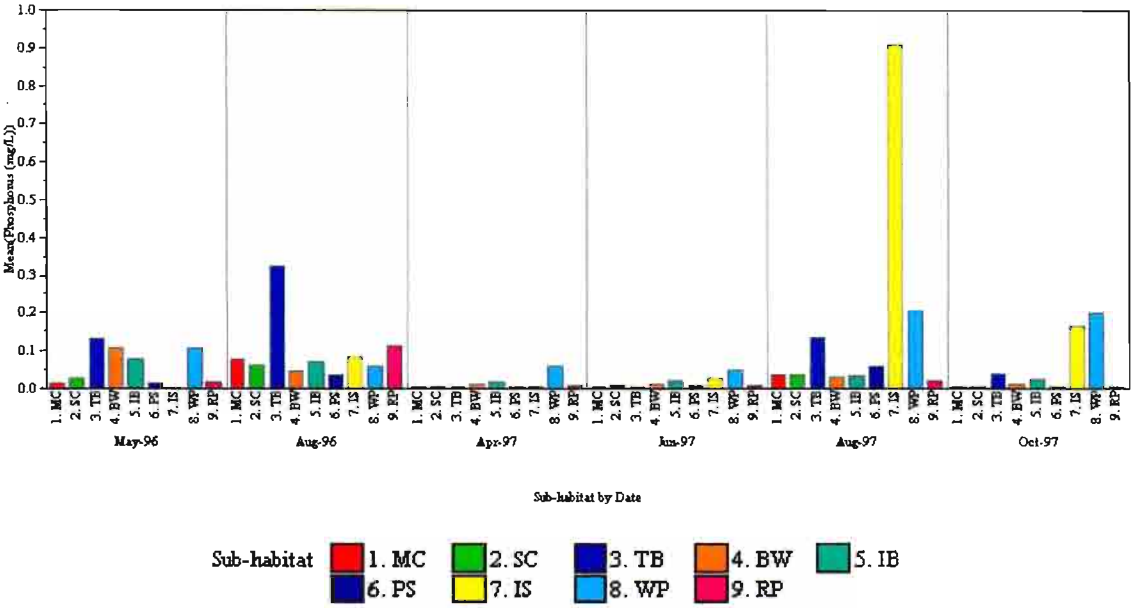


Figure 5-30. Spatial patterns of mean phosphorus concentration by habitat subtypes in the Middle Platte River, and their seasonal changes during the study period, 1996-1997.

5.3 Major dissolved ions

5.3.1 Calcium (Ca)

The mean calcium concentration in surface water of the Middle Platte River was 54.6 (± 13.8) mg/L during the study seasons ($n = 377$). The spatial distribution of calcium was significantly different (ANOVA: $F_{(8, 94.162)} = 13.71$, $p < 0.0001$), with a trend for a decrease in concentration along the gradient: permanent slough or pond --> backwater --> side-channel --> main channel. The main channel had the lowest calcium content (Table 5-3, Figure 5-31). Most of calcium concentrations in samples from main channels were lower than the mean level of calcium for the entire river floodplain. Calcium concentration was higher during summer and lower in fall and spring, except in spring 1996 (Table 5-4, Figure 5-32) (ANOVA: $F_{(5, 150.5)} = 25.38$, $p < 0.0001$). Figure 5-33 shows seasonal changes in mean calcium levels within the aquatic habitat subtypes. Multiple comparison analysis showed that the entire habitat subtypes except intermittent sloughs and wet meadow ponds had significant seasonal differences in calcium concentration. Calcium levels in the main and side-channels were relatively less variable than in riverine habitats. Figure 5-34 illustrates the temporal change in the calcium spatial distribution pattern among habitat types. It appears similar to the pattern described above, except that in late spring 1996. Trends in calcium decline were the same, but the slopes of the gradients were less in spring and fall, and abrupt in summers. Multiple comparison analysis showed that there was no significant difference in mean calcium concentration in spring 1996 and 1997. The distribution of calcium in late May 1996 was likely influenced by a flood event after several days of heavy rain (samples were collected after the flood). The highest calcium concentrations were found in wet meadow sloughs. For example, water samples collected from two wet meadow sloughs and one shallow water pond on Mormon Island Crane Meadow exhibited calcium levels of 50-67 mg/L in late May 1996, which increased to 124-157 mg/L in August 1996. That is, the calcium concentration increased almost three times within three months. In spring 1997, water samples from the same sites had calcium levels down to 45.2-55.2 mg/L. This decline was explained by detailed field surveys of soil and vegetation, and land-use history gathered from local landowners. In November 1995 and April 1996, landowners burned the wet meadow and grassland plots to maintain native wet meadow species. These burned plots were upstream of the wet meadow sloughs and the pond. Cations were released from the burned plant ash and concentrated in the sloughs and pond by surface runoff. Intermittent sloughs had the lowest mean calcium concentration.

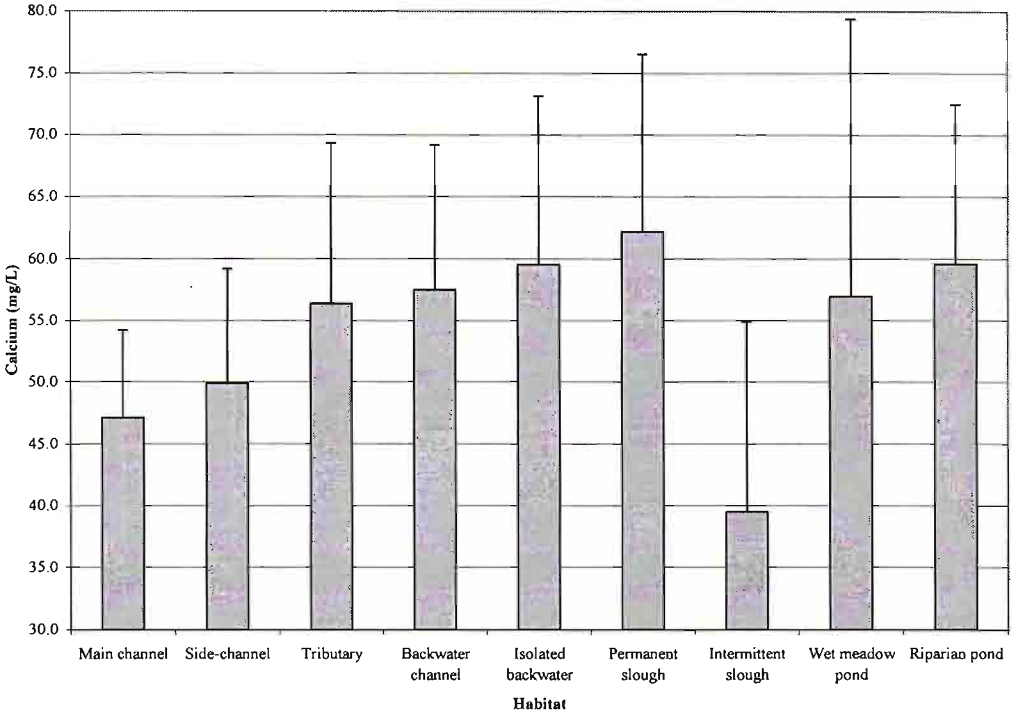


Figure 5-31. Mean (+ SD) calcium (Ca) concentration of the habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 377).

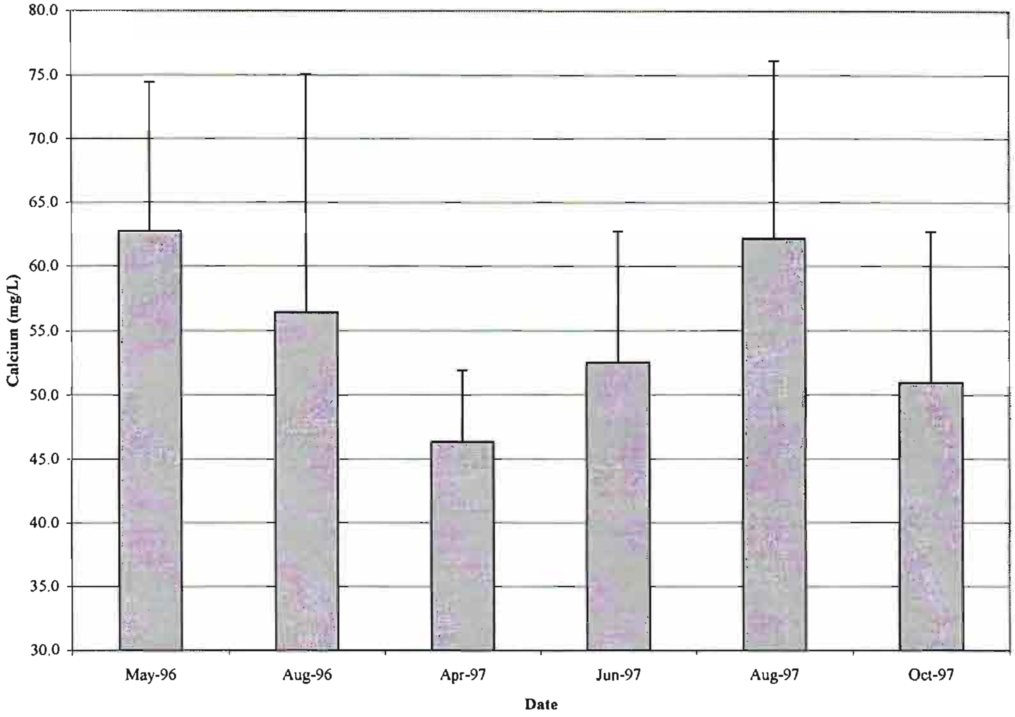


Figure 5-32. Seasonal changes in mean (+ SD) calcium (Ca) concentration in the Middle Platte River during the study period, 1996-1997 (n =377).

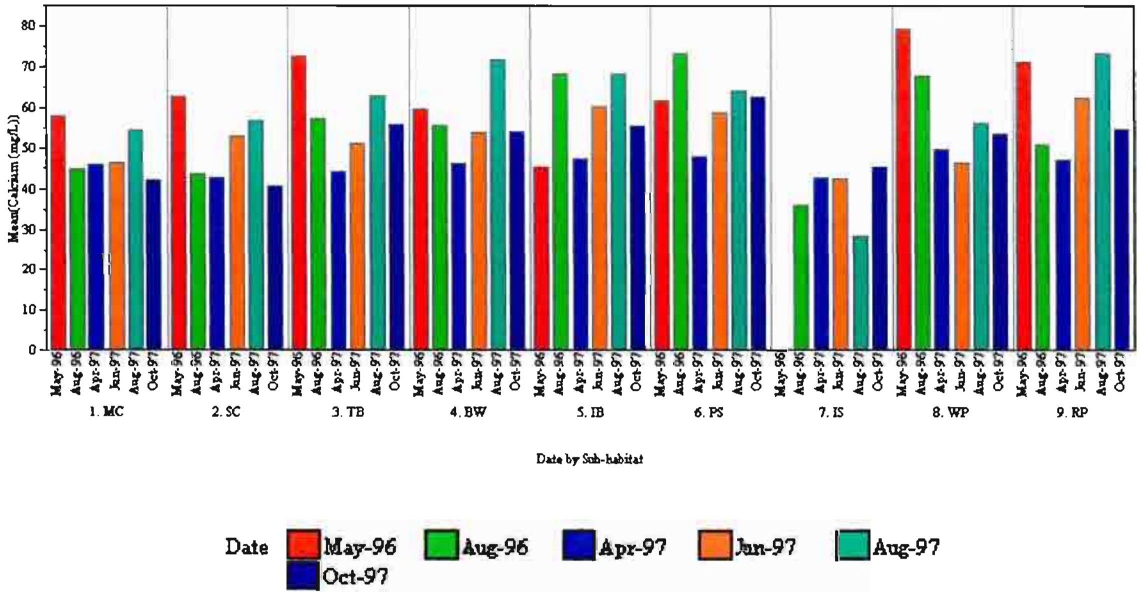


Figure 5-33. Seasonal changes in mean calcium (Ca) concentration by habitat subtypes in the Middle Platte River, 1996-1997.

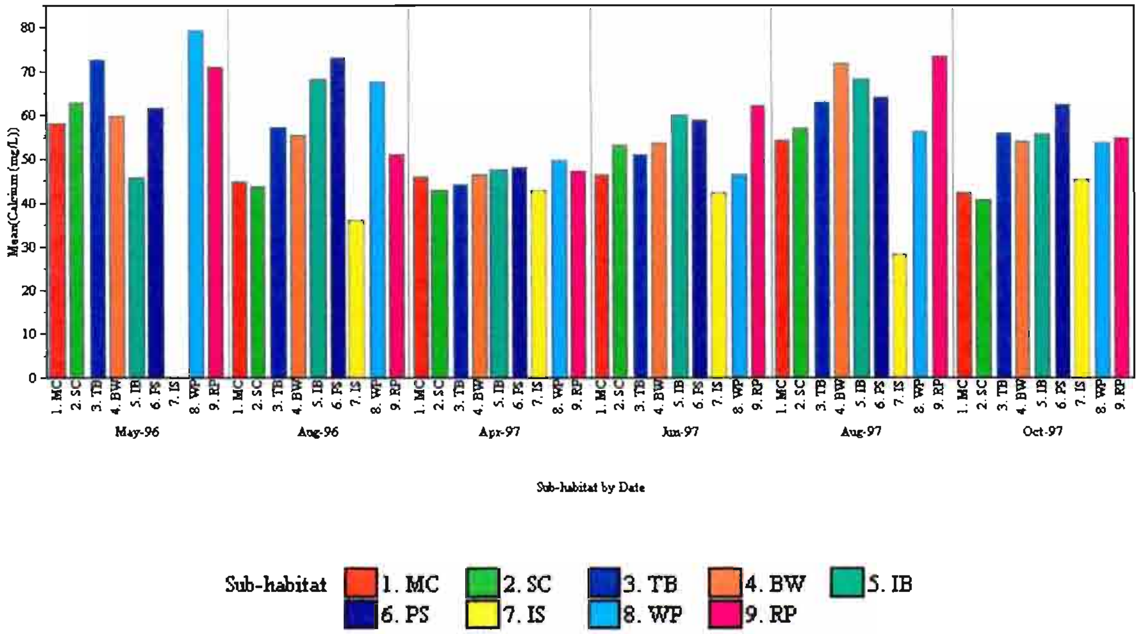


Figure 5-34. Spatial patterns in mean calcium (Ca) concentration by habitat subtypes in the Middle Platte River, and their seasonal changes during the study season, 1996-1997.

5.3.2 Magnesium (Mg)

Magnesium in surface water had a similar distribution pattern to that of calcium. The mean magnesium level for all surface water samples (n = 381) collected from the river and floodplain was 21.4 (± 3.9) mg/L during the study period. The spatial distribution of magnesium in surface water followed the same trend as that of calcium (Table 5-3, Figure 5-35), but was less statistically significant than calcium (ANOVA: $F_{(8, 95.06)} = 4.80$, $p < 0.0001$). Intermittent sloughs had the lowest content of magnesium in water. Seasonal changes in magnesium concentration were not significant (ANOVA: $F_{(5, 150.98)} = 2.41$, $p = 0.0393$) (Table 5-4, Figure 5-36). Temporal changes in magnesium levels within each habitat type (Figure 5-37) and seasonal changes in the distribution pattern across habitat types (Figure 5-38) were also less distinct than that of calcium. No significant fluctuation except relatively low values in May 1996 was observed.

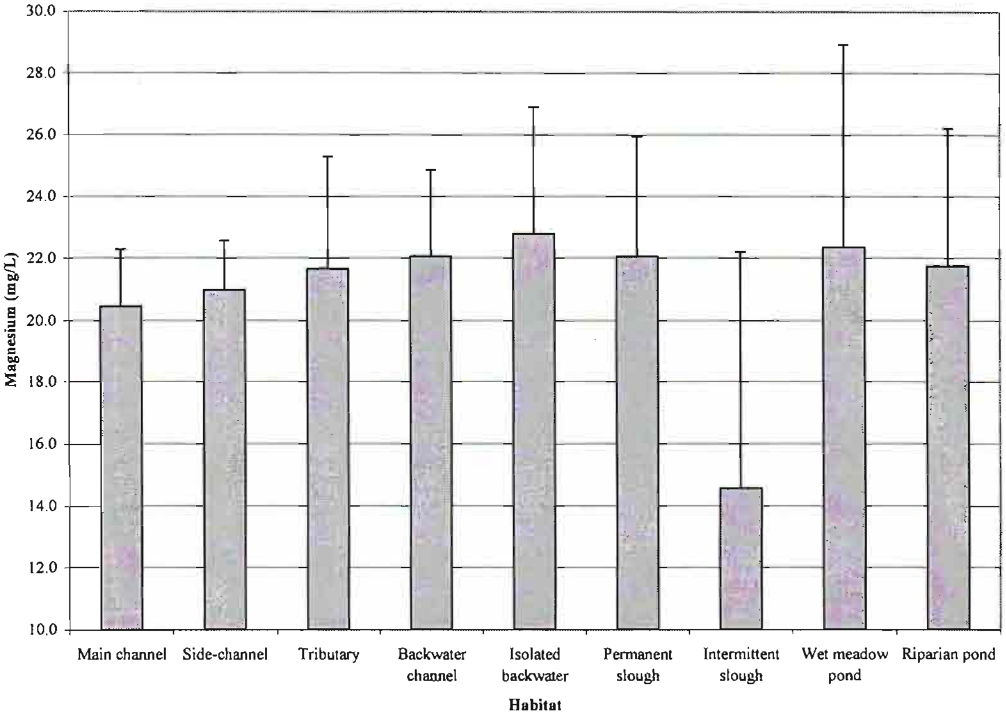


Figure 5-35. Mean (+ SD) magnesium (Mg) concentration by habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 381).

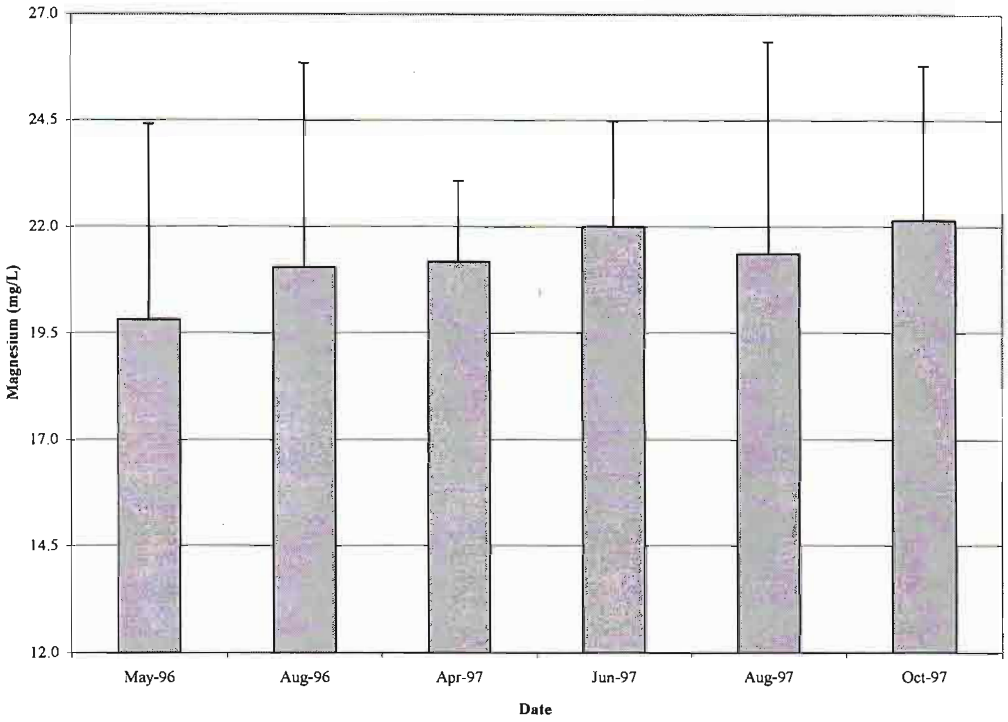


Figure 5-36. Seasonal changes in mean (+ SD) magnesium (Mg) in the Middle Platte River during the study period, 1996-1997 (n =381).

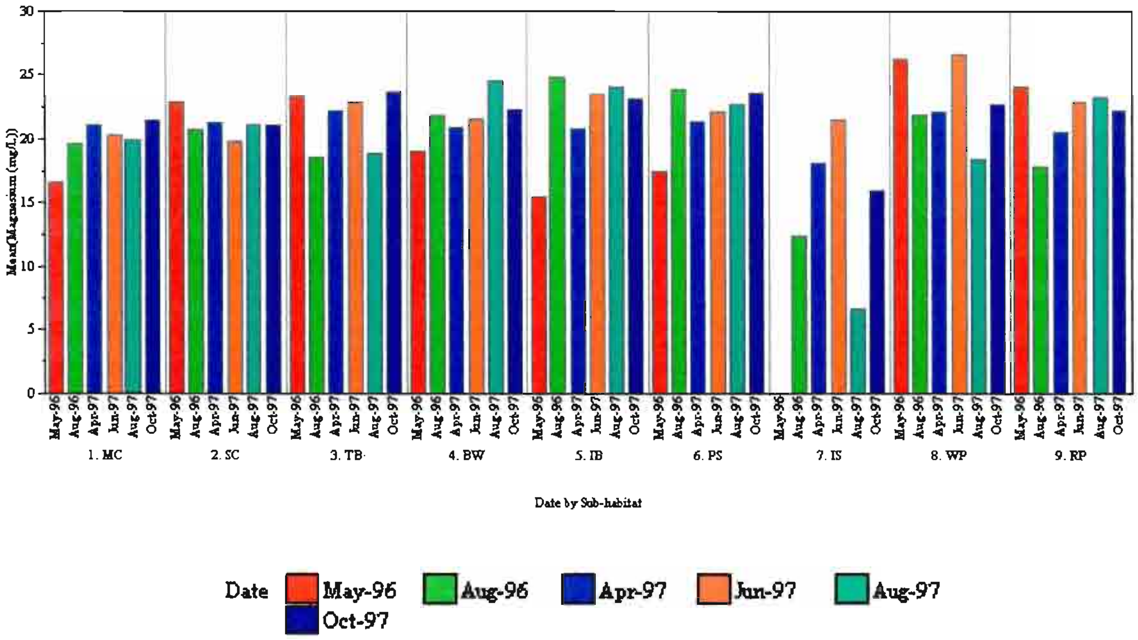


Figure 5-37. Seasonal changes in mean magnesium (Mg) concentration by habitat subtypes in the Middle Platte River, 1996-1997.

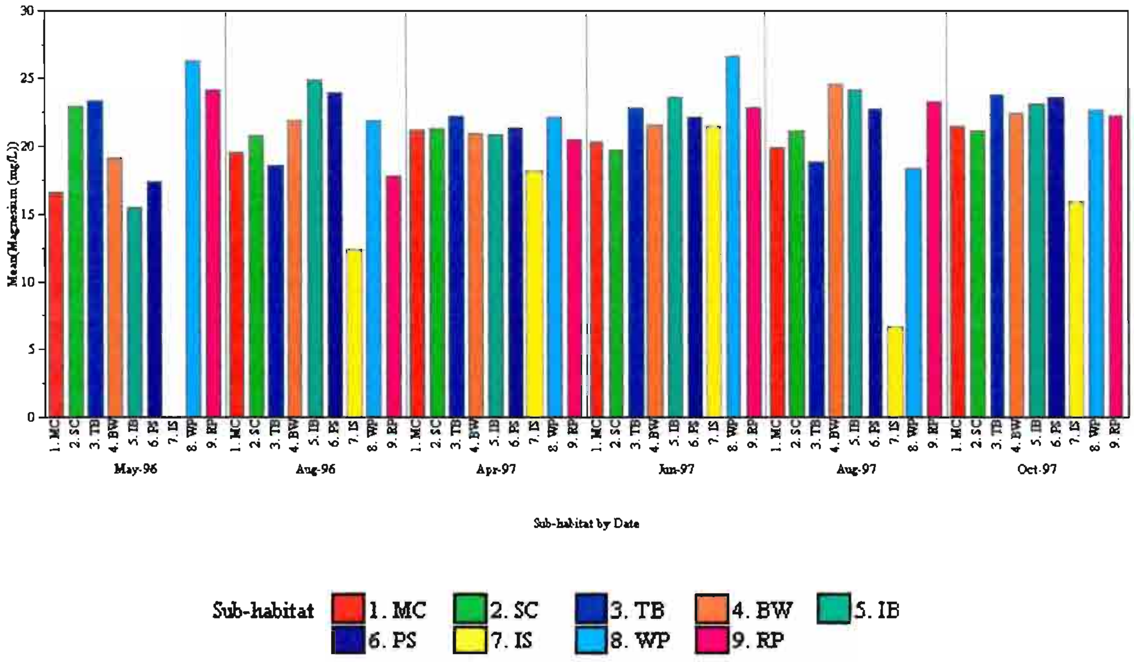


Figure 5-38. Spatial patterns in the mean magnesium (Mg) concentration by habitat subtypes in the Middle Platte River, and their seasonal changes during the study period, 1996-1997.

5.3.3 Potassium (K)

Potassium concentrations in surface water of the middle Platte River varied a little seasonally (ANOVA: $F_{(5,\ 151.96)} = 2.42$, $p = 0.0381$) (Table 5-4, Figure 5-39). The mean potassium level of the whole surface water in the river and floodplains was 10.3 (± 2.4) mg/L ($n = 381$) during study period. The potassium concentration differed significantly (ANOVA: $F_{(8,\ 94.38)} = 13.15$, $p< 0.0001$) across habitat types (Table 5-3, Figure 5-40): Mean potassium concentrations in permanent wet meadow sloughs was the lowest: 7.7 mg/L; tributary and intermittent sloughs had higher concentrations at 12.5 and 14.0 mg/L, respectively. Concentration in pond, backwater, and main channel habitats were around 10.0-10.5 mg/L (Table 5-3). Seasonal variations in potassium concentration were higher in wet meadow sloughs and isolated water bodies than in other lotic and semi-lotic habitats (Figure 5-41). The pattern of potassium distribution across the aquatic habitats was not significant seasonally; however the magnitude of the difference in mean potassium levels appeared lower in lotic habitats and the fluctuation was larger in the intermittent slough and wet meadow pond (Figure 5-42).

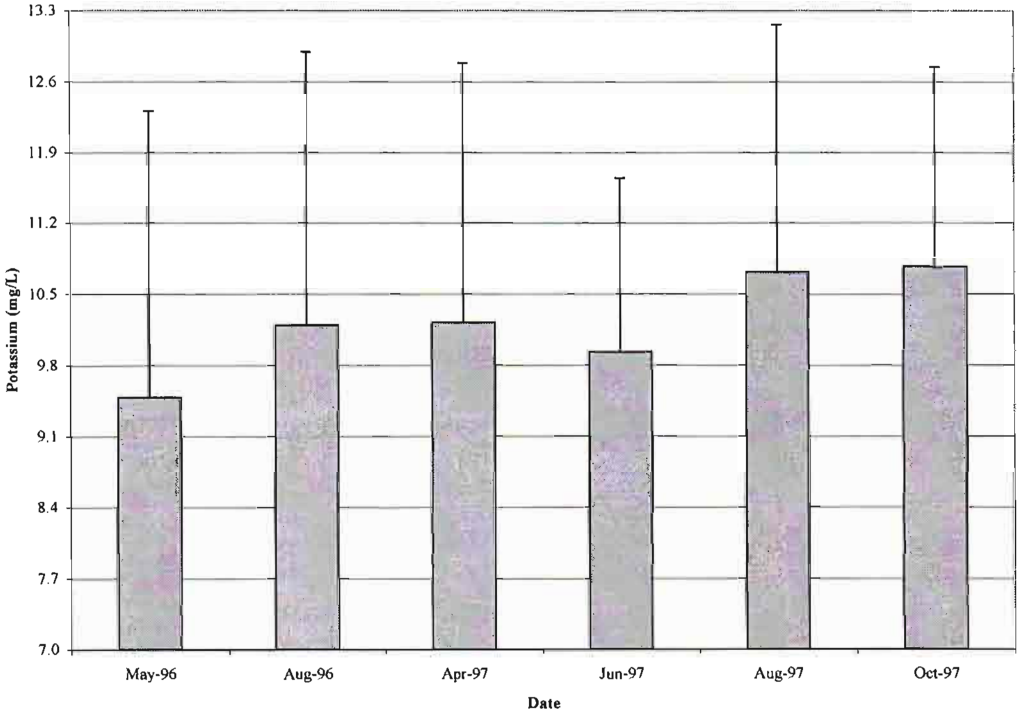


Figure 5-39. Seasonal changes in mean (+ SD) potassium (K) concentration in the Middle Platte River during the study period, 1996-1997 (n =381).

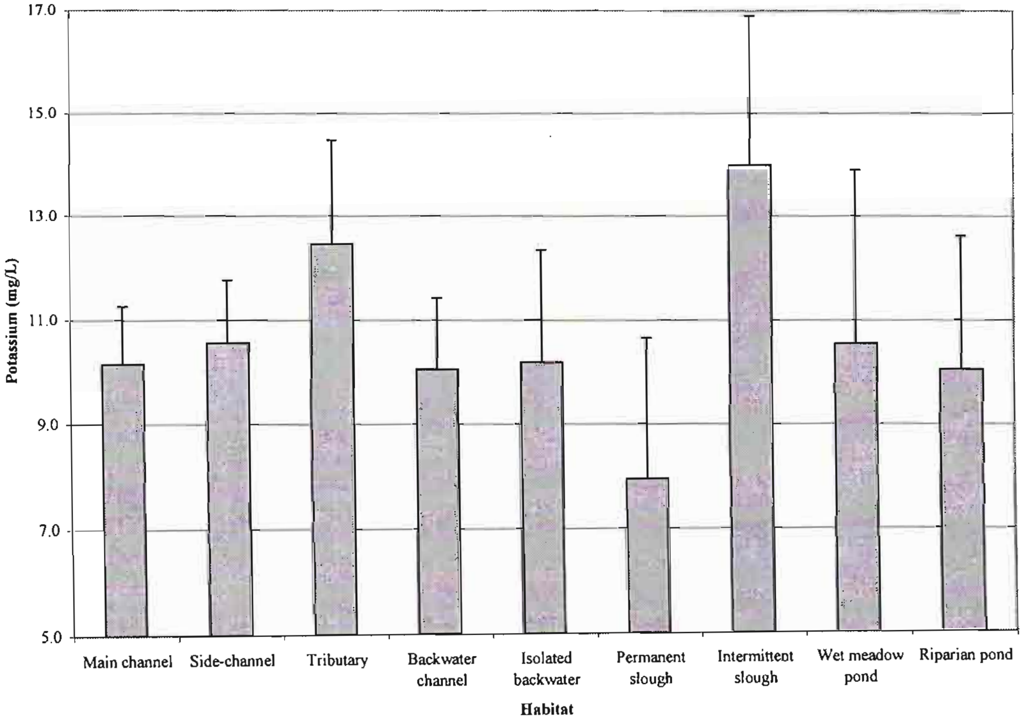


Figure 5-40. Mean (+ SD) potassium (K) concentration by habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 381).

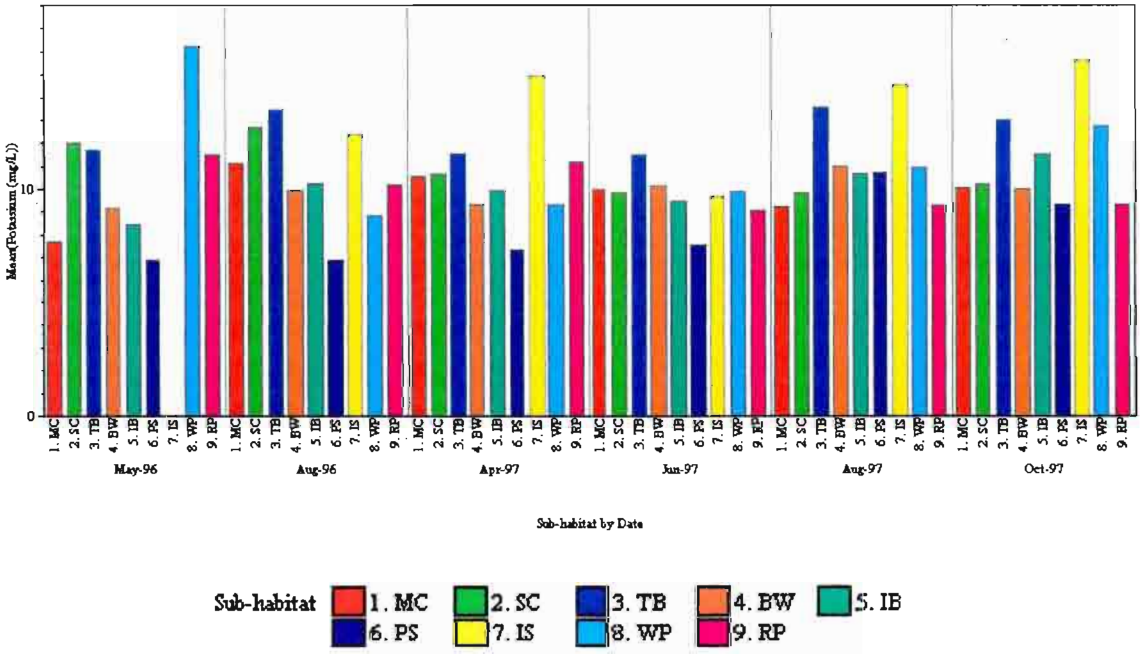


Figure 5-42. Spatial patterns in mean potassium (K) concentration by habitat subtypes in the Middle Platte River, and their seasonal changes during the study period, 1996-1997.

5.3.4 Sodium (Na)

Sodium concentrations in surface waters varied only slightly in1996, but fluctuated significantly in 1997 (ANOVA: $F_{(5,\ 140.31)} = 454.0$, $p < 0.0001$). The mean of all samples ($n = 381$) was 60.2 (± 19.4) mg/L. The lowest mean sodium concentration was in spring 1997 (32.2 mg/L), while in other seasons were from 55.4-71.0 mg/L (Table 5-4, Figure 5-43). Samples collected during low flows (May and August, 1996 and August, 1997) had a higher standard deviation in sodium concentration than those collected from high flows (April, June, and October, 1997) (Table 5-4). Backwater, wet meadow, and other isolated water bodies had somewhat higher sodium concentrations than main and side-channels (ANOVA: $F_{(8,\ 96.812)} = 4.36$, $p = 0.0002$) (Table 5-3, Figure 5-44), which might imply effect of groundwater to these lentic habitats. Seasonal changes in mean sodium concentration among aquatic habitat subtypes (Figure 5-45) were similar to potassium fluctuations (Figure 5-41). There was no significant difference in the mean sodium concentration, except in spring 1997. Seasonal distribution patterns in each of the habitat subtypes were very similar except for ponds. Figure 5-46 illustrates spatial patterns of mean sodium across aquatic habitats and their seasonal changes during the study period. The distribution of sodium concentration across aquatic habitats was homogeneous.

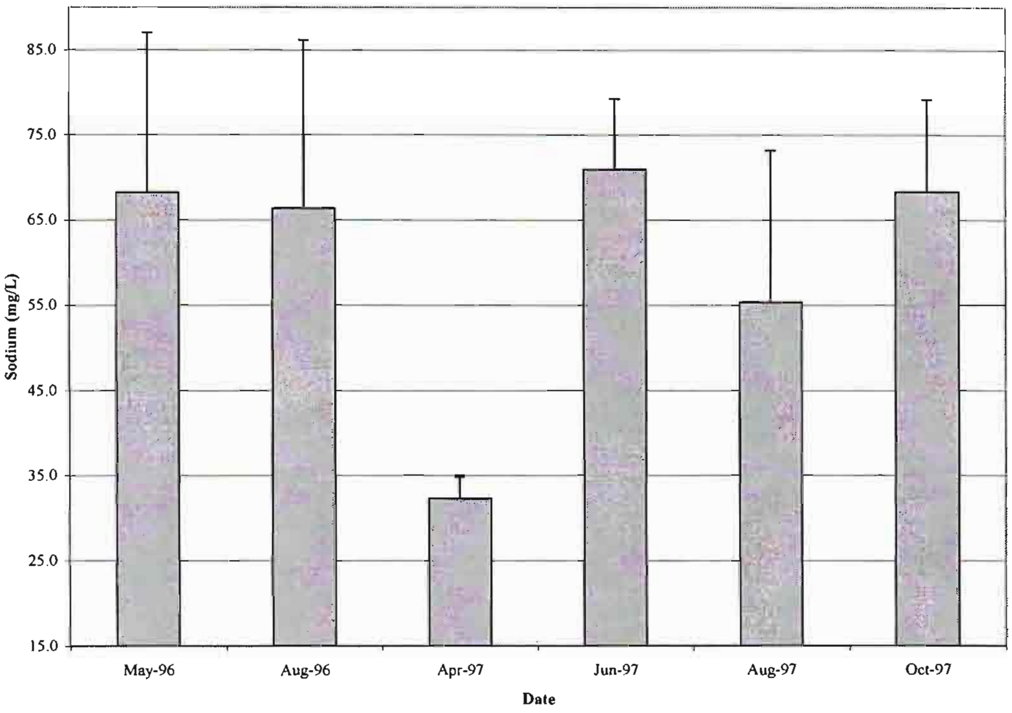


Figure 5-43. Seasonal changes in mean (+ SD) sodium (Na) concentration in the Middle Platte River during the study period, 1996-1997 (n =381).

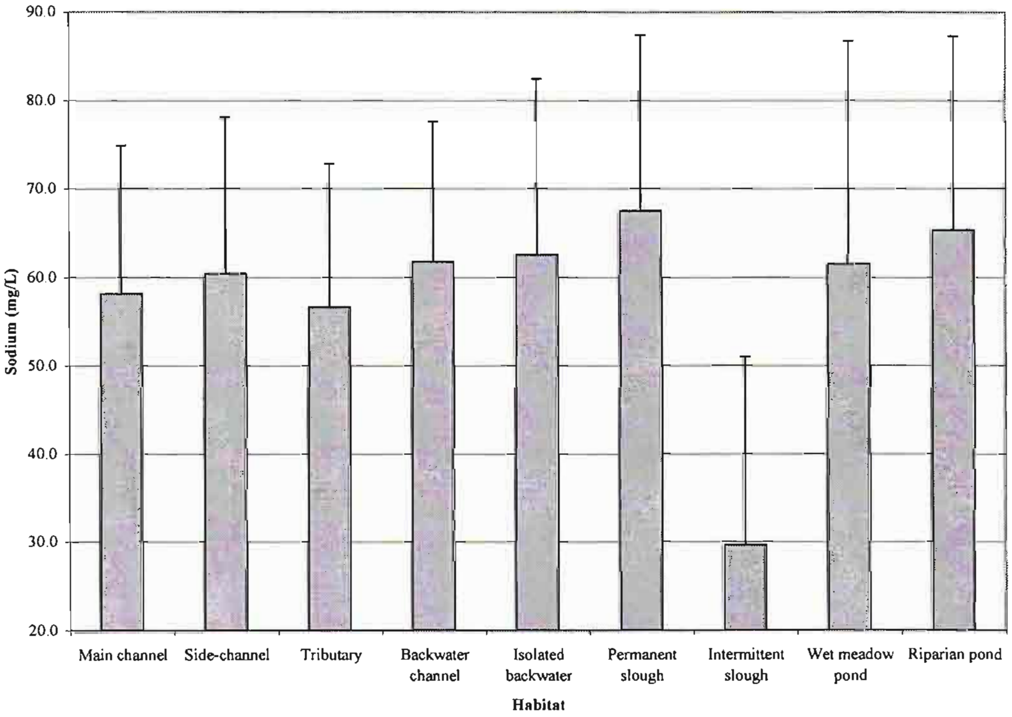


Figure 5-44. Mean (+ SD) sodium (Na) concentration by habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 381).

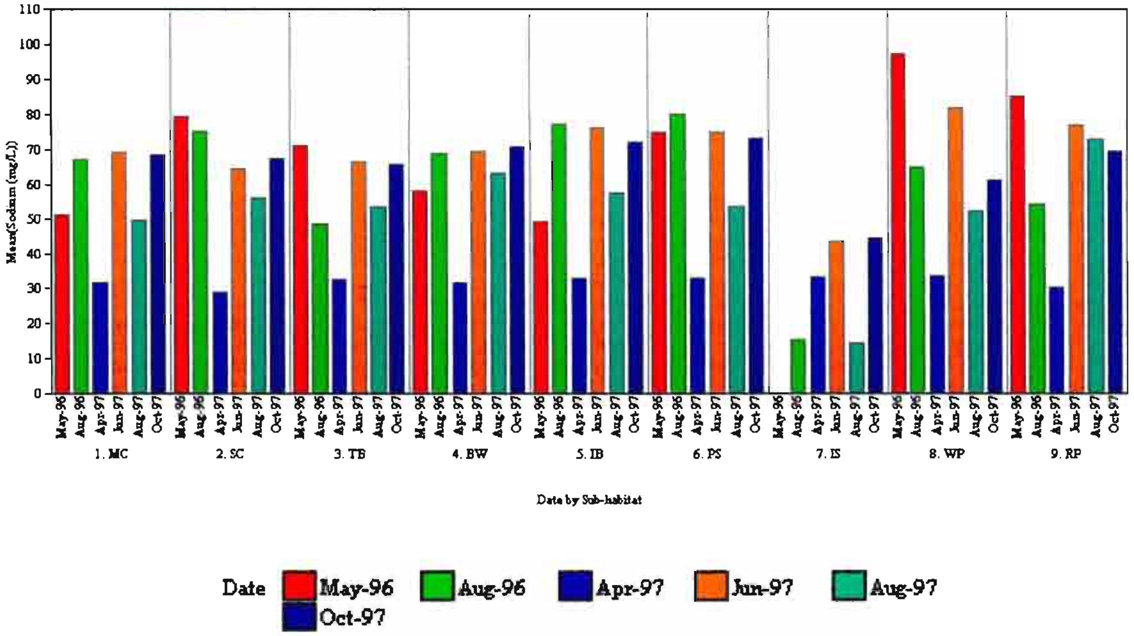


Figure 5-45. Seasonal changes in mean sodium (Na) concentration by habitat subtypes in the Middle Platte River, 1996-1997.

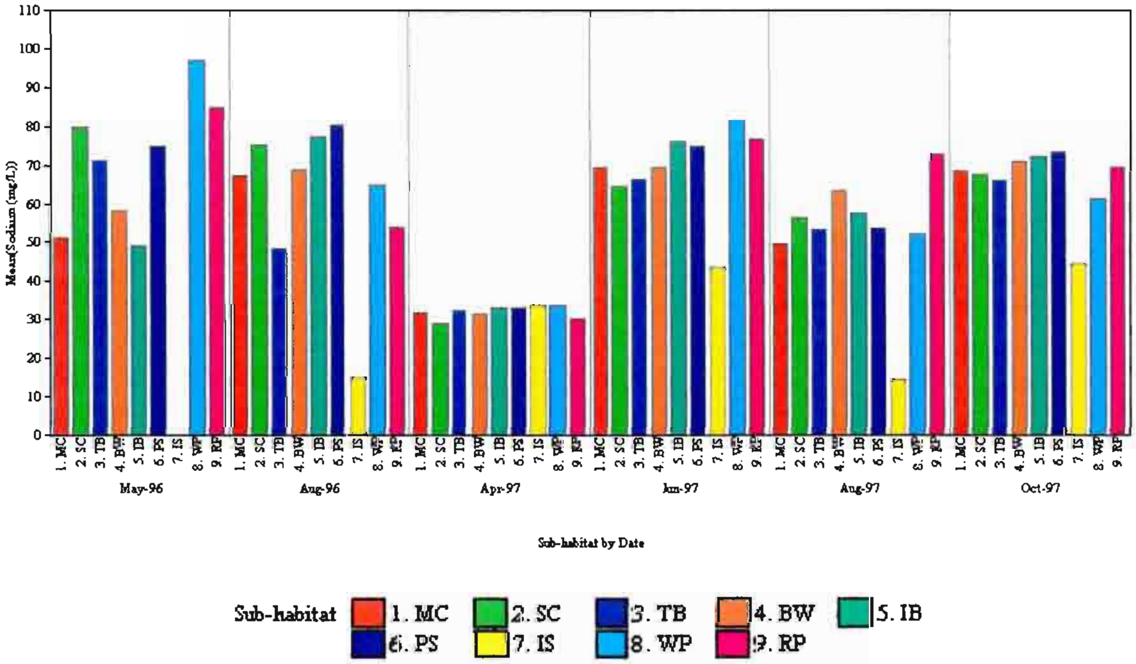


Figure 5-46. Spatial patterns in mean sodium (Na) across habitat subtypes in the Middle Platte River, and their seasonal changes during the study period, 1996-1997.

5.3.5 Chloride

The mean chloride concentration for all surface water samples collected from the river and its floodplain was 38.2 (± 11.0) mg/L (n = 378) during the study period. Seasonal variation in chloride (ANOVA: $F_{(5,\ 156.39)} = 55.04$, $p < 0.0001$) was remarkable. Mean chloride concentrations in 1997 were 30 to 50 % higher than those in 1996 (Table 5-4, Figure 5-47), but still within normal levels compared with other reports for the same reach of the river (Drever 1982; Engberg 1983; Frenzel et al. 1998). Mean chloride concentration across habitat subtypes was very close, with no statistical differences found (ANOVA: $F_{(8,\ 90.624)} = 1.96$, $p = 0.0603$) (Table 5-3, Figure 5-48). There were significant increases in chloride in both backwater and wet meadow habitats since summer 1996 and through 1997 (Figure 5-49). The same increase occurred in main channels and side-channels, but a large (50 %) increase occurred in spring, 1997 then declined back to about 35-40 mg/L where it remained through the rest of 1997. Seasonal differences in the distribution of chloride were not obvious (Figure 5-50). Statistical analysis showed that there is no significant difference in chloride concentration among riverine habitats in spring. Chloride concentrations in the intermittent slough fluctuated more than other types in summer and fall. Overall, seasonal changes in the patterns of chloride concentration across habitat types was not significant in the spring, but was significant in the summer and fall. Permanent sloughs had slightly higher chloride levels, while intermittent sloughs were usually lower than other habitat types.

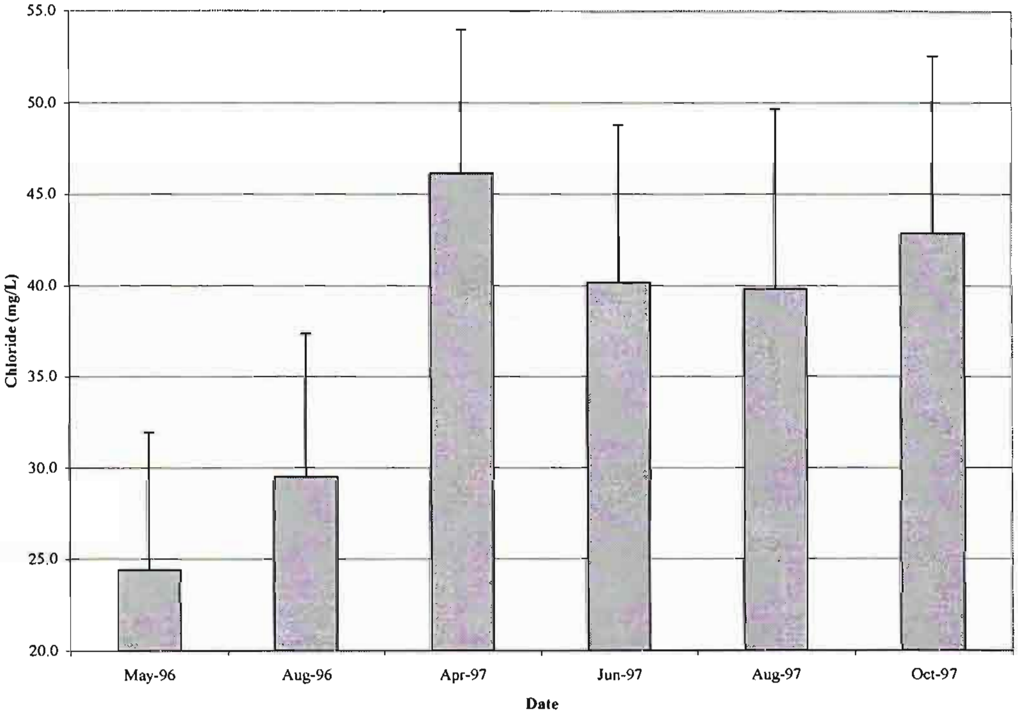


Figure 5-47. Seasonal changes in mean (+ SD) chloride in the Middle Platte River during the study period, 1996-1997 (n =378).

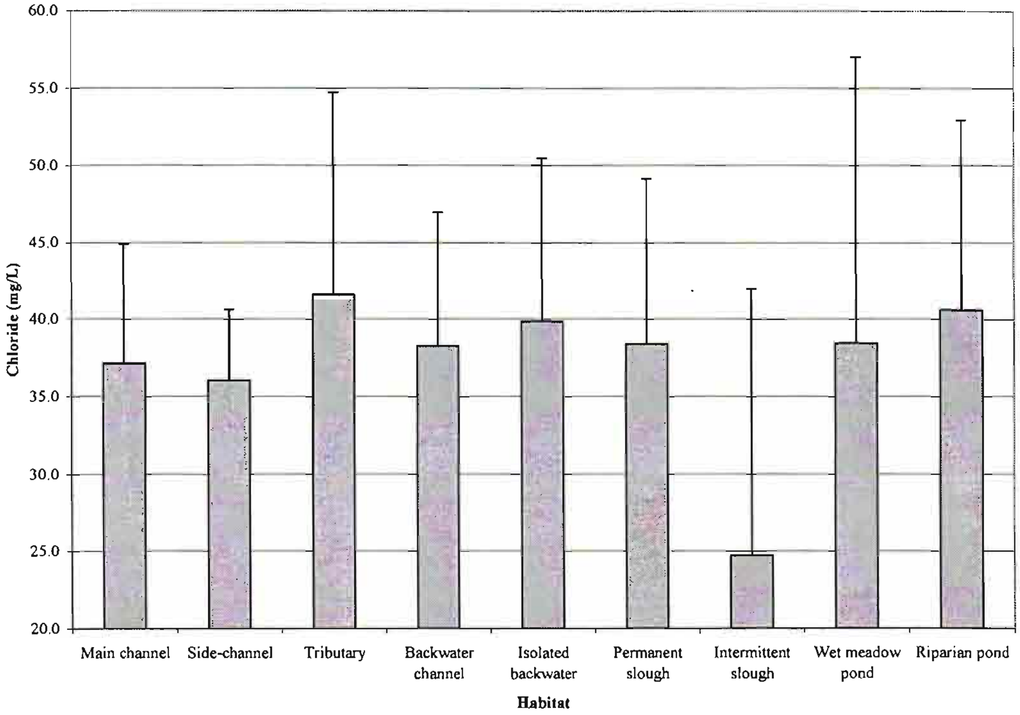


Figure 5-48. Mean (+ SD) chloride concentration by habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 378).

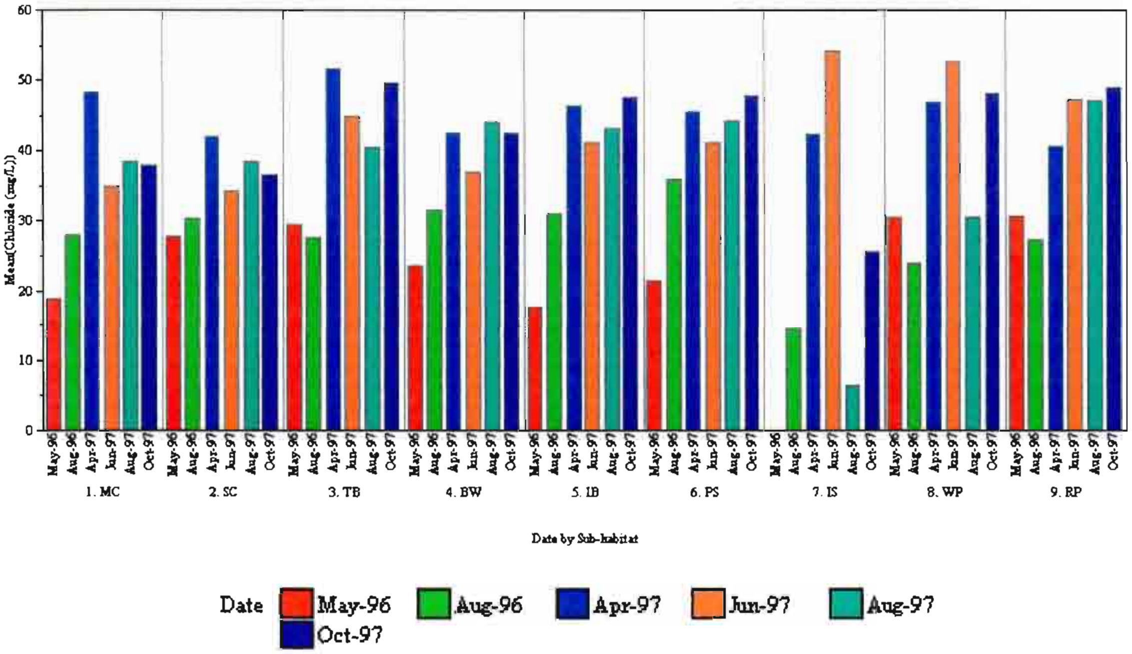


Figure 5-49. Seasonal changes in mean (+ SD) chloride by habitat subtypes in the Middle Platte River, 1996-1997 (n=378).

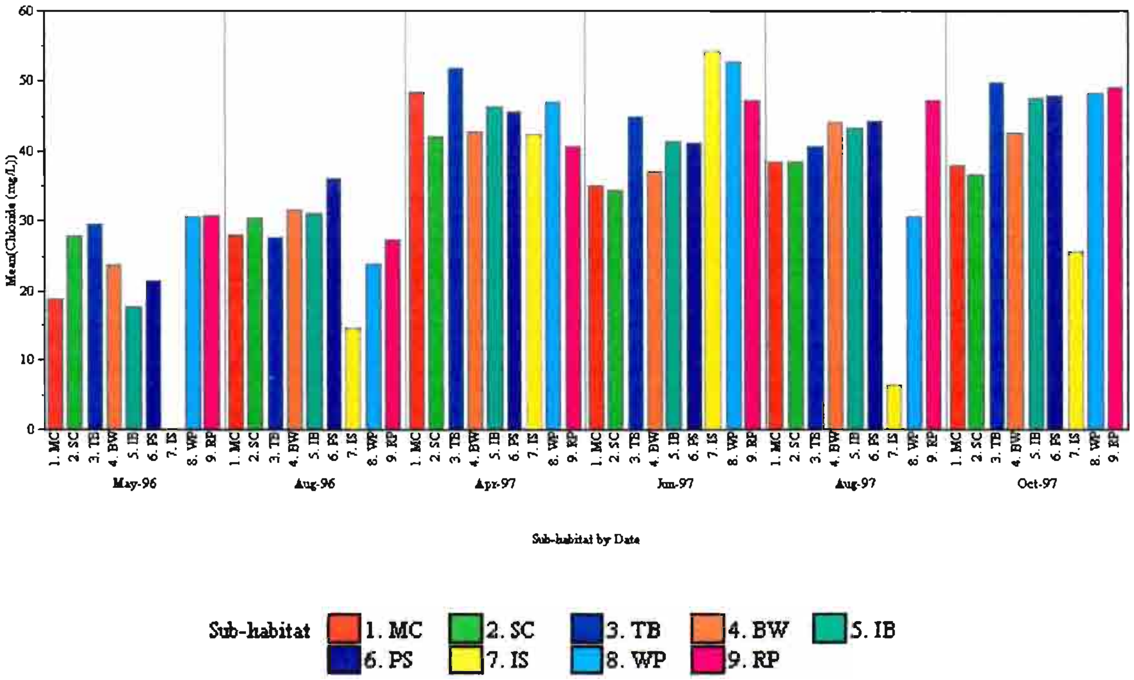


Figure 5-50. Spatial patterns in mean chloride across habitat subtypes in the Middle Platte River, and their seasonal changes during the study period, 1996-1997.

5.3.6 Sulfate

The mean sulfate concentration for all surface water samples collected from the river and floodplains was 278.9 (± 97.0) mg/L (n = 379). Seasonal changes (ANOVA: $F_{(5, 154.34)} = 14.99$, $p< 0.0001$) and spatial distribution of sulfate (ANOVA: $F_{(8, 94.431)} = 5.19$, $p< 0.0001$) were similar to those of chloride. The sulfate concentrations in 1997 were higher than those in 1996 (Figure 5-51). Sulfate concentrations were 15-20 % different between lotic and lentic habitats, with exception of the intermittent slough (Figure 5-52). For all study sites in the Middle Platte River, there was a general trend for sulfate to vary less in main channel and side-channel habitats, with broad ranges in other low flow or static water habitats, especially during summer (Figure 5-53, Figure 5-54).

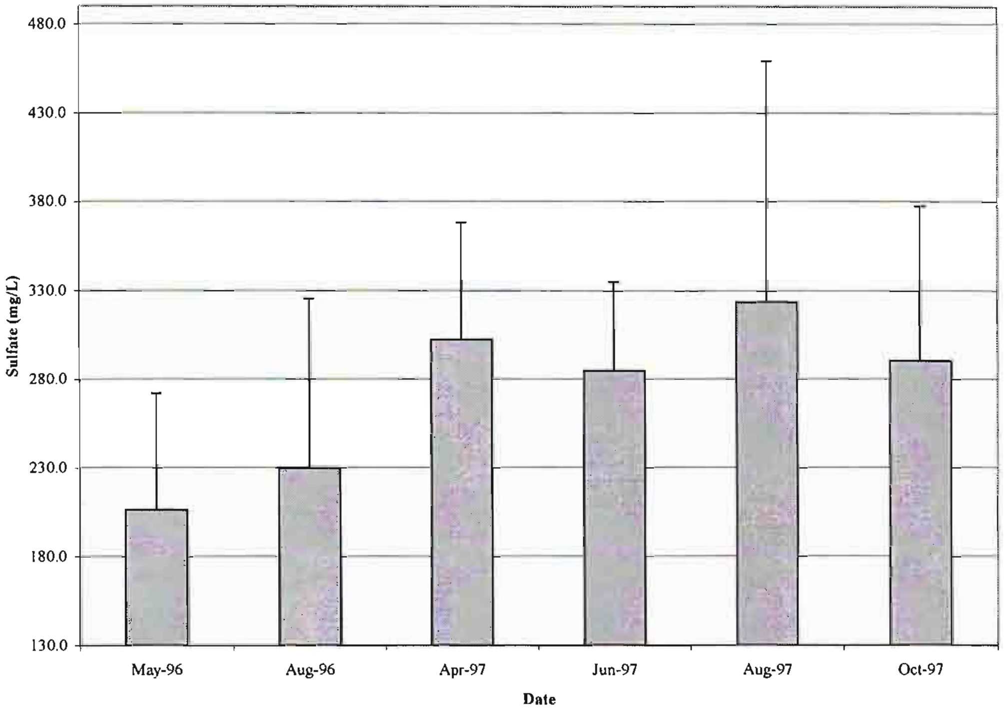


Figure 5-51. Seasonal changes in mean (+ SD) sulfate in the Middle Platte River during the study period, 1996-1997 (n =379).

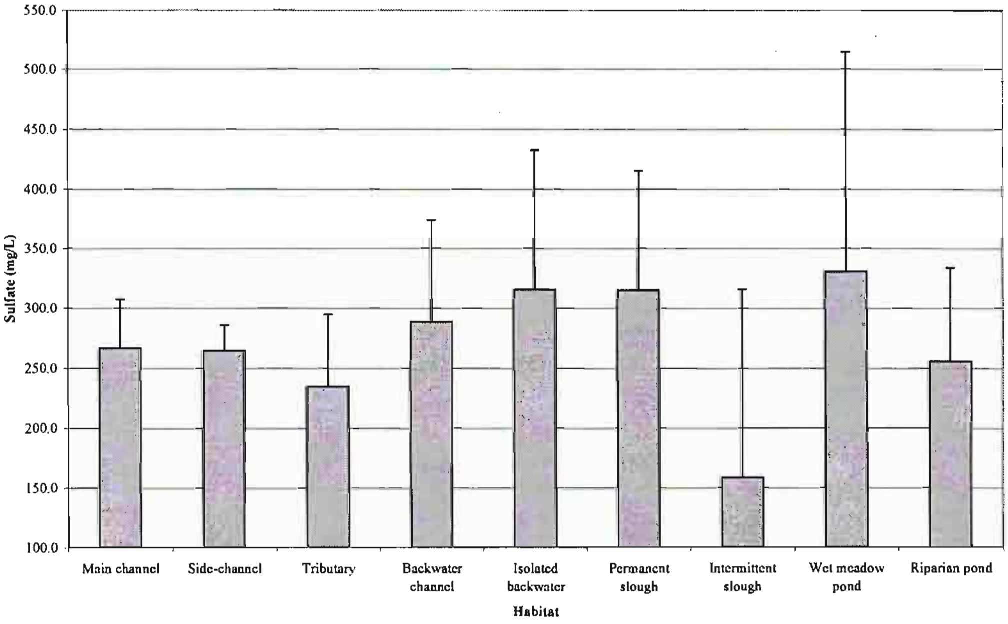


Figure 5-52. Mean (+ SD) sulfate concentrations by habitat subtypes in the Middle Platte River during the study period, 1996-1997 (n = 379).

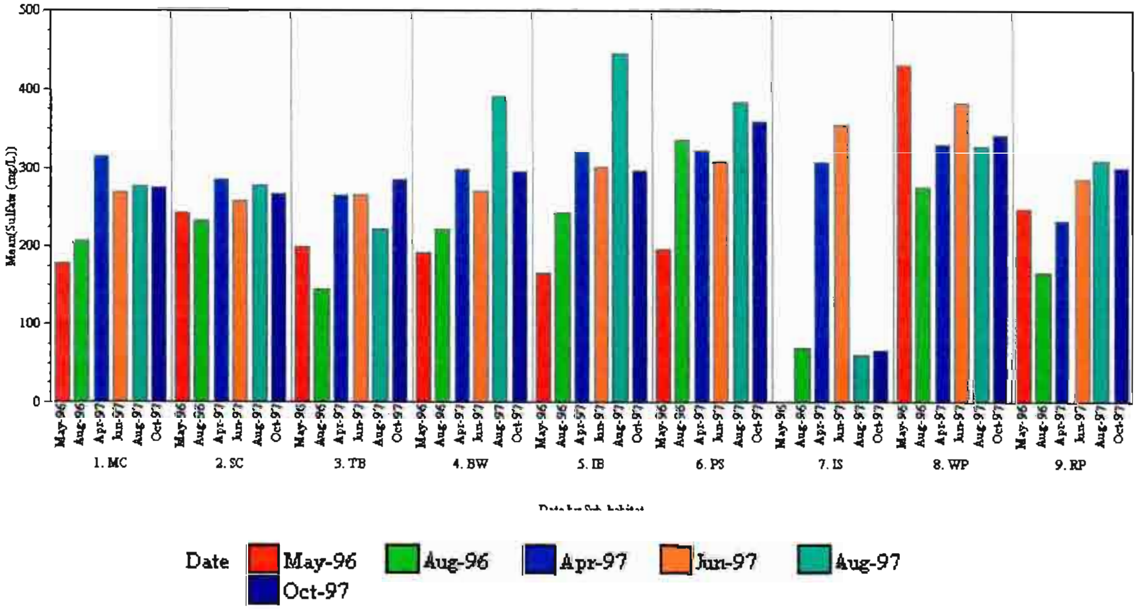


Figure 5-53. Seasonal changes in mean sulfate concentration within habitat subtypes in the Middle Platte River, 1996-1997 (n = 379).

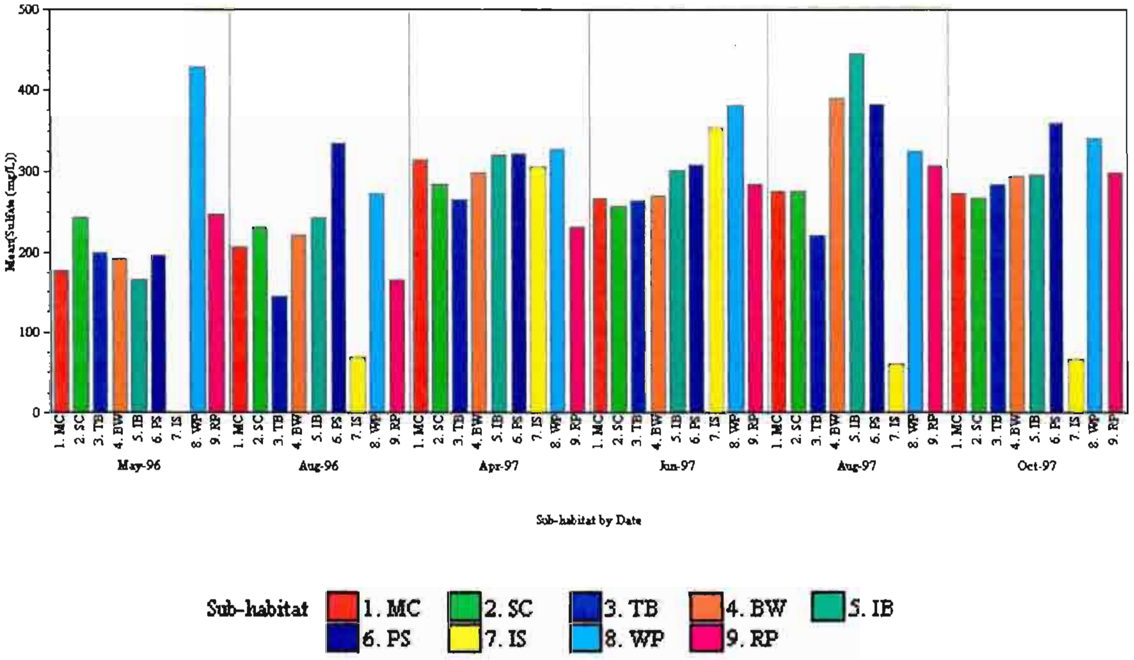


Figure 5-54. Spatial patterns in mean sulfate concentration across habitat subtypes in the Middle Platte River, and their seasonal changes during the study period, 1996-1997 (n = 379).

5.4 Trace elements

Trace elements, especially arsenic, cadmium, lead, selenium, and zinc are environmentally important because of their potential toxicity in small quantities both to ecosystems and humans. Table 5-5 and 5-6 summarize the chemical analysis results for the sixteen trace constituents in surface water samples from the Middle Platte River and its floodplain. Some of the elements, such as Bi, Co, and Pb were in relatively low (< 0.05 %) concentrations, or below detection limits. Table 5-5 summarizes the statistical results for the four main habitat types. The results showed no spatial heterogeneity of the trace elements in surface waters except iron and manganese, which were extremely high in backwater and wet meadow slough types (Table 5-5). These higher values were found mainly in summer 1996 (Table 5-6). Table 6-8 compares the results of trace element analysis (excluding bismuth and titanium) with those from USGS reports for three stream gauging stations along the Middle Platte River during 1981-1990 (Boohar et al. 1996, 1997, 1998; Frenzel et al. 1998). Overall, most of the trace elements had similar ranges as in the USGS data, except manganese and zinc. Zinc concentrations were about two-fold higher in the present study. Manganese levels were more than ten-fold higher than the USGS figures. There was some concern that the higher concentrations of iron and manganese found in most backwater habitats might be related to hunting activities, since there were many spent shells evident in backwater bodies. Backwater sites are habitat for white-tail deer, ducks, turkeys, etc.

Table 5-5. Spatial change in trace element concentrations (µg/L) summarized by the main aquatic habitats in the Middle Platte River during the study period, 1996-1997.

Element	Statistic	Main Channel	Side Channel	Backwater	Slough
Al	n	84	62	142	37
	Mean	11.5	12.3	10.6	9.5
	Std. Dev.	6.1	13.2	4.8	2.3
	Max.	50.0	110.0	30.0	10.0
As	n	84	62	142	37
	Mean	4.0	3.0	2.5	1.5
	Std. Dev.	0.6	1.6	1.2	0.6
	Max.	5.5	5.5	7.3	3.4
B	n	84	62	142	37
	Mean	103.4	98.3	106.6	79.7
	Std. Dev.	22.9	23.3	35.7	31.3
	Max.	134.0	139.0	256.0	223.0
Bi	n	69	54	117	26
	Mean	0.1	0.2	0.2	0.1
	Std. Dev.	0.4	0.4	0.5	0.2
	Max.	2.1	1.9	3.0	0.9
Cd	n	84	62	142	37
	Mean	0.0	0.0	0.0	0.0
	Std. Dev.	0.2	0.1	0.1	0.0
	Max.	1.5	0.2	0.3	0.2
Co	n	84	62	142	37
	Mean	0.2	0.3	0.4	0.4
	Std. Dev.	0.1	0.1	0.3	0.2
	Max.	0.7	0.9	1.6	0.8
Cr	n	84	62	142	37
	Mean	1.0	1.1	1.5	1.6
	Std. Dev.	1.1	1.5	1.4	1.7
	Max.	4.0	6.0	6.0	6.0
Cu	n	84	62	142	37
	Mean	2.0	2.3	2.1	2.9
	Std. Dev.	0.6	2.5	1.9	3.3
	Max.	4.7	19.7	15.4	18.5

Table 5-5. (Continued) Spatial heterogeneity in trace element concentrations (μg/L) summarized by main aquatic habitats the Middle Platte River during the study period, 1996-1997.

Element	Statistic	Main Channel	Side Channel	Backwater	Slough
Fe	n	84	62	142	37
	Mean	4.2	8.7	10.9	31.4
	Std. Dev.	11.2	15.8	34.3	57.8
	Max.	70.0	80.0	340.0	330.0
Mn	n	84	62	142	37
	Mean	2.1	25.6	199.7	80.3
	Std. Dev.	4.9	77.0	372.7	128.7
	Max.	34.0	474.0	2338.0	670.0
Mo	n	84	62	142	37
	Mean	4.9	6.2	5.9	3.6
	Std. Dev.	0.7	1.5	4.0	1.5
	Max.	6.3	9.2	25.9	6.1
Ni	n	84	62	142	37
	Mean	1.8	2.1	3.6	2.4
	Std. Dev.	0.4	0.8	3.5	0.7
	Max.	3.6	5.8	38.9	4.6
Pb	n	84	62	142	37
	Mean	0.0	0.0	0.0	0.1
	Std. Dev.	0.0	0.1	0.1	0.4
	Max.	0.1	0.2	0.7	2.4
Ti	n	84	62	142	37
	Mean	4.3	5.2	6.1	10.2
	Std. Dev.	1.6	7.8	14.0	23.1
	Max.	7.0	65.0	157.0	125.0
V	n	84	62	142	37
	Mean	7.0	5.7	2.8	1.5
	Std. Dev.	1.0	1.8	1.9	1.2
	Max.	9.0	10.4	8.5	4.1
Zn	n	84	62	142	37
	Mean	42.8	34.9	38.3	27.2
	Std. Dev.	57.9	30.7	92.3	32.1
	Max.	444.7	160.7	1038.0	186.0

Table 5-6. Seasonal change in trace element concentrations (μg/L) in the Middle Platte River floodplain aquatic habitats during the study period, 1996-1997.

Element	Statistic	May-96	Aug-96	Apr-97	Jun-97	Aug-97	Oct-97
Al	n	30	59	52	62	60	62
	Mean	11.7	10.7	14.0	12.7	9.2	8.7
	Std. Dev.	7.5	2.5	14.3	5.8	3.3	4.2
	Max.	50.0	20.0	110.0	40.0	20.0	20.0
As	n	30	59	52	62	60	62
	Mean	2.4	3.1	2.2	3.0	3.6	2.7
	Std. Dev.	1.1	1.4	1.5	1.2	1.2	1.1
	Max.	7.3	5.5	4.8	4.8	5.9	4.5
B	n	30	59	52	62	60	62
	Mean	90.4	65.5	96.0	103.6	130.3	113.9
	Std. Dev.	24.1	12.6	21.5	19.8	38.1	14.9
	Max.	139.0	98.0	121.0	171.0	256.0	139.0
Bi	n	30	0	52	62	60	62
	Mean	0.1		0.2	0.3	0.2	0.0
	Std. Dev.	0.2		0.4	0.5	0.5	0.1
	Max.	0.9		1.9	2.0	3.0	0.6
Cd	n	30	59	52	62	60	62
	Mean	0.0	0.0	0.1	0.0	0.0	0.0
	Std. Dev.	0.0	0.0	0.1	0.0	0.1	0.2
	Max.	0.0	0.1	0.2	0.1	0.3	1.5
Co	n	30	59	52	62	60	62
	Mean	0.5	0.3	0.2	0.3	0.4	0.3
	Std. Dev.	0.2	0.2	0.1	0.2	0.2	0.2
	Max.	1.1	1.1	0.4	0.8	1.6	1.3
Cr	n	30	59	52	62	60	62
	Mean	3.8	1.6	0.6	0.8	1.2	0.9
	Std. Dev.	1.5	0.6	0.6	1.0	1.8	1.0
	Max.	6.0	3.0	2.0	3.0	6.0	3.0
Cu	n	30	59	52	62	60	62
	Mean	6.5	2.0	1.7	1.7	2.0	1.6
	Std. Dev.	4.6	0.5	0.4	0.5	0.7	0.4
	Max.	19.7	3.0	2.7	4.2	4.7	3.8

Table 5-6. (Continue) Seasonal change in trace element concentrations (µg/L) in the Middle Platte River floodplain aquatic habitats during the study period, 1996-1997.

Element	Statistic	May-96	Aug-96	Apr-97	Jun-97	Aug-97	Oct-97
	n	30	59	52	62	60	62
Fe	Mean	56.7	13.4	2.7	7.1	6.0	2.7
	Std. Dev.	58.7	42.9	8.0	24.7	9.6	9.8
	Max.	340.0	330.0	40.0	180.0	40.0	60.0
	n	30	59	52	62	60	62
Mn	Mean	250.8	246.6	12.0	48.9	63.3	57.5
	Std. Dev.	244.8	469.5	31.2	151.9	214.2	168.3
	Max.	761.0	2338.0	144.0	700.0	1105.0	907.0
	n	30	59	52	62	60	62
Mo	Mean	5.0	4.4	4.3	5.1	8.5	5.0
	Std. Dev.	1.8	1.4	1.5	1.4	5.0	1.6
	Max.	9.2	8.9	7.9	7.9	25.9	9.2
	n	30	59	52	62	60	62
Ni	Mean	3.6	2.4	2.1	2.4	3.1	2.8
	Std. Dev.	1.2	1.2	0.9	1.2	1.8	4.9
	Max.	5.9	8.9	5.4	7.2	9.3	38.9
	n	30	59	52	62	60	62
Pb	Mean	0.2	0.1	0.0	0.0	0.0	0.0
	Std. Dev.	0.4	0.0	0.0	0.1	0.0	0.1
	Max.	2.4	0.2	0.1	0.7	0.2	0.3
	n	30	59	52	62	60	62
Ti	Mean	13.7	3.9	5.4	4.4	6.3	5.7
	Std. Dev.	36.8	12.6	1.3	0.7	2.6	2.5
	Max.	157.0	76.0	9.0	6.0	20.0	24.0
	n	30	59	52	62	60	62
V	Mean	2.2	4.2	4.2	5.2	5.2	3.7
	Std. Dev.	1.5	3.1	2.3	2.4	2.6	2.3
	Max.	6.8	9.0	7.9	8.3	10.4	6.6
	n	30	59	52	62	60	62
Zn	Mean	10.3	10.4	76.1	40.3	66.2	13.9
	Std. Dev.	7.6	2.7	138.4	14.9	78.0	5.2
	Max.	34.1	21.0	1038.0	113.0	444.7	25.6

Table 5-7. Comparison of surface water quality in main channel of Middle Platte River. [* Sources of data and sample locations: **A**. This project, all aquatic habitats, 1996-1998; **B**. This project, main channel only, 1996-1998; **C**. USGS, Platte River near Overton, 1981-1990; **D**. USGS, Platte River near Grand Island, 1981-1990].

Element	Source *	n	Value at indicated percentile				
			10th	25th	50th	75th	90th
Temperature (C)	A	360	9.6	12.9	19.3	23.4	25.8
	B	112	9.1	12.3	21.4	24.2	27.1
	C	116	0.0	2.5	13.0	20.5	27.0
	D	113	0.5	2.0	12.5	21.0	26.5
pH (on site)	A	362	7.34	7.61	8.12	8.39	8.64
	B	113	8.02	8.18	8.37	8.62	8.73
	C	104	7.9	8.0	8.3	8.5	8.7
	D	101	8.0	8.1	8.2	8.5	8.6
Specific conductance (on site) (us/cm, 25 C)	A	324	887	916	957	1064	1190
	B	110	870	904	934	952	1025
	C	112	790	850	890	960	1000
	D	110	830	870	910	1000	1100
Dissolved oxygen (on site, mg/L)	A	352	3.86	6.90	8.88	10.58	11.85
	B	112	7.51	8.38	9.77	10.60	11.01
	C	115	7.6	8.6	10.0	12.0	13.0
	D	113	8.4	9.1	10.0	12.0	13.0
Nitrite+nitrate (dissolved, as N) (mg/L)	A	325	0.00	0.00	0.39	1.10	2.25
	B	84	0.38	0.74	1.06	1.30	1.58
	C	92	0.45	0.73	1.1	1.5	1.7
	D	37	0.10	0.17	0.54	0.98	1.4
Nitrogen, ammonia (dissolved, as N) (mg/L)	A	323	0.00	0.00	0.00	0.01	0.09
	B	84	0.00	0.00	0.00	0.01	0.10
	C	63	<.01	0.03	0.06	0.12	0.19
	D	43	<.01	<.01	0.03	0.06	0.10
Phosphorus (dissolved as P, mg/L)	A	325	0.01	0.01	0.01	0.04	0.08
	B	84	0.01	0.01	0.01	0.04	0.08
	C	91	0.02	0.04	0.06	0.11	0.15
	D	37	0.01	0.02	0.05	0.08	0.10
Calcium (dissolved) (mg/L)	A	321	41.10	46.03	52.80	61.97	74.26
	B	84	39.50	42.06	46.95	50.70	56.80
	C	107	65	72	79	86	92
	D	113	60	68	77	85	92
Magnesium (dissolved) (mg/L)	A	325	18.79	20.07	21.50	23.50	25.22
	B	84	18.66	19.66	20.60	21.40	22.15
	C	107	21	23	25	27	30
	D	113	22	23	26	28	30
Sodium (dissolved) (mg/L)	A	325	32.83	51.46	67.40	72.90	79.48
	B	84	32.05	37.10	64.65	69.88	73.70
	C	113	68	75	82	86	91
	D	105	77	82	88	93	100
Potassium (dissolved) (mg/L)	A	325	7.29	9.22	10.10	11.10	12.70
	B	84	9.05	9.70	10.10	10.60	11.74
	C	90	9.5	10	12	13	15
	D	37	9.6	11	12	13	15
Chloride (dissolved) (mg/L)	A	322	26.7	33.9	38.3	45.4	50.0
	B	84	26.8	34.0	37.5	39.1	47.9
	C	109	22	25	29	35	38
	D	113	25	27	32	36	40
Sulfate (dissolved) (mg/L)	A	323	199	253	273	310	355
	B	84	207	262	270	278	315
	C	97	180	200	230	260	300
	D	101	200	220	240	280	300

Table 5-8. Comparison of trace element concentrations (µg/L) in Middle Platte River during the study period, 1996-1997 [* Sources of data and sample locations: **A**. This project, all aquatic habitats, 1996-1998; **B**. This project, main channel only, 1996-1998; **C**. USGS, Platte River near Overton, 1981-1990; **D**. USGS, Platte River near Grand Island, 1981-1990; **E**. USGS, Platte River near Duncan, 1981-1990].

Element	Source*	n	Value at indicated percentile				
			10th	25th	50th	75th	90th
Aluminum (µg/L)	A	325	10.0	10.0	10.0	10.0	20.0
	B	84	10.0	10.0	10.0	10.0	20.0
	E	32	<10.0	<10.0	10.0	20.0	30.0
Arsenic (Dissolved, (µg/L)	A	325	1.1	1.8	3.0	4.0	4.5
	B	84	3.2	3.6	4.0	4.4	4.7
	E	40	3.0	4.0	4.0	5.0	5.0
Boron (Dissolved, (µg/L)	A	325	63.0	75.5	106.0	117.0	131.8
	B	84	64.0	96.8	110.0	117.0	127.5
	C	91	110.0	120.0	140.0	150.0	160.0
	D	37	110.0	130.0	140.0	150.0	170.0
Cadmium (Dissolved, (µg/L)	A	325	0.0	0.0	0.0	0.0	0.1
	B	84	0.0	0.0	0.0	0.0	0.1
	E	40	<1.0	<1.0	<1.0	<1.0	<2.0
Chromium (Dissolved, (µg/L)	A	325	0.0	0.0	1.0	2.0	3.0
	B	84	0.0	0.0	1.0	2.0	2.5
	E	36	<1.0	<1.0	<1.0	2.0	10.0
Cobalt (Dissolved, (µg/L)	A	325	0.2	0.2	0.2	0.4	0.6
	B	84	0.2	0.2	0.2	0.2	0.2
	E	40	<3.0	<3.0	<3.0	<3.0	<3.0
Copper (Dissolved, (µg/L)	A	325	1.2	1.4	1.7	2.3	3.0
	B	84	1.4	1.6	1.9	2.3	2.5
	E	40	2.0	3.0	4.0	6.0	10.0
Iron (Dissolved, as Fe, ug/L)	A	325	0.0	0.0	0.0	10.0	30.0
	B	84	0.0	0.0	0.0	0.0	10.0
	C	91	<3.0	<4.0	<7.0	10.0	25.0
	D	37	<3.0	<7.0	<10.0	16.0	20.0
Lead (Dissolved) (µg/L)	A	325	0.0	0.0	0.0	0.1	0.1
	B	84	0.0	0.0	0.0	0.1	0.1
	E	38	<1.0	<1.0	<1.0	<5.0	<5.0
Manganese (Dissolved) (µg/L)	A	325	0.0	0.0	1.0	45.5	380.8
	B	84	0.0	0.0	0.0	1.0	8.5
	C	90	2.0	4.0	6.0	11.0	19.0
	D	37	1.0	2.0	5.0	6.0	11.0
Molybdenum (Dissolved) (µg/L)	A	325	3.2	4.1	5.0	5.8	7.9
	B	84	4.1	4.4	4.9	5.4	5.7
	E	32	<10.0	<10.0	<10.0	<10.0	<10.0
Nickel (Dissolved) (µg/L)	A	325	1.4	1.7	2.2	3.1	4.1
	B	84	1.3	1.5	1.7	2.1	2.2
	E	40	<1.0	1.0	2.0	4.0	5.0
Vanadium (Dissolved) (µg/L)	A	325	1.1	1.8	4.1	6.7	7.8
	B	84	5.9	6.3	6.8	7.8	8.2
	E	32	<6.0	<6.0	<6.0	6.0	10.0
Zinc (Dissolved) (µg/L)	A	325	7.4	10.3	25.0	44.5	62.9
	B	84	8.2	10.7	30.5	53.2	81.0
	E	40	3.0	6.0	9.0	20.0	34.0

5.5 Summary

Surface water quality data for the habitats of the Middle Platte River have not been systematically reported. The USGS has long-term water quality records (1960-1968, 1976-1990) for the main channel of the Platte River near Overton (Boohar et al. 1996, 1997, 1998; Engberg 1983), about 6 km upstream of the present study reach, and another site near Grand Island (1972-1990) (Engberg 1983; Frenzel et al. 1998). USGS records from 1981 to 1990 are summarized in Table 5-7, for data collected from the Overton and Grand Island gauging stations; data from this study are separated for the main channel water (MC) and for entire Middle Platte River Valley (MPRV). Temperature measurements were not made in winter, thus our mean temperature data statistics are higher than those of the USGS. Results of this physicochemical study are comparable to previous studies (Drever 1982; Engberg 1983; Frenzel et al. 1998).

In general, surface water temperatures in river habitats were not significantly different. However, during the summer adjacent habitats were different from the main channel. Mean surface water temperatures in the main channels were 3-4 °C higher than the adjacent habitats, except intermittent sloughs and isolated shallow water ponds in riparian zones where mean temperatures were higher than in the main channel. There was a relatively homogenous distribution of mean surface water temperature across the river landscape in spring and fall.

Mean pH values were spatially heterogeneous among lotic and lentic habitat patches. Backwater and wet meadow slough habitats had lower mean pH values (7.5-7.6), while the main and side channels had mean pH of > 8.2; tributary and isolated pond habitats had pH values between 7.8 and 8.0. There was no significant seasonal change in the spatial pattern of pH found.

Dissolved oxygen concentrations were also higher in the lotic habitats (> 9.0 mg/L) and lower in relatively lentic habitats (< 8.5 mg/L). Spatial distribution patterns of DO had notable seasonal changes during the study period.

Conductivity in lentic habitat types was about 100-200 μs/cm, higher than in lotic habitats except intermittent wet meadow slough, which had the lowest conductivity. Ponds had similar conductivities as the lentic aquatic habitats. The lateral gradient of the conductivity was diminished in spring and during high stream flow periods. Variations in conductance were higher in slough and pond habitats than in the lotic habitats (Figure 5-11). Seasonal changes in mean specific conductance were not significant for the entire river landscape (Figure 5-12) but were significant in the semi-lentic habitats (Figure 5-13). Salinity values had similar spatial patterns as those of conductivity.

The distribution of nutrients in surface water was heterogeneous across habitat patches. High mean nitrogen (NO_3-N + NO_2-N) concentrations were found mainly in tributaries, whereas remaining aquatic habitats usually had nitrogen (NO_3-N + NO_2-N) concentrations lower than 1 mg/L. Mean concentrations of ammonium (NH_4-N) were below 0.05 mg/L for all of habitat types studied, except tributaries and wet meadow ponds which had 0.08-0.09 mg/L and high variation among sites. Mean nitrogen (NO_3-N + NO_2-N) concentrations were higher in spring, with peaks of ammonium (NH_4-N) in summer. Mean phosphorus concentrations were 0.10-0.22 mg/L in the tributary, intermittent slough and wet meadow pond habitat subtypes, and below 0.05 mg/L in other subtypes. Higher mean phosphorus levels appeared in summer. These temporal and spatial distribution patterns were strongly associated with agricultural land use, for instance higher nutrient concentrations were found in managed wet meadow habitats after land use in these areas was shifted to livestock grazing.

Mean concentrations of major dissolved ions were also significantly different across the riverine landscape. Concentrations of calcium and magnesium had similar distribution patterns, with increasing concentration from the main channel and side-channel to tributary, backwater, and permanent wet meadow slough and pond habitats. The exception was the intermittent wet meadow slough, which had the lowest concentrations of calcium and magnesium. Mean concentration of calcium varied seasonally; it was low in spring and fall and higher in summer. Seasonal changes in the mean concentration of magnesium were not significant. Mean concentrations of potassium and sodium were relatively homogeneous among riverine habitats, with the exception of tributary and wet meadow slough habitats. Tributaries had higher mean levels of potassium, whereas no significant difference in sodium was found between the tributary and main channel. Mean concentrations of potassium in the intermittent slough were highest among habitat subtypes, and lowest in permanent sloughs. This was opposite of sodium distributions in the permanent slough and wet meadow pond habitats (compare Figure 5-40 and Figure 5-44). Seasonal changes in potassium were not significant. Mean concentrations of sodium were low in spring 1997, with no significant change over remaining seasons during the study period.

Most of the higher concentrations of the major ions were found in wet meadow areas recently burned for management purposes. The fact that burning events increase dissolved ions concentration in surface water implies that fire, as one of the favorable wet meadow management methods for wildlife conservation, may have biochemical effects on aquatic biota in the adjacent river and associated habitats. If the fire occurred in spring, cations or anions released from ash would concentrate into sloughs, ponds, or backwaters, resulting in peak concentrations in surface water in early summer. However, this is the most important biological period for many aquatic species, such as spawning fish and other freshwater species. Because pH is controlled by equilibrium of dissolved compounds, additional ash entering the system within a relatively short period of time may alter the entire carbonate buffering system. Slightly change of pH may disturb an aquatic community. From this point of view, fire treatment to maintain native grasslands might be better conducted during later fall or winter seasons rather than spring.

Mean concentrations of chloride and sulfate were not significantly different in their distributions across riverine habitats, except both of them were very low in the intermittent wet meadow sloughs. Seasonal changes in the mean concentrations of chloride and sulfate were highly significant in samples from 1996 and 1997, which might be a result of the fire treatments on many adjacent wet meadow sites during winter 1996 and spring 1997.

Trace elements analyses showed no significant difference in concentration distributions across habitats; however iron and manganese concentrations were much higher than these reported by the USGS. High concentrations of iron and manganese were found mostly in backwater, side-channel, and tributary types of aquatic habitats, which are frequently used for ducks and deer hunting. Thus, over-hunting on some of the riverine habitats might cause some environmental risk and should be seriously considered in protecting the health of the riverine ecosystem.

Chapter 6. Major findings and conclusions

6.1 Hydrological connectivity

Due to the dynamic nature of the braided channels and stream flow in the Middle Platte River floodplain, for a complete understanding of the hydrological connectivity in a braided river floodplain, it is necessary to consider both water flow connection and hydrological interaction between the main channel and riverine habitats. The braided floodplain riverine landscape may be viewed as a mosaic of interacting riverine habitat patches connected with the main channel. The hydrological connectivity can be determined through: (a) spatially interpreting the surface water connection between the main channels and associated riverine habitats; (b) analyzing the strength of the riverine habitat hydrological interaction with the main channel in response to the instream flow variation; and (c) comparing the strength of the hydrological interaction across the riverine patches.

6.1.1 Identification of hydrological connection in diverse riverine habitat types

This study presents the first detailed data sets of spatial hydrological connections of the riverine habitat patches over the studied reaches. The field surveys and interpretations of remote sensing image in this study suggest varied degrees of the surface water flow connection between the main channel and side-channel and backwater habitats (patches), and no direct surface water connection between the main channel and wet meadow and pond habitats in the floodplain, except during overbank flood.

In addition, fluvial geomorphologic features and hydrographs are distinct among the riverine habitat types. Geomorphological criteria such as channel width, depth, and streambed material are practical and efficient parameters for quantifying the riverine water bodies. The hydro-geomorphological classification of the aquatic habitats generated in this study offers an integrating way to handle habitat diversity in the complex, braided fluvial system.

Although riverine tributaries that parallel to the stream channels are similar to side-channels in geomorphology, their hydrologic regime patterns and physicochemical characteristics can be significantly different in time and space. These differences are mainly the result of upland inflow and agriculture runoff contributing to the riverine tributaries. Therefore, the distinction between the riverine tributary and the side-channel habitats must be made.

6.1.2 Quantification of the hydrological interactions in the riverine landscape

Hydrological connectivity with the main channel of the braided river is the key to characterizing the riverine habitat properties. The correlation and regression analysis results in this study clearly highlight the strength of riverine habitats in response to the instream flow changes and the role of different environmental variables in explaining hydrological conditions of the riverine habitats. My study results suggest that:

(1) the significance of the hydrological correlation of a riverine habitat to the main channel stream flow change directly depends on the degree of its surface water connection with the main channel;

(2) the riverine habitat patches are generally arrayed in ranges of their hydrological connectivity and geographic location from the main channel; and,

(3) it was found that groundwater discharge to the sloughs and ponds in wet meadow and riparian habitats maintains relatively stable flow regime and thermal conditions in these habitats, even during the relatively dry and hot summer season. Thus, although the ponds in riparian and wet meadow habitats occupy a relatively small portion of the riverine areas, they are important components of the riverine landscape and function in sustaining the floodplain biodiversity.

6.1.3 Relative importance of the climatic factors to the riverine habitats

The relative importance of the climatic factors (i.e. temperature, precipitation, and evapotranspiration) to hydrological changes in the riverine habitat varies among the habitat subtypes. It relates to the geographical location of a riverine habitat from the main channel and the landscape attributes of the riverine habitat. My study results suggest that the climatic factors contribute little to explanation of water level variations (<6%) in the side-channel and backwater habitats. However, temperature and precipitation play a significant role on interpretation of the water level changes (11-32 %) occurring in sloughs and riparian ponds. The evapotranspiration factor, by working together with the discharge and precipitation, may improve the prediction on the hydrological changes in those longer side-channels surrounded by low-density shrubs and trees.

6.1.4 Spatial patterns and dynamics of the riverine habitats

River discharge affects the size and shape of riverine habitat patches, and alters magnitudes of the water and sediment movement in the riverine patches. Spatial variations in fluvial sedimentation, constitution, and habitat topography result in a mosaic of riverine habitat patch types (e.g. backwater versus side-channel; slough versus pond). Based on spatial analysis data, the riverine habitat hydrological connection, total riverine patch areas, and mean patch size increase during the high-water-flow period, and decrease during the base-water-flow period. Numbers of the riverine patches and total of the patch edges increase when the river discharge drops, indicating a fragmented, disconnected, reduced riverine landscape.

6.2 Physicochemical heterogeneity

Results from this study illustrated that the aquatic habitat characteristics in the floodplain varied spatially and temporally in response to change of river discharge during different seasons and habitat types. The aquatic habitats differed significantly in several physicochemical parameters, such as temperature, dissolved oxygen, pH, and conductivity (Table 5-2).

Mean surface water temperature was relatively homogeneous across the river landscape in spring and fall. During summer however, the temperature in adjacent habitats was different from the main channel. Mean surface water temperatures in these habitats were 3-4 °C lower than in the main channels. However, intermittent sloughs and shallow water ponds in riparian zones had higher mean temperatures than the main channel.

Dissolved oxygen and pH were higher in the lotic habitats and lower in the relatively lentic habitats. Disconnected backwater and wet meadow slough habitats had the lowest mean pH values and DO concentrations. Conductivity had the opposite pattern, with higher mean specific conductance in backwater and slough habitats. However, variations of the mean specific conductance were significant larger in the lentic than in the lotic habitats. Seasonal variations of the specific conductance were generally small in the lotic habitats. Significant seasonal fluctuations of the specific conductance occurred in some lentic and semi-lentic habitats.

The tributary and the wet meadow pond are two types of habitats that function as nitrogen sinks. The mean concentration of nitrate and nitrite in tributary habitats was two-fold higher than that in the main channel, and about ten times higher than in backwater and permanent wet meadow sloughs. Ammonium concentrations in the tributary and wet meadow ponds were 3 to 4 times higher than those in other aquatic habitats (Figure 5-23). Mean phosphorous concentrations had a similar pattern. “Hot spots” of phosphorous were found in intermittent sloughs, wet meadow ponds, and tributaries, and were 2 to 5 times higher than in other aquatic habitats (Figure 5-27). Temporal patterns of nutrient distributions in the river landscape suggested a strong relationship with agricultural land use in the floodplain. Spatial distribution of dissolved ions was generally homogeneous across the landscape, with relative higher values in semi-lentic and lentic habitats, except chloride and potassium, which were relatively high in tributaries. Increases in the mean concentrations of dissolved ions, such as K, Na, Ca, and Mg in wet meadow habitats were likely associated with burning for vegetation management purposes on wet meadow habitats.

6.3 Research limitations and recommendations for future studies

6.3.1 Limitations in this study

The riverine habitat diversity was examined in the context of a braided river floodplain ecosystem, with special focuses on the hydrological connectivity and the physicochemical attributes of the aquatic patches at the habitat and landscape scales. Compared with the studies of surface water connectivity, groundwater connection is invisible, and it is more difficult to characterize the subsurface hydrological connectivity. For those riverine habitats without direct surface water connection with the main channel, the difficulty in describing the subsurface groundwater process implies that the study on those habitats is heavily dependent upon modeling techniques. My study results suggest that surface water routing in wet meadow sloughs does not correlate to the main channel regime at the habitat/reach scale and daily to weekly time scales. The reasons are likely due to the free-flowing slough surface water and relatively long distances from the main channel. The slough water depths are controlled by the micro-topography and slopes of the slough channels. Identifying the subsurface hydrological connection and interaction, on the other hand, is more complex without detailed multi-dimensional hydraulic surveys of the wet meadow aquifer.

The physicochemical heterogeneity discussed above is related to the surface hydrological connectivity and complexity of riverine habitats in the braided river floodplain. Other factors may affect the distribution of physicochemical parameters, such as release and adsorption of solutes by alluvial sediments, flow transport and mass balance, biological uptake of nutrients, etc. (Malard et al. 2000). However, the groundwater physicochemical attributes were not studied due to labor and financial limitations.

6.3.2 Recommendations for future studies

Up-scaling hydrogeological and ecological studies from reaches to watersheds remains a major research challenge today (Sophocleous 2000). The operational hierarchic patch dynamic framework applied in my study may be used for the scaling-up tasks. Methodologies used in my research project are suitable for syntheses of the aquatic habitat and landscape characteristics from reaches up to the entire river valley. The attributes of the riverine habitat patches have been achieved from high resolution and large scale maps, and stored in the GIS-based digitized spatially explicit models. These riverine landscape feature data products are ready to be used for future research in the Middle Platte River floodplains. For example, they may be up-scaled from the reaches/habitats to the river valley/watershed ecosystems by changing the modeling cell sizes and extend the modeling domain. These digital data and information are essential for watershed resources management, river ecosystem health assessment, riverine landscape planning, and wildlife conservation and habitat restoration.

The SW-GW exchange processes in this large stream-fluvial plain system were examined in context of the riverine habitats with multiple regression and correlation analyses. Change of the SW-GW exchange process in the main channel along the longitudinal dimension of the river was not the focus of this study. Clearly, the SW-GW exchange processes are in three dimensions, and vary over multiple geomorphic conditions. A landscape scale study on the longitudinal change of the riverscape, and a watershed scale studies based on the results from my research works may provide more comprehensive views of the biodiversity in the Middle Platte River valley and the entire watershed.

Physicochemical and spatial analysis results demonstrate the riverine habitat heterogeneity and landscape patterns in response to river discharge. The hydrological connectivity serves as a driving force for biodiversity of the river ecosystem. Thus, an effective biodiversity conservation strategy should focus on sustaining hydrological connectivity, so that the river itself may structure its braided flowpaths and maintain hydrologic and ecologic interactions among riverine landscape components.

This research contributes to our understanding of the complexity of the riverine landscape in the Middle Platte River. It is also relevant to a fundamental question: how does the hydrological connectivity affect the river ecosystems? The fruitful research products (GIS based riverine landscape digital maps and data) and conclusions from this study demonstrate the spatial and temporal riverine patterns and the effects of hydrological and climatic factors on landscape processes. They may serve for river ecosystem assessment, planning, habitat restoration and conservation, and water resources management.

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Appendix A

Study areas, transects, monitoring sites, and environmental features

Study Area	*Transect*	*Site*	*Stream Gauge ID*	*Piezometer ID*	*Aquatic Habitat*	*Land Use*	*Hydrological Connection*	*Remarks*
1. Mormon Island, Hall County								
	T01	S01	g01	p03, p04, p05	Wet meadow; ephemeral sloughs	Wildlife refuge	**us**	**g, f**
		S02	g01 g02	p01, p05, p08	Wet meadow; intermittent slough	Wildlife refuge	**us**	**g, f**
		S03	g02	p06, p07, p08	Backwater pond in riparian; wet meadow	Wildlife refuge; hayfreld	**us**	**g, f**
	T02	S04	g03	p09	Backwater arm near riverbank in riparian	Wildlife refuge	**cd**	
		S05	g04	p10	Intermittent backwater in main channel behind big sandbar	Wildlife refuge; mechanically cleanal sandbar for crane habitat	**cs**	**b**
		S48	g05	none	Intermittent pond in wet meadow	Wildlife refuge	**us**	**g, f**
2. Wolback, Hall County								
	T31	S06	g04	p11, p12	Ephemeral slough links ponds and flow to a ditch	Pasture, permanent grazing	**cd**	**a**
	T32	S49	s13	p13	Isolated backwater pond in riparian	pasture, riparian	**cd**	**a**
		S50	s14	p14	Ditch linked to main channel	Agricultural runoff, Riparian	**cd**	**a**
3. Crane Meadows, Hall County								
	T03	S07	g06, g07	p15, p16, p17, p18	spring fed permanent slough in wet meadow	Wildlife refuge	**us**	**b, g, f**
	T04	S08	g08	p19	Backwater pond in riparian	Wildlife refuge	**us**	**b**
		S09	g08	p20	Intermittent slough in wet meadow	Wildlife refuge; controlled grazing	**us**	**g, f**
	T05	S10	s22	p21, p22	Permanent slough with beaver pond in riparian/wet meadow	Wildlife refuge; controlled grazing	**us**	**g, b**
	T06	S11	g09	p23	Permanent slough in wet meadow	Wildlife refuge	**us**	**g**
		S12	g09	p24, p25	Intermittent pond in riparian	Wildlife refuge; controlled grazing	**us**	**g**
4. Brown Tract, Hall County								
	T07	S13	g10	p26	Backwater pond in riparian	Wildlife refuge	**us**	**b**
		S14	g10	p27	Backwater in riparian	Wildlife refuge	**us**	**b**
5. Caveney Tract, Hall County								
	T08	S15	g11	p29	Backwater pond in riparian	Wildlife refuge; controlled grazing	**cu**	**b**
6. Wood River, Hall County								
	T09	S16	g12	p31	Backwater pond in riparian	Wildlife refuge	**cu**	**b**
7. Dahms Tract, Hall County								
	T10	S17	g13	p32	Backwater in riparian	Wildlife refuge	**cu**	**b**
		S18	g13	p33	Backwater pond in riparian	Wildlife refuge	**cu**	**b**
8. Uridil, Hall County								
	T11	S19	g14	p34	Small backwater arm in a tributary channel	Riparian, and wildlife refuge; hayfield	**cd**	**b**
		S20	g14	p35, p36	Man-made slough-pond in grassland	Native grassland	**us**	**r, f**
9. Martin's Ranch, Hall County								
	T12	S21	g15	p39	Side-channel; riparian	Wildlife management; recreation	**cs**	**p**
		S22	g15	p38	Beaver ponds	Wildlife management; recreation	**us**	**b, p**

		S23	g15	p37	Pond in riparian	Wildlife management; recreation	**us**	**p**
	T13	S24	g16	p40	Side-channel; riparian	Wildlife management; recreation	**cs**	**p**
10. Dipple, Buffalo County								
	T14	S25	g17	p41	Backwater/Slough in riparian	Wildlife management; hunting	**cu**	**b, p, r**
	T15	S26	s42	p42, p43, p44, p45	Permanent slough in riparian/meadow	Riparian, pasture, and hayfield	**cu**	**f, g, r**
	T16	S27	none	p46, p47, p48	Wet meadow with an ephemeral slough	Pasture, intermittent grazing	**us**	**f, g, r**
	T17	S28	s51	p49, p50, p51	Permanent slough/beaver ponds in riparian/meadow	Riparian; pasture	**us**	**b, f, g, r**
	T18	S29	s54	p52, p53, p54	Permanent slough in riparian/meadow	Riparian; pasture	**cu**	**f, g, r**
11. Hornady, Buffalo County								
	T19	S30	g19	p56, p57	Backwater in riparian	Hunting; wildlife management	**cs**	**b, r**
12. Speidell Tract, Buffalo County								
	T20	S31	g20, s59	p58, p59	Permanent backwater in main channel behind a big sandbar	Wildlife management	**cs**	**r**
	T21	S32	g21	p60, p61, p62, p63, p64	Side-channel; riparian	Wildlife management; restoration	**cs**	**r**
	T22	S33	g22, s68	p65, p66, p67, p68, p69	Side-channel; riparian	Wildlife management; restoration	**cs**	**r**
13. Wyoming's, Buffalo County								
	T23	S34	g23	p70, p71, p72	Backwater pond in clear-cut riparian	Wildlife management	**cd**	**r**
	T24	S35	g24	p73, p74, p77	Pond in clear-cut riparian	Wildlife management	**us**	**r**
	T25	S36	g25	p75	Pond on clear-cut sandbar/wet meadow (former riparian)	Wildlife management	**us**	**r**
		S37	g25	p76	Side-channel; riparian	Wildlife management	**cs**	**r**
14. John's Property, Buffalo County								
	T26	S38	g26	none	Tributary, riparian, and wet meadow	Cropland; pasture	**cs**	**a, g**
		S39	g26	p78	Wet meadow; intermittent slough	Wildlife refuge	**us**	**f, r**
	T27	S40	(g26, g28)	p79, p80, p81	Man-made slough and pond in wet meadow	Native grassland; wildlife management	**us**	**b, f, r**
15. Cottonwood Ranch, Buffalo County								
	T28	S41	g27, s82, (g28, g29)	p82	Tributary, riparian, and wet meadow	Wildlife management	**cs**	**a, g, p**
		S42	g27, g28	p83	Backwater in riparian	Wildlife management	**cd**	**g, p**
	T29	S43	g29	p84, p85	Tributary, riparian, and wet meadow	Wildlife management	**cs**	**a, b, g, p**
	T30	S44	s87, (g29)	p86, p87, p88	Beaver ponds on tributary	Wildlife management	**cs**	**a, b, g, p**
		S45	g30	p89	Isolated pond in riparian	Wildlife management	**us**	**g, p**
		S46	g30	p90	Backwater in riparian	Wildlife management	**cs**	**g, p**
		S47	g30	none	Side-Channel; riparian	Wildlife management	**cs**	**g, p**

Key:

Hydrologic Connection: cs-- connected to a stream with surface flow; **us**-- unconnected to a stream with surface water; **cu**-- connected to stream with surface flow at upstream only; **cd**-- connected to stream with surface flow at downstream only;

Remarks: a-- intermittent agriculture runoff; **b**-- beaver damming observed; **f**-- fire management; **g**-- seasonal grazing; **p**-- park or recreation; **r**-- restoration site;

Appendix B

Geographic Locations and Soil/sediment Features of the Study Areas

Study Area	Geographic Location		Soil Series	Feature Descriptions
	Latitude	Longitude		
Mormon Island, Hall County	40N48'54" 40N47'11"	98W23'00" 98W26'26"	Platte; Wann	Loam; Deep fine sandy loam
Wolback, Hall County	40N48'02" 40N47'11"	98W23'00" 98W25'18"	Platte-Sarpy	Loam, find sand
Crane Meadows, Hall County	40N48'03" 40N47'12"	98W26'26" 98W28'08"	Platte; Wann	Loam; Deep fine sandy loam
Brown Tract, Hall County	40N48'04" 40N47'38"	98W28'25" 98W28'08"	Platte; Wann	Loam; Deep fine sandy loam
Caveney Tract, Hall County	40N47'12" 40N46'59"	98W30'25" 98W30'17"	Wann	Fine sandy loam
Dahms Tract, Hall County	40N45'03" 40N44'50"	98W34'08" 98W34'25"	Sarpy; Wann	Find sand; Find sandy loam
Wood River, Hall County	40N44'51" 40N44'25"	98W35'16" 98W36'07"	Platte; Wann	Loam; Find sandy loam
Uridil, Hall County	40N43'20" 40N42'55"	98W37'16" 98W38'58"	Platte; Volin	Loam; Silt loam
Martin's Ranch, Hall County	40N44'25" 40N43'47"	98W38'07" 98W38'41"	Platte-Sarpy	Loam, find sand
Dipple, Buffalo County	40N41'51" 40N42'30"	98W48'38" 98W46'56"	Platte; Volin	Loam; Silt loam
Hornady, Buffalo County	40N40'21" 40N39'55"	98W53'11" 98W54'53"	Loamy alluvial land	Loam to find sand, gravel
Speidell Tract, Buffalo County	40N40'01" 40N39'36"	99W00'34" 99W01'34"	Platte; Loamy alluvial land	Silty to sandy alluvium; Loam to find sand, gravel
Wyoming's, Buffalo County	40N38'37" 40N40'21"	99W02'50" 99W00'34"	Loamy alluvial land	Loam to find sand, gravel
John's Property, Buffalo County	40N41'11" 40N40'19"	99W20'27" 99W19'19"	Platte; Loamy alluvial land	Silty to sandy alluvium; Loam to find sand, gravel
Cottonwood Ranch, Buffalo County	40N41'10" 40N40'17"	99W27'16" 99W28'58"	Platte; Wann	Loam; Deep fine sandy loam

Appendix C

Water Levels, Precipitations, and Hydrographs of the Study Sites

(Listed by order of transects; total 41 sheets)

Note:

Curves in a figure of Appendix C demonstrate: (1) changes in stream level in a main channel or a side-channel, and surface water level and groundwater table in one or more riverine habitats along a transect on each of the monitoring dates; (2) daily mean discharges in the main channel at the closest USGS stream gauging station; and (3) three-day moving mean precipitation based on rainfall data collected from the nearest weather station. Dotted lines separate the dates by year.

Explanation of notations:

T*i*-S*j* – Transect ID number and site ID number. Each of the study areas has at least one, and some of them have up to four transects; each transect has at least one monitoring site with stream gauge and piezometer(s). There are total 32 transects and 50 sites in 15 study areas (the $i = 01, 02, \ldots, 32$; $j = 01, 02, \ldots, 50$).

g*k* – ID of a standard iron water level gauge, associated with water level in a stream channel or in a water body of riverine aquatic habitat ($k = 01, 02, \ldots 90$);

p*k* – ID of a PVC Piezometer, associated with groundwater table in a water body of riverine aquatic habitat ($k = 01, 02, \ldots 90$);

s*k* – ID of a PVC water level gauge (usually used the same PVC pipe of a piezometer) installed at a site where surface water level in a water body of riverine aquatic habitat was measured. The surface water level was read from outside of the piezometer, which was named with same ID order number ($k = 01, 02, \ldots 90$);

Tm – daily mean air temperature;

P – daily total precipitation;

ET - daily potential evapotranspiration;

Tm3 – three day moving average of the air temperature;

P3 – three day moving average of the total precipitation;

ET3 - three day moving average of the potential evapotranspiration;

Tm4 – four day moving average of the air temperature;

P4 – four day moving average of the total precipitation;

ET4 - four day moving average of the potential evapotranspiration.

List of figures in Appendix C

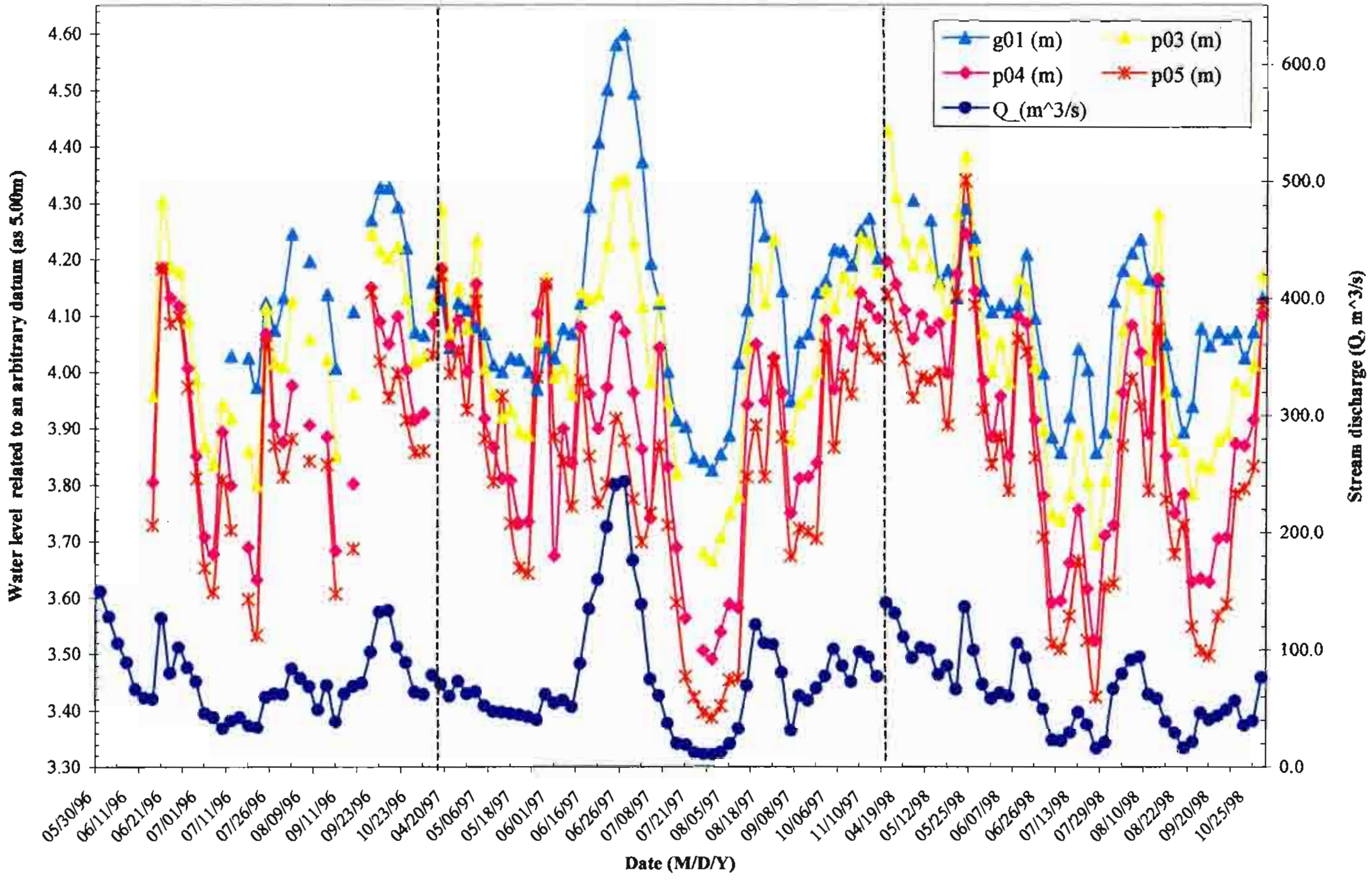

Figure C-01. Hydrograph and water levels along the transect 01 at site 01 (T01-S01).

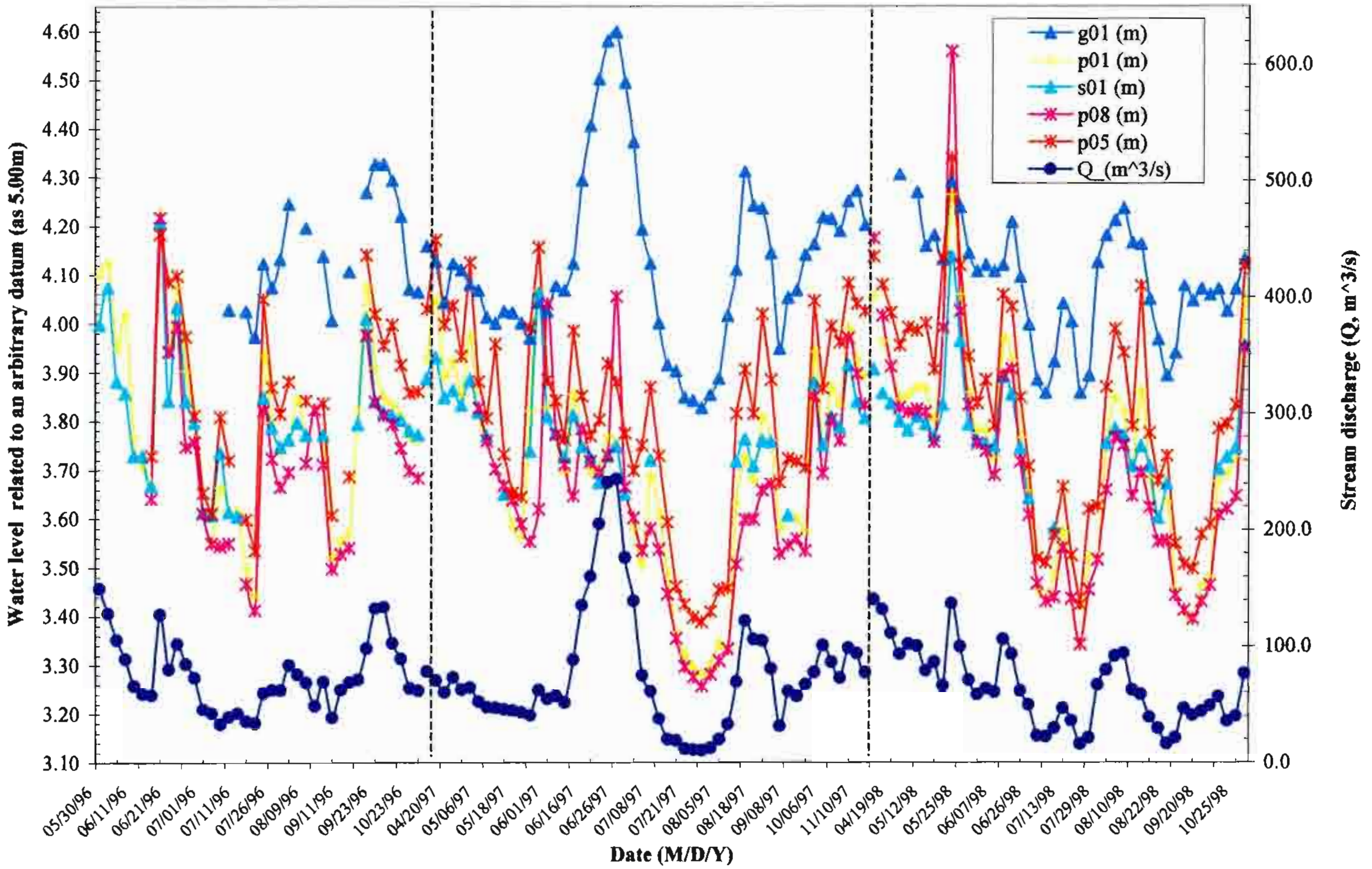

Figure C-02 (a). Hydrograph and water levels along the transect 01 at site 02 (T01-S02).

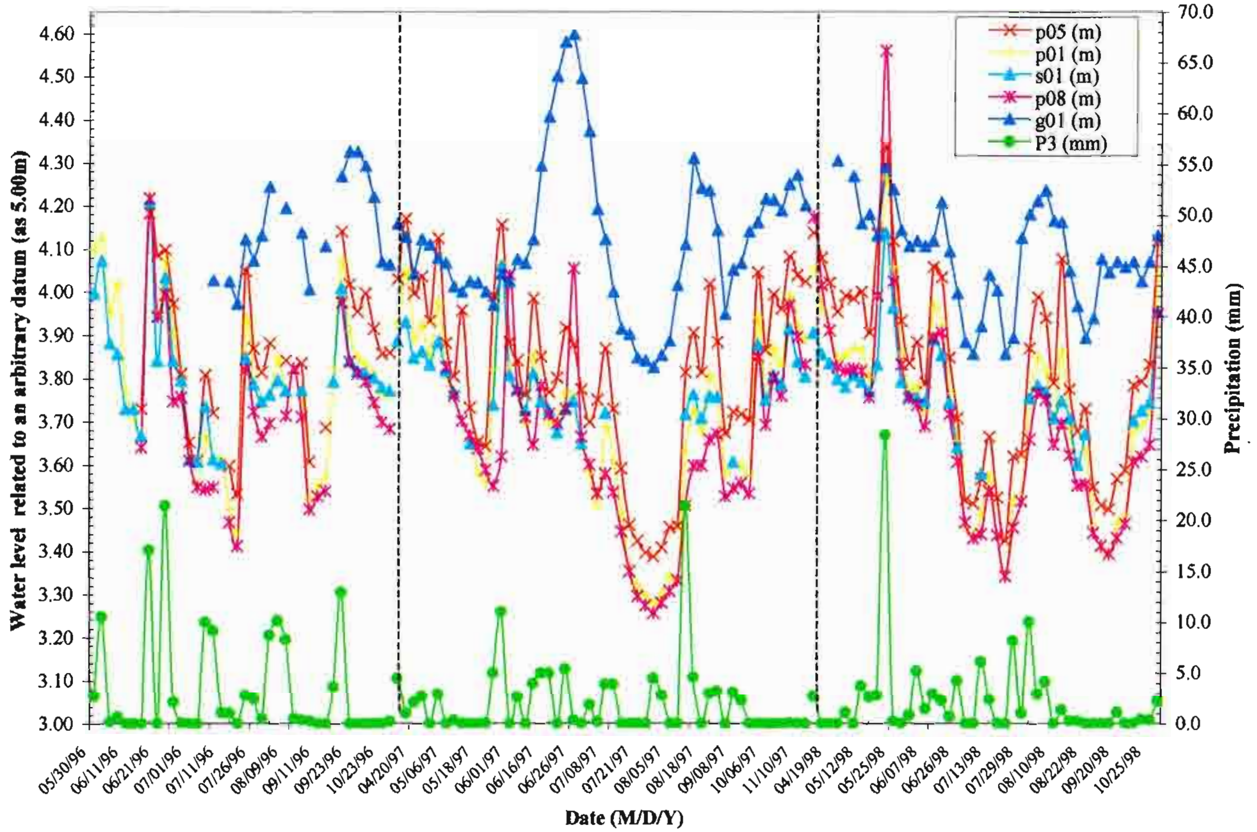

Figure C-02 (b). Precipitation and water levels along the transect 01 at site 02 (T01-S02).

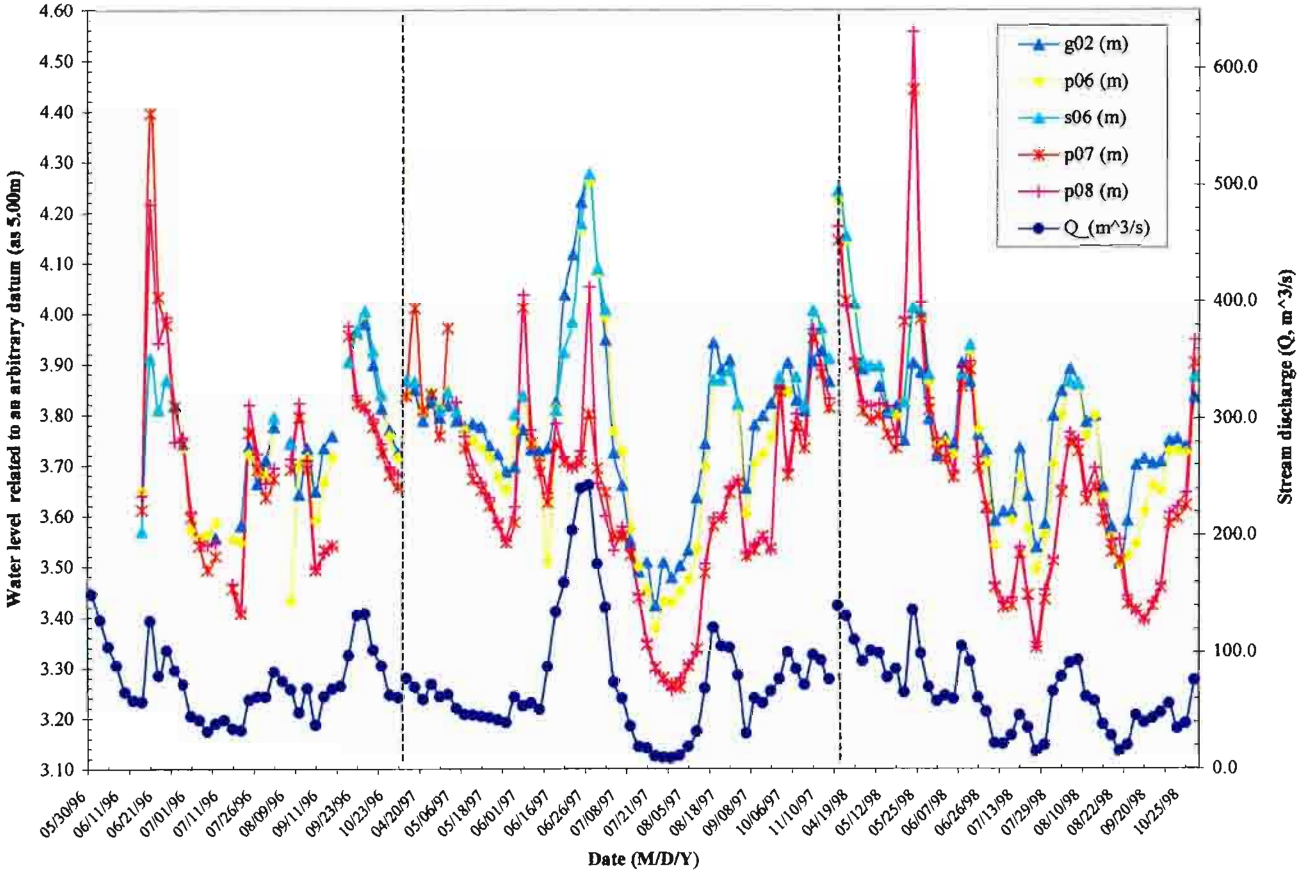

Figure C-03 (a). Hydrograph and water levels along the transect 01 at site 03 (T01-S03).

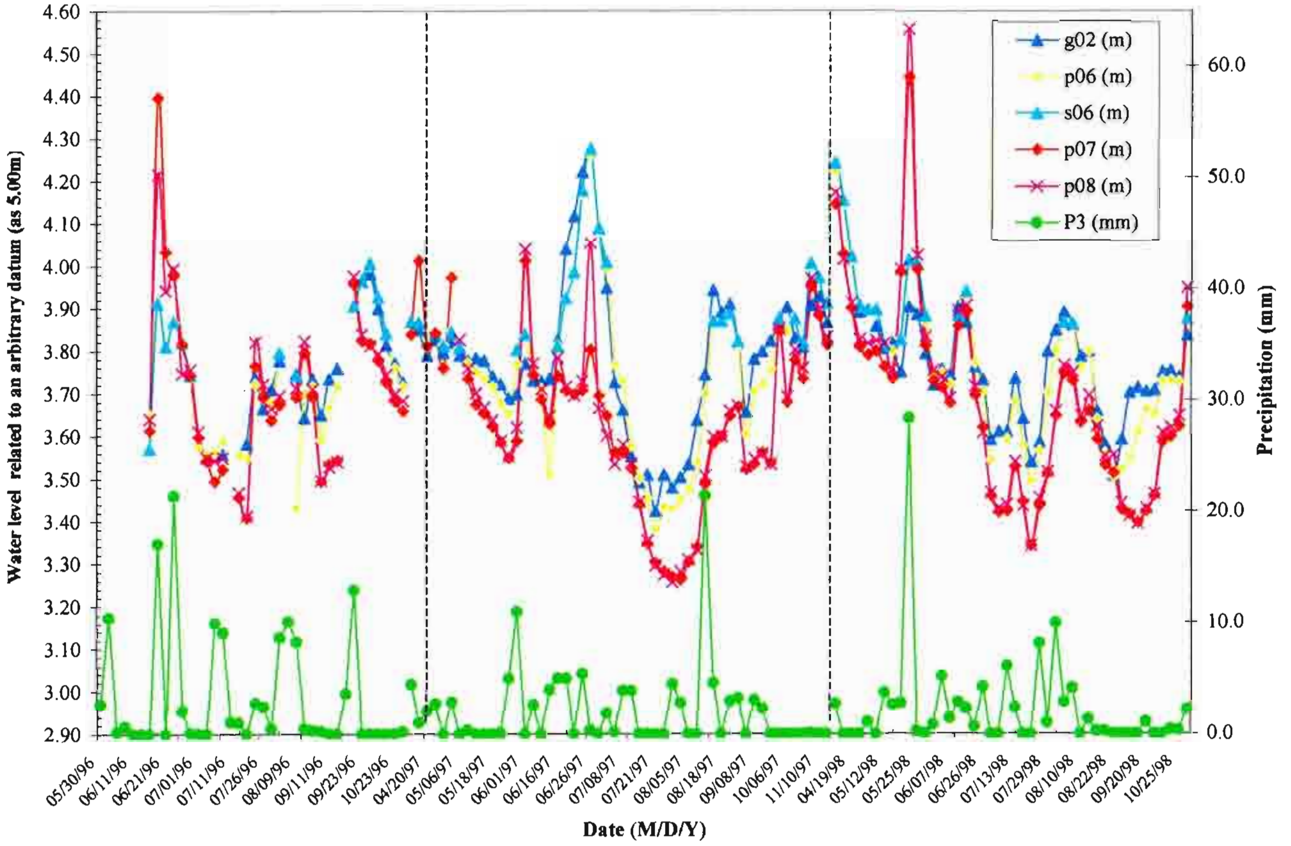

Figure C-03 (b). Precipitation and water levels along the transect 01 at site 03 (T01-S03).

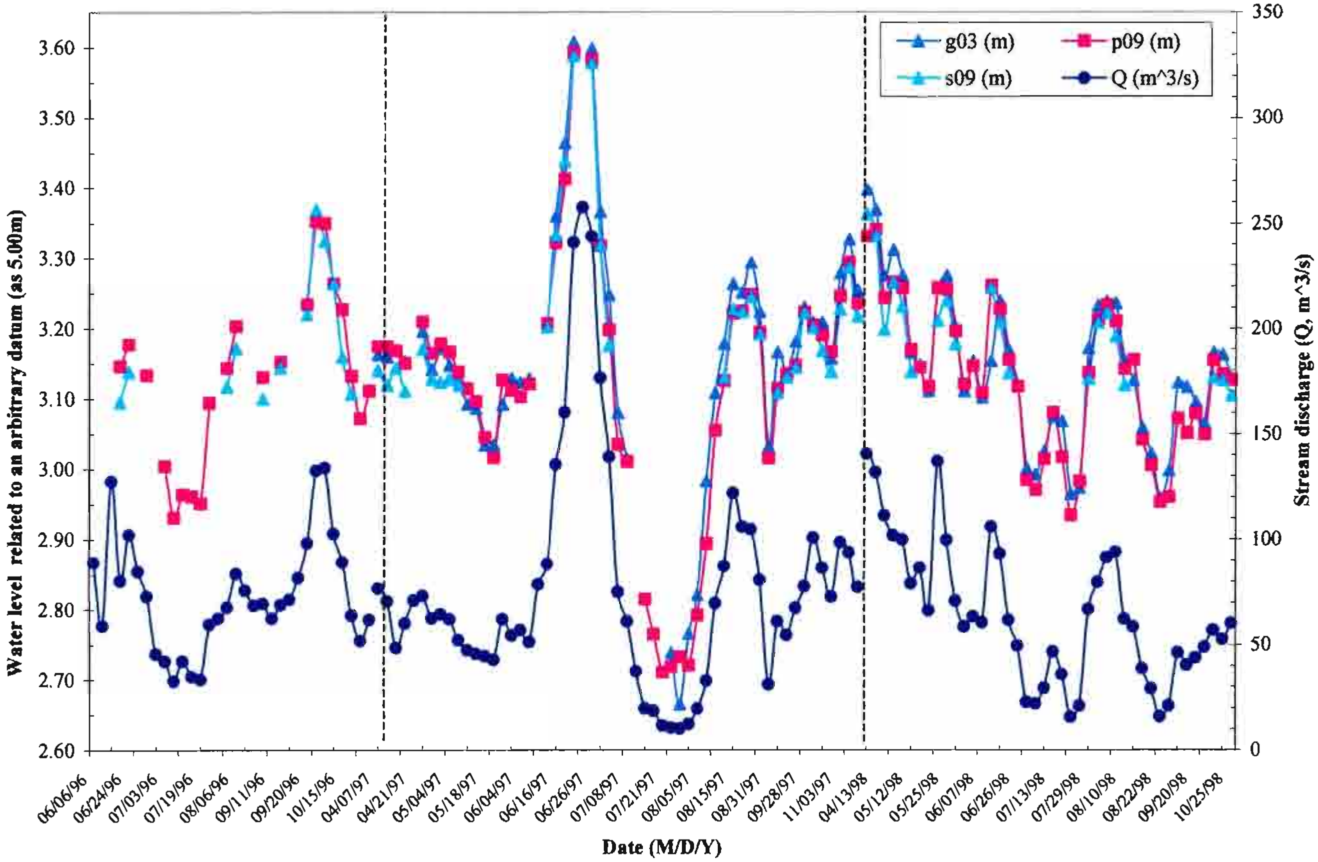

Figure C-04. Hydrograph and water levels along the transect 02 at site 04 (T02-S04).

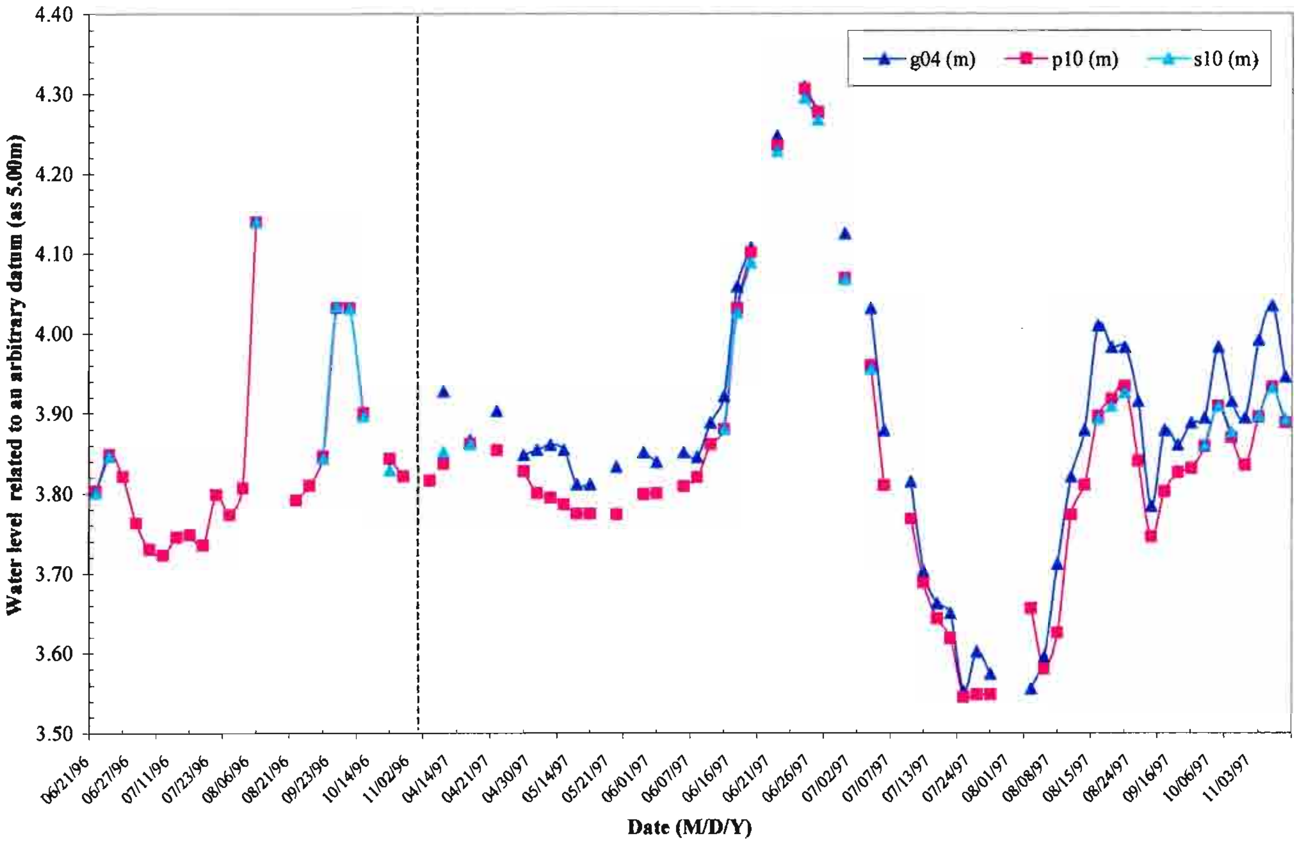

Figure C-05. Water levels at site 05 along the transect 02 (T02-S05).

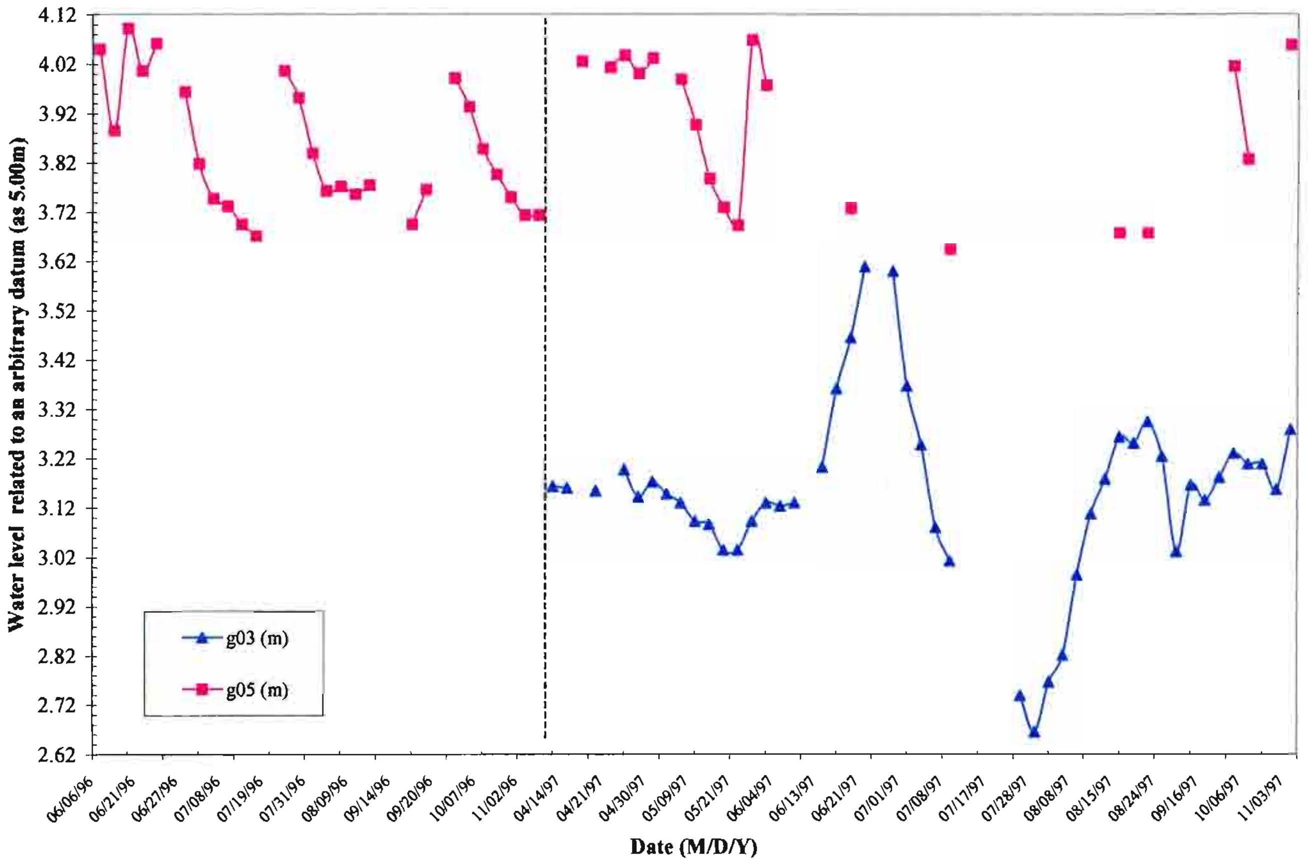

Figure C-48. Water levels at site 48 along the transect 02 (T02-S48).

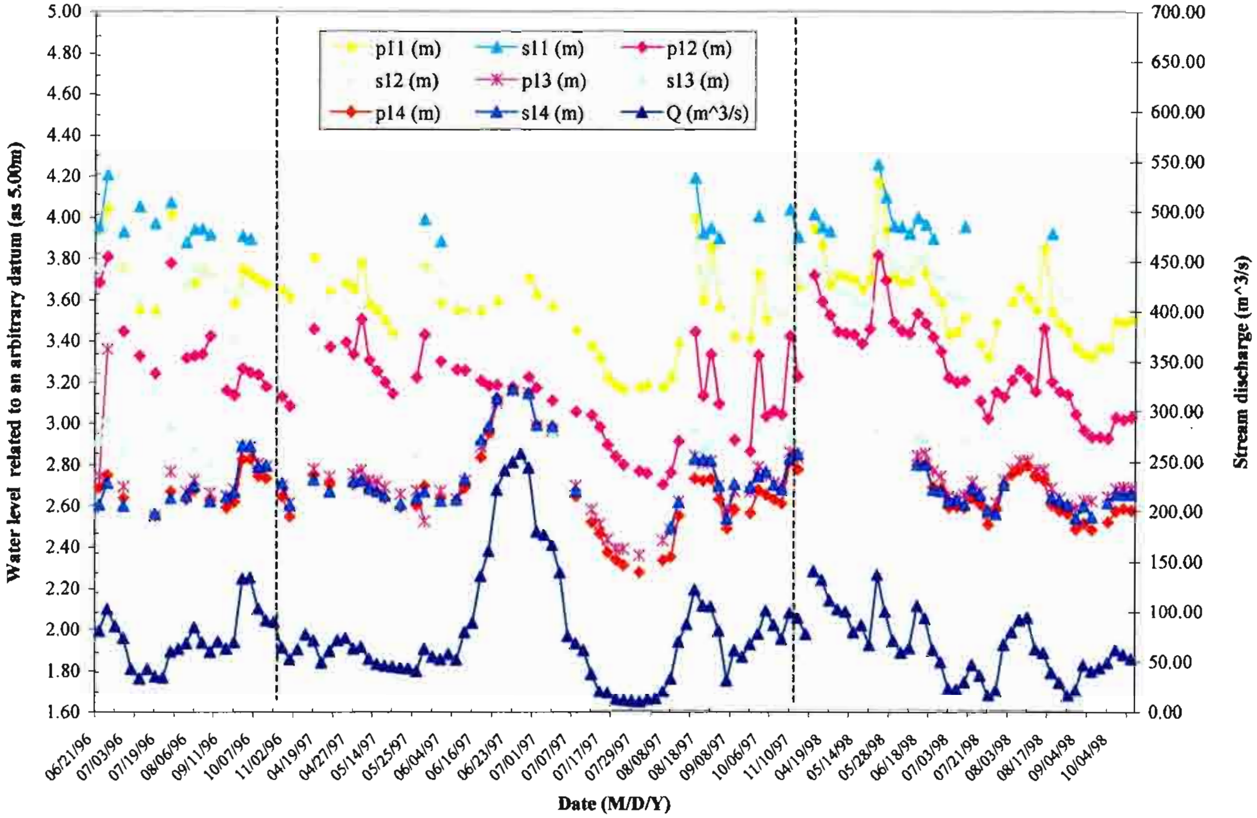

Figure C-06. Hydrograph and water levels from the transect 31 to 32 (T31-S06, T32-S49 & S50).

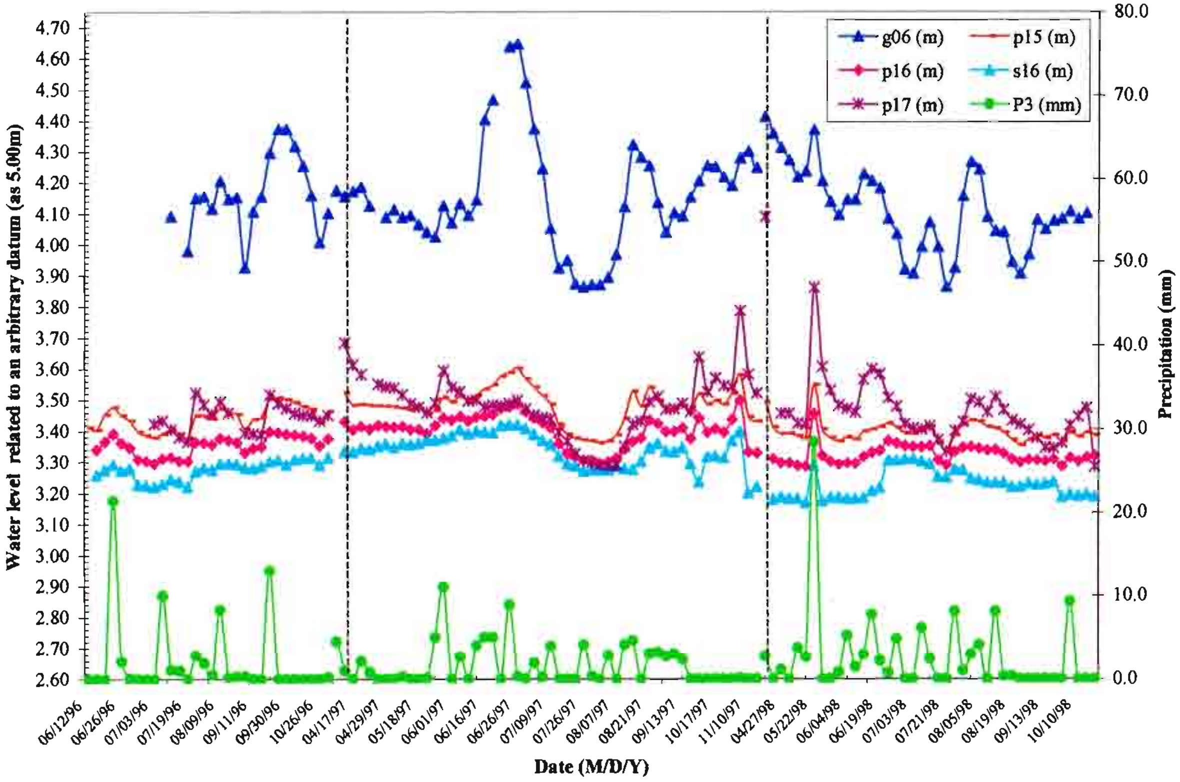

Figure C-07. Precipitation and water levels along the transect 03, at site 07 (T03-S07).

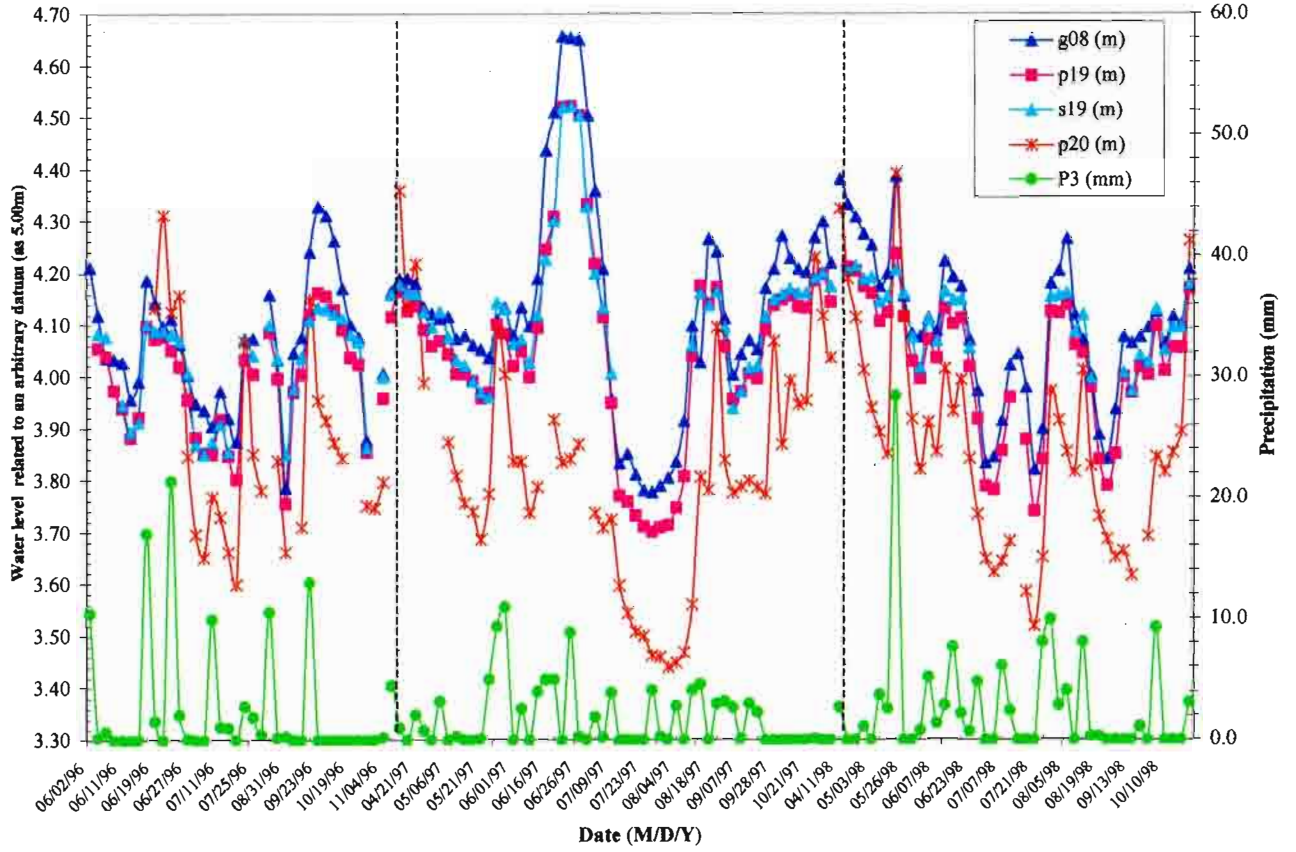

Figure C-08. Precipitation and water levels along the transect 04, at site 08 and site 09 (T03-S08 and T03-S09).

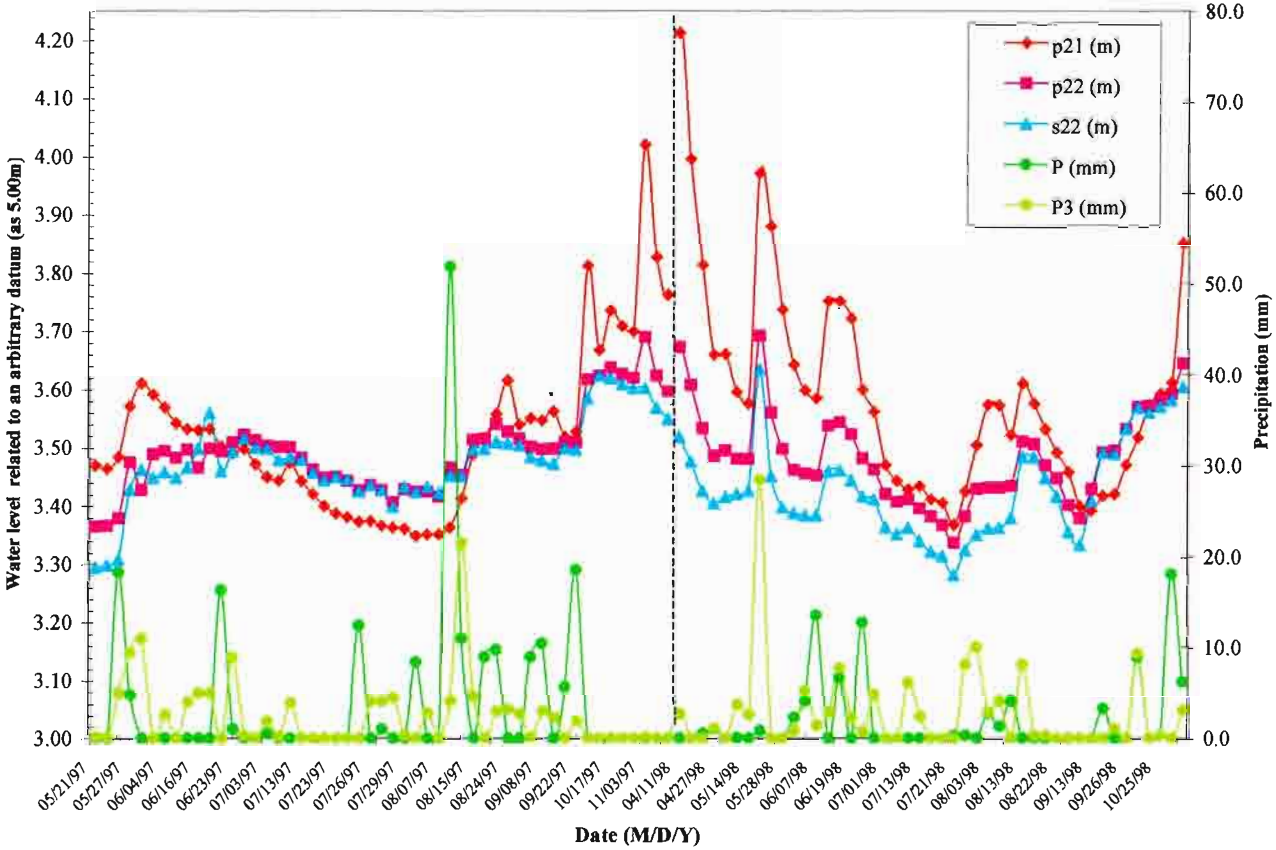

Figure C-09. Precipitation and water levels along the transect 05, at site 10 (T05-S10).

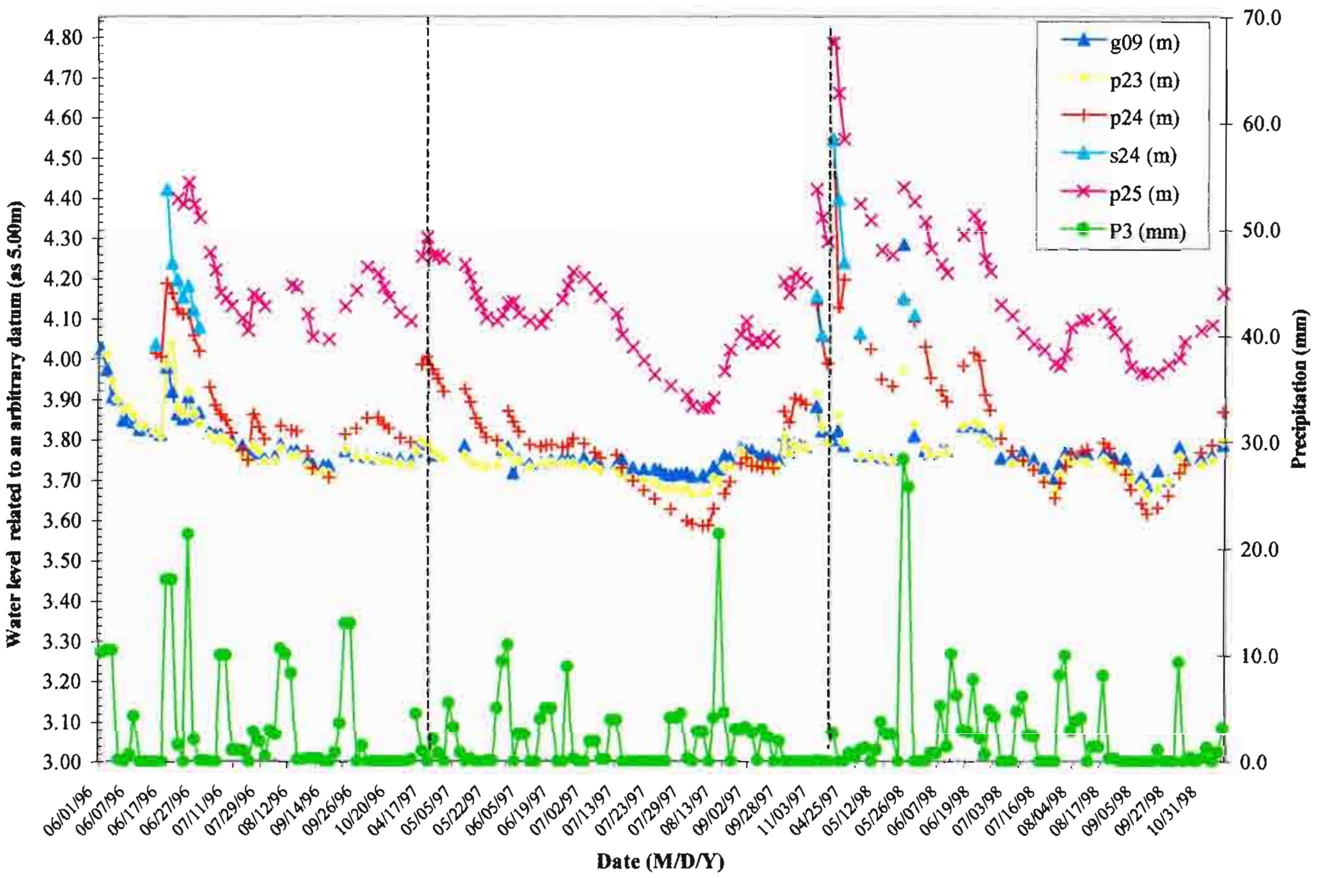

Figure C-10. Precipitation and water levels along the transect 06, at site 11 and site 12 (T06-S11 and T06-S12).

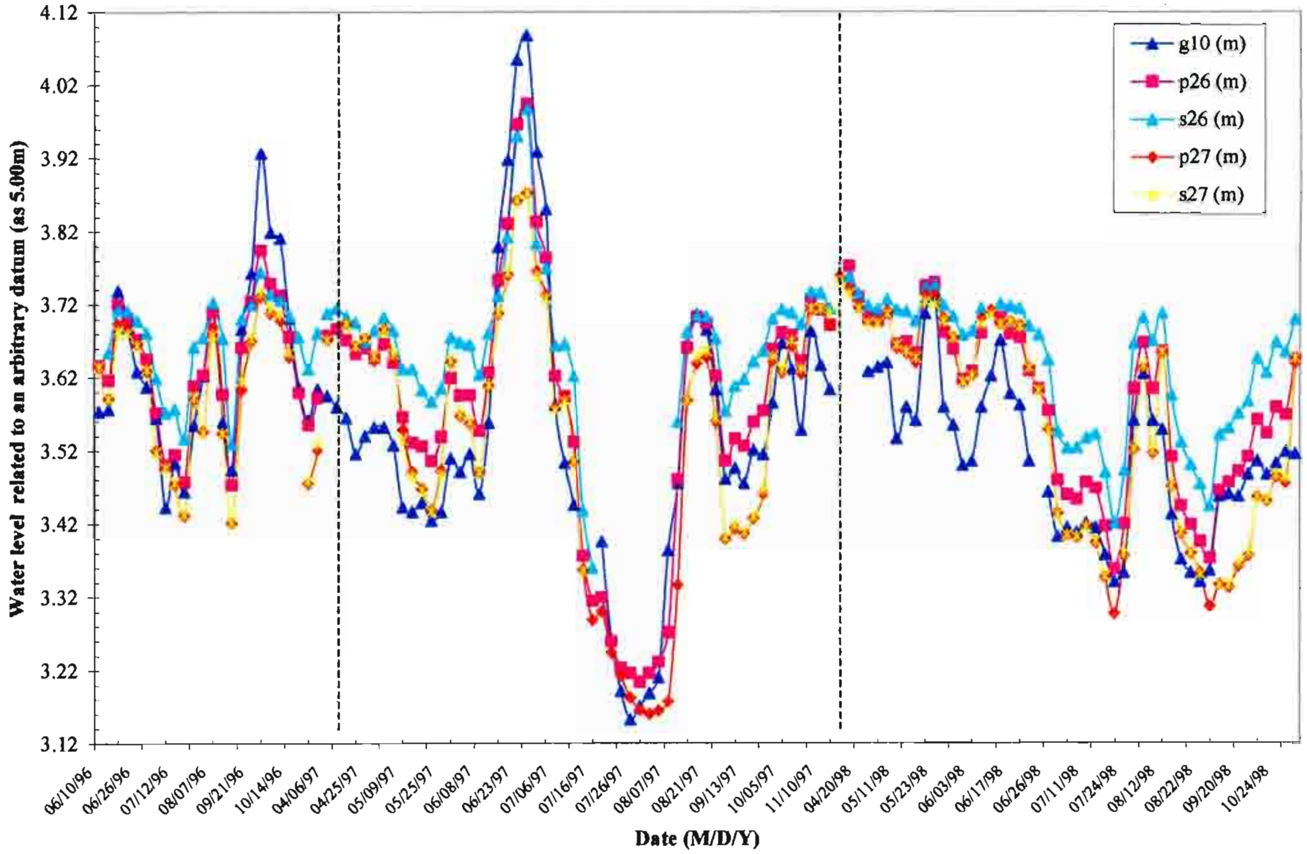

Figure C-11. Water levels at Site 13 and Site 14, along the transect 07 (T07-S13, and T07-S14).

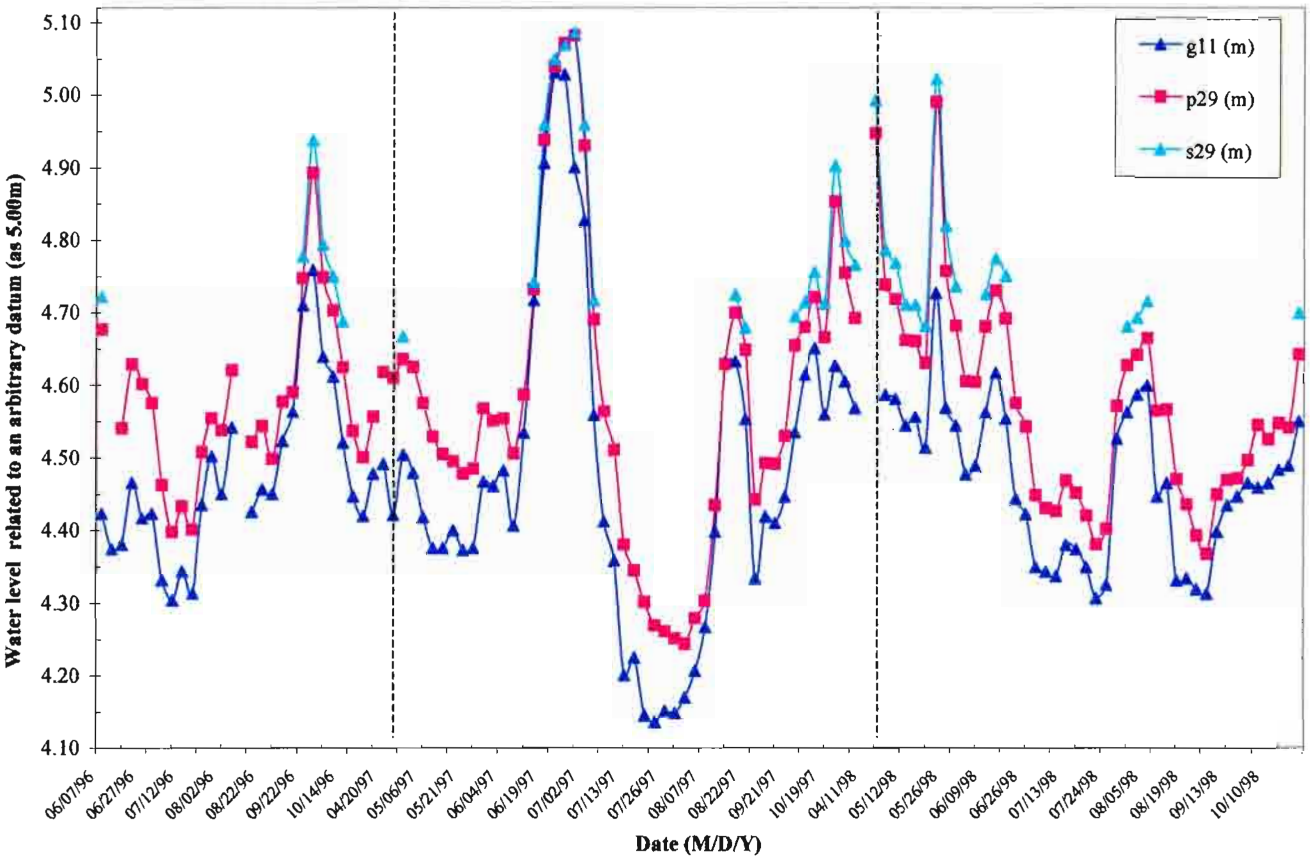

Figure C-12. Water levels at Site 15, the transect 08 (T08-S15).

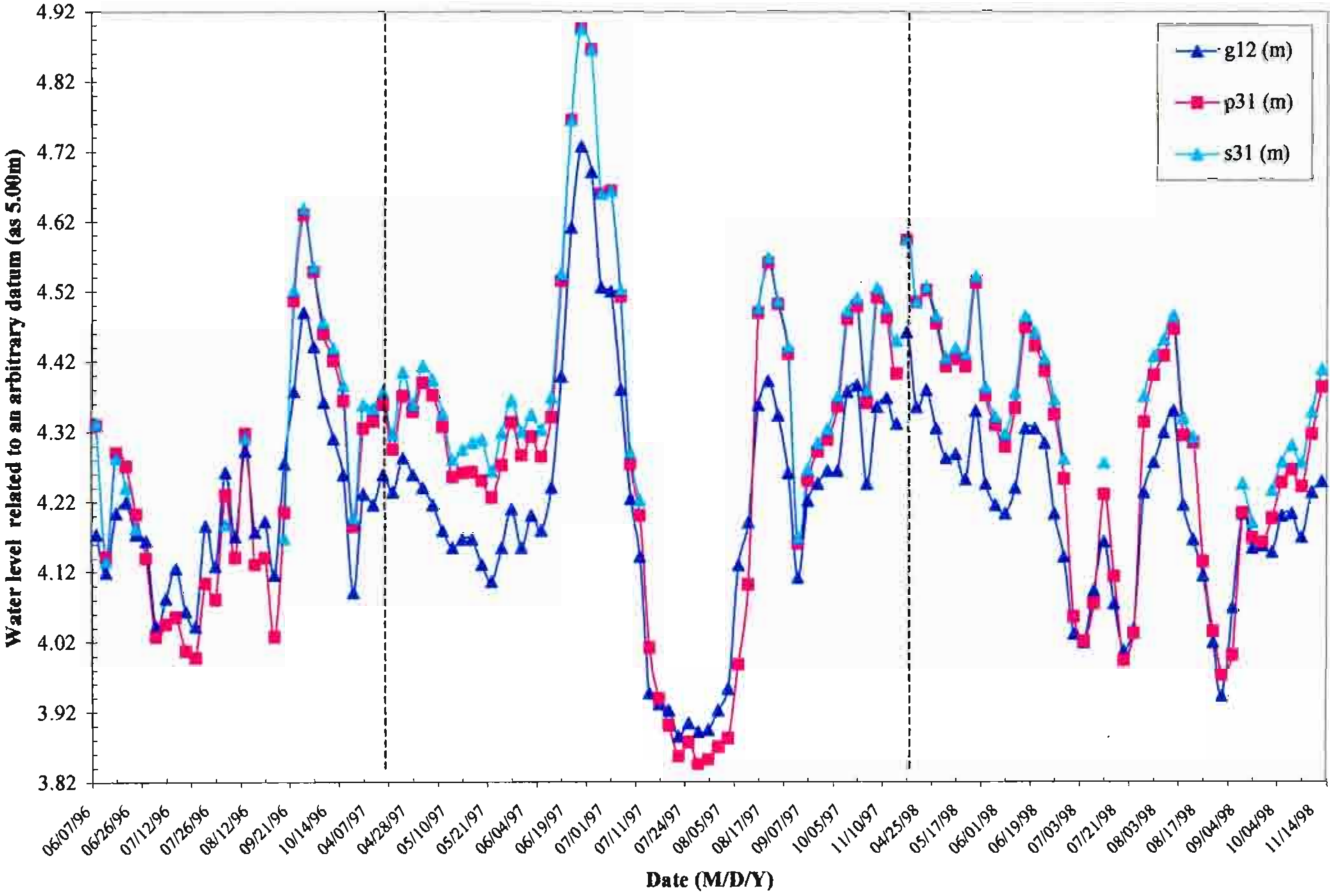

Figure C-13. Water levels at Site 16, the transect 09 (T09-S16).

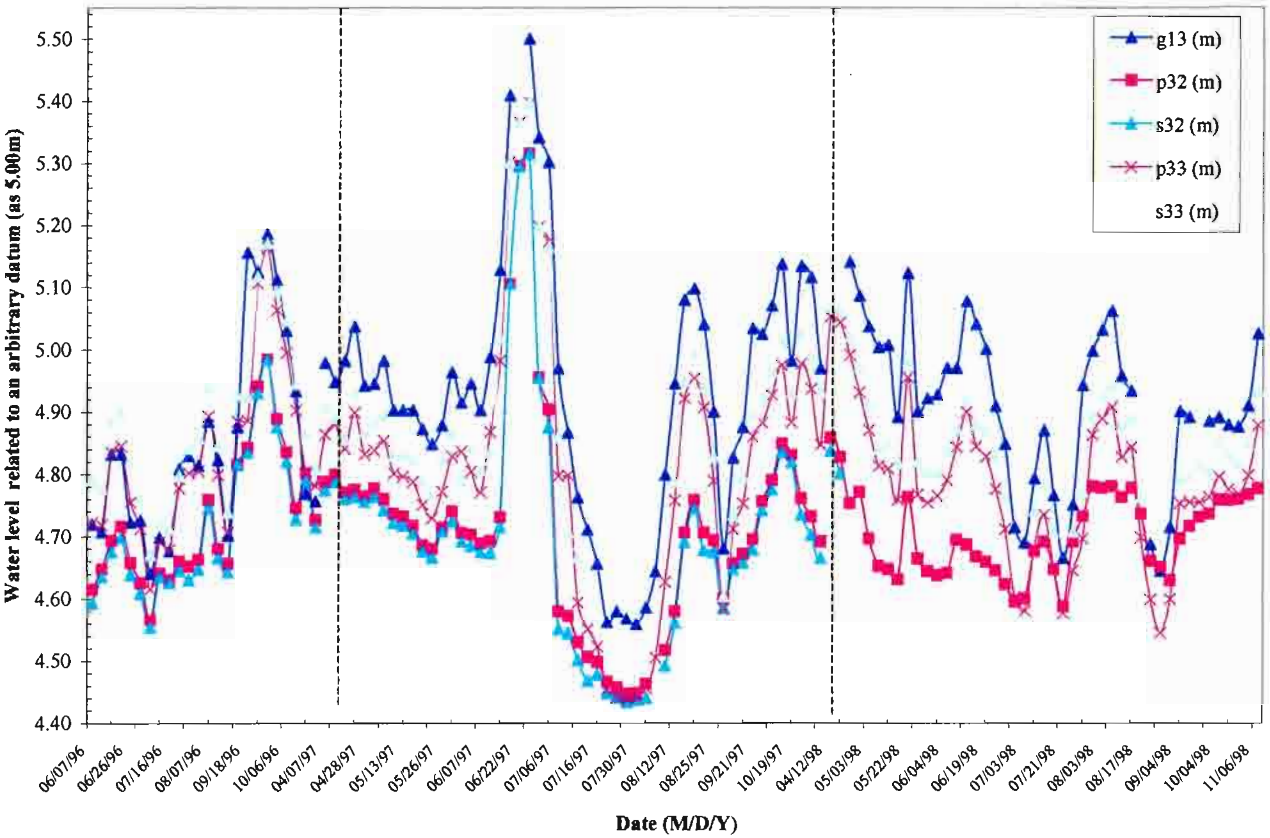

Figure C-14. Water levels at Site 17 and Site 18, along the transect 10 (T10-S17, and T10-S18).

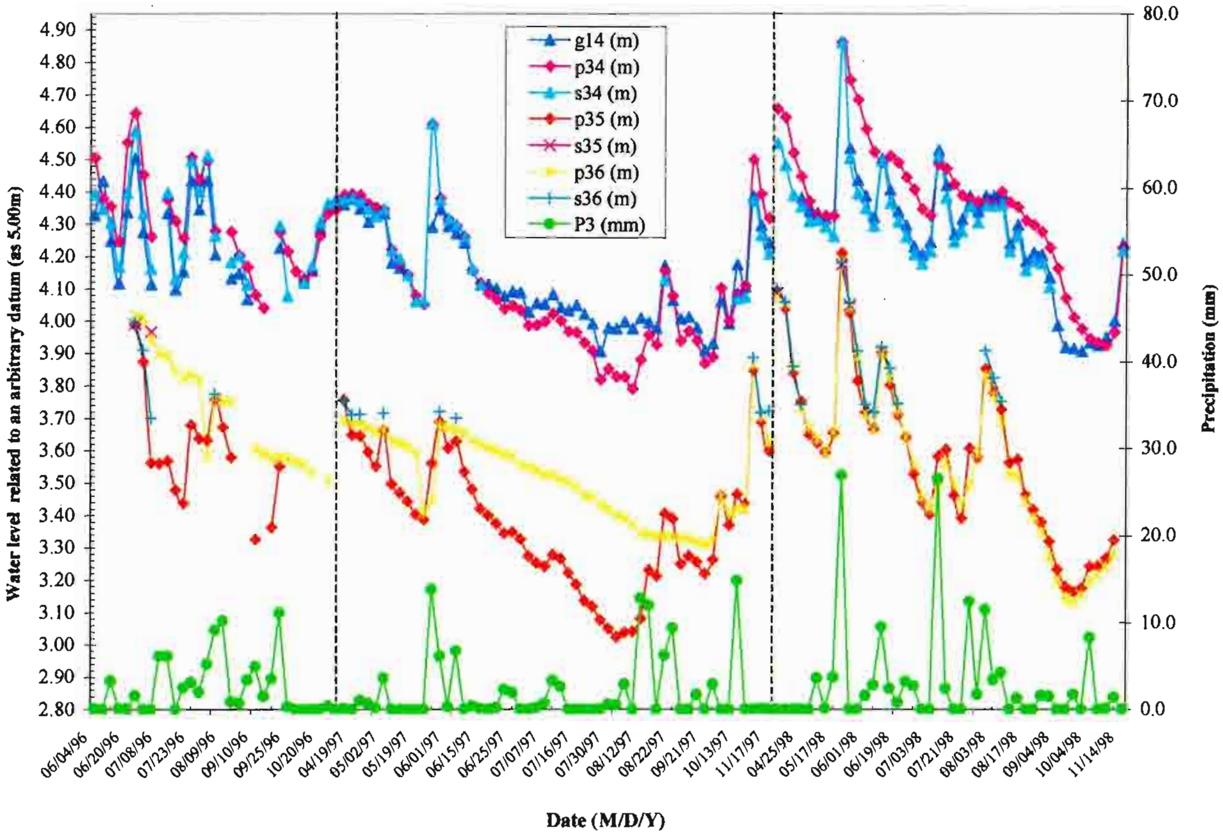

Figure C-15. Precipitation and water levels at Site 19 and Site 20, along the transect 11 (T11-S19, and T11-S20).

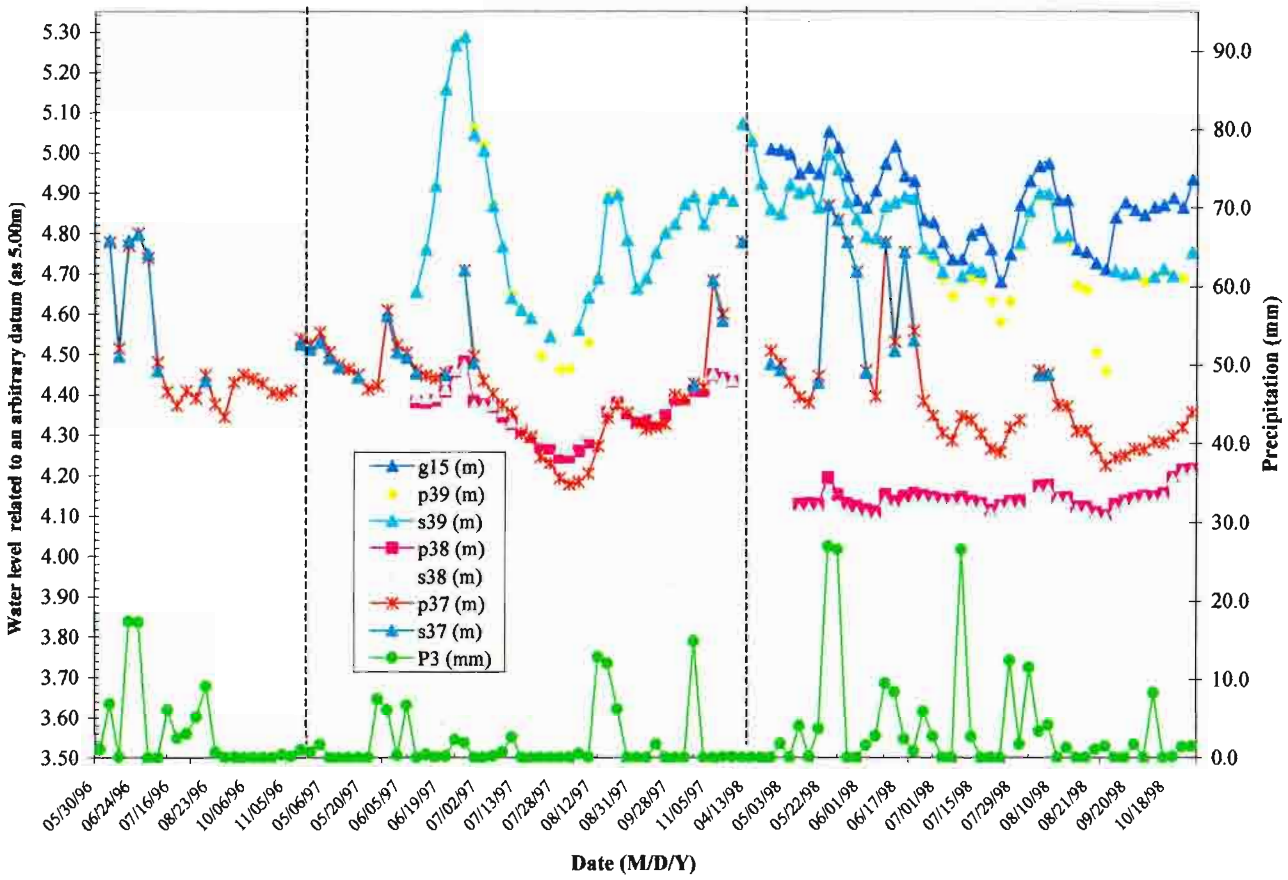

Figure C-16. Precipitation and water levels at site 21, Site 22, and site 23 along the transect 12 (T12-S21, T12-S22, and T12-S23).

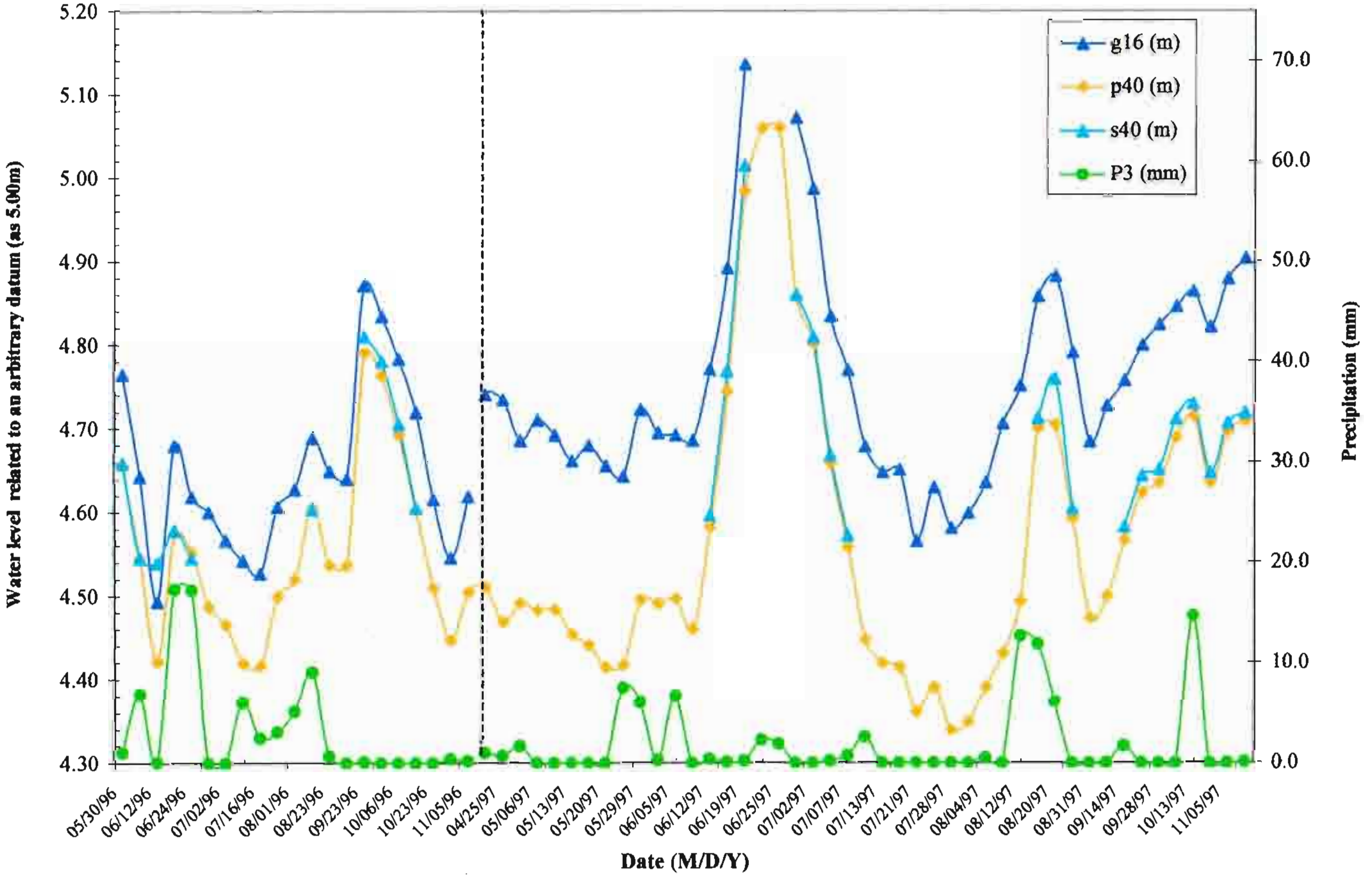

Figure C-17. Precipitation and water levels at site 24, along the transect 13 (T13-S24).

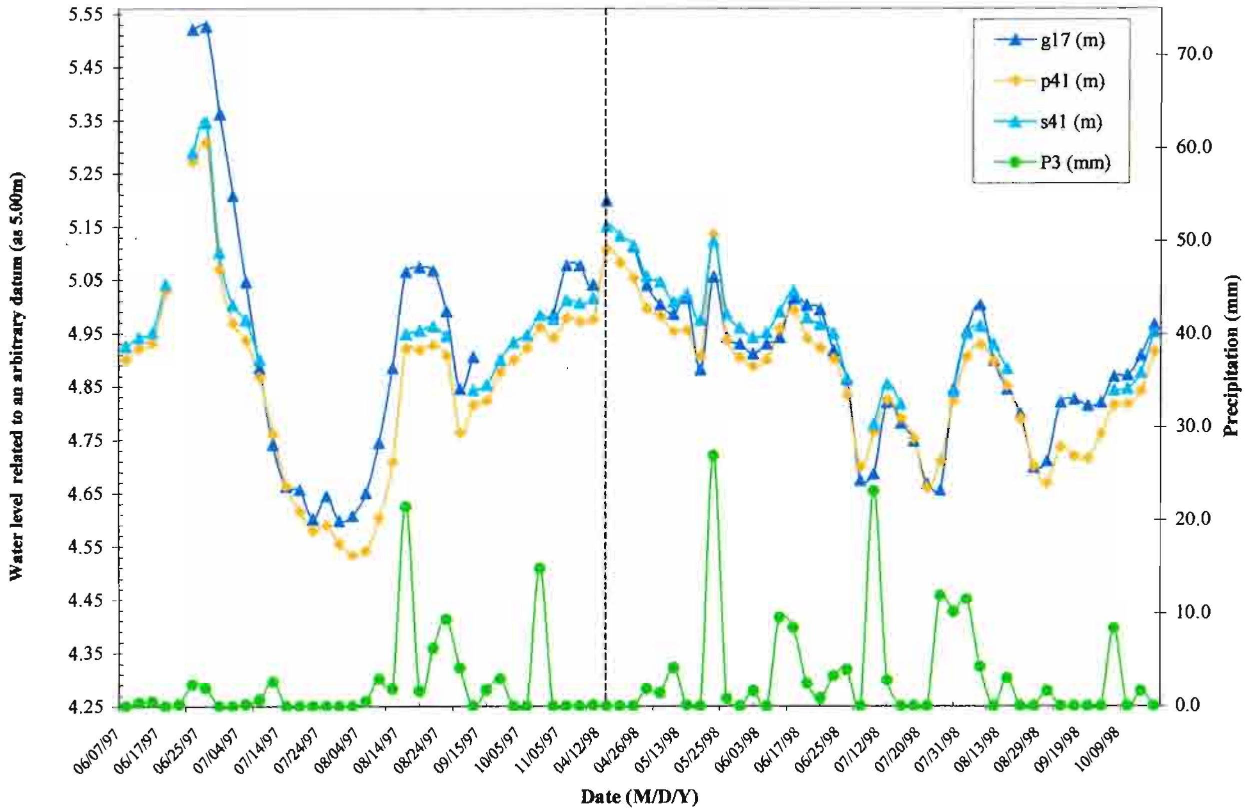

Figure C-18. Precipitation and water levels at site 25, along the transect 14 (T14-S25).

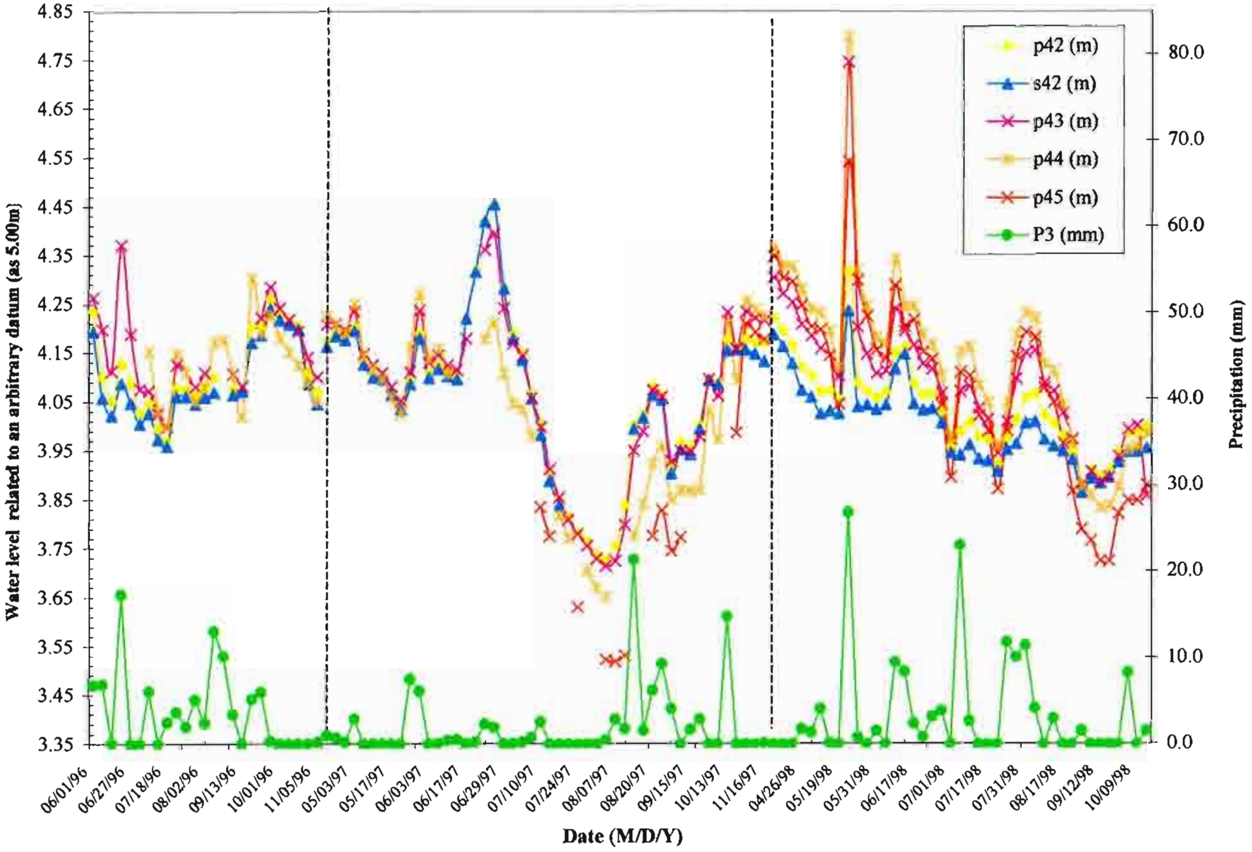

Figure C-19. Precipitation and water levels at site 26 along the transect 15 (T15-S26).

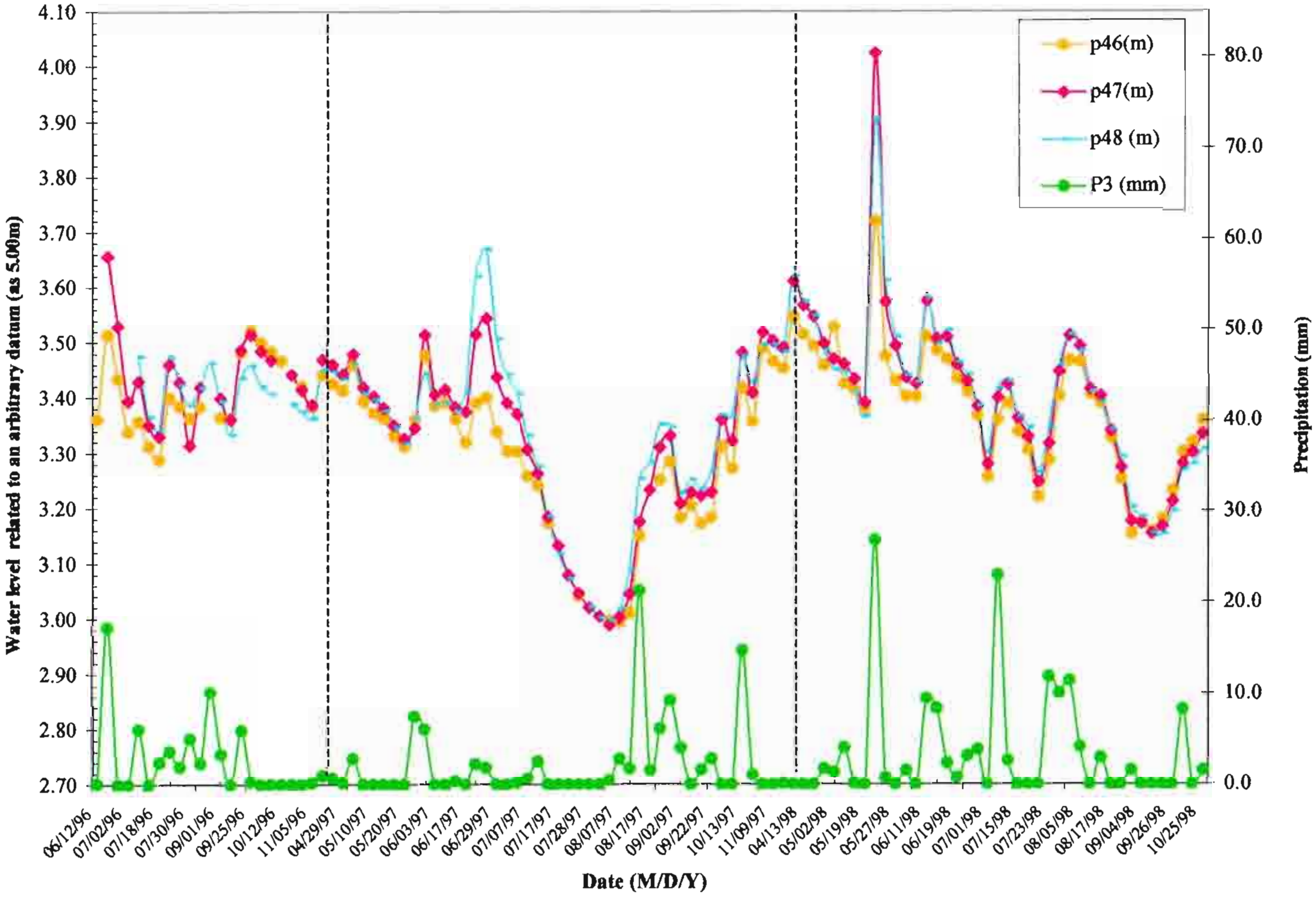

Figure C-20. Precipitation and water levels at site 27 along the transect 16 (T16-S27).

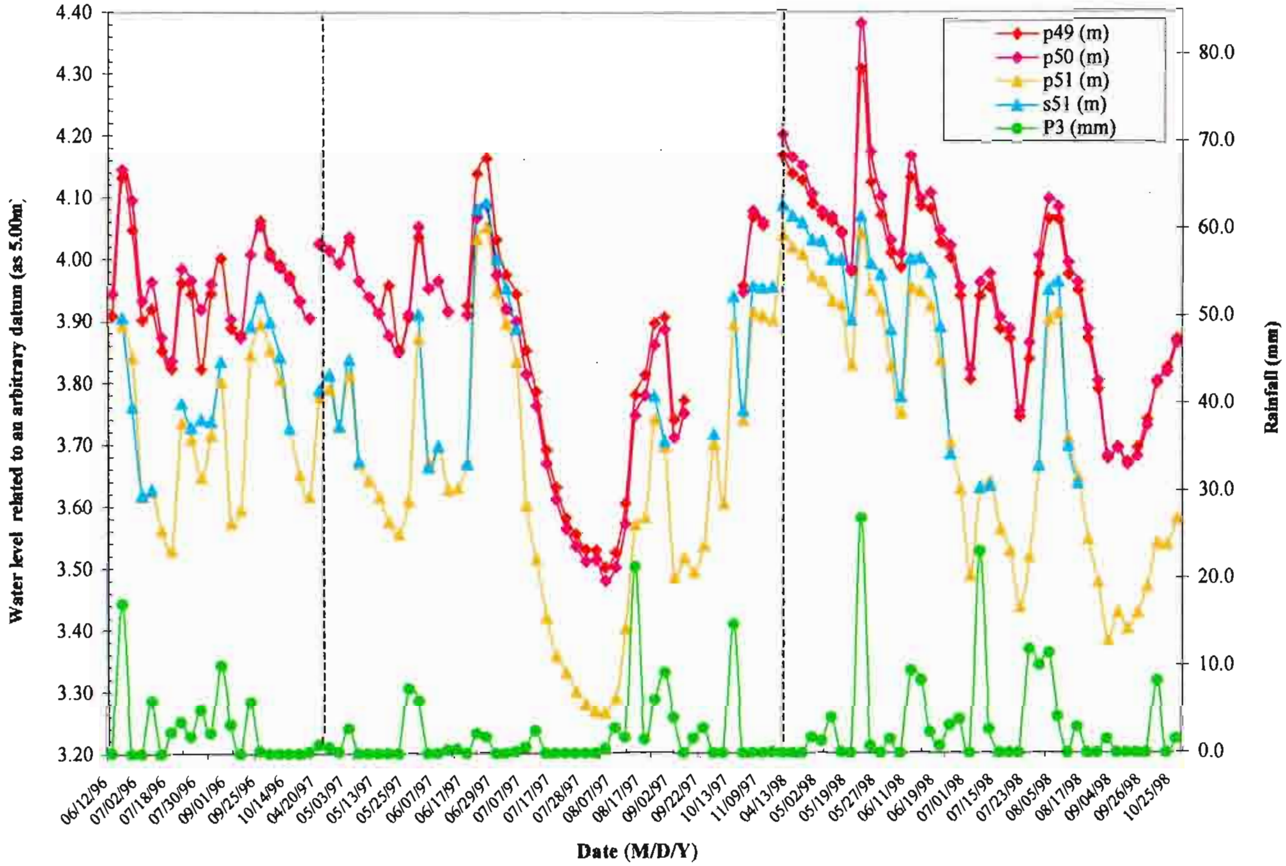

Figure C-21. Precipitation and water levels at site 28 along the transect 17 (T17-S28).

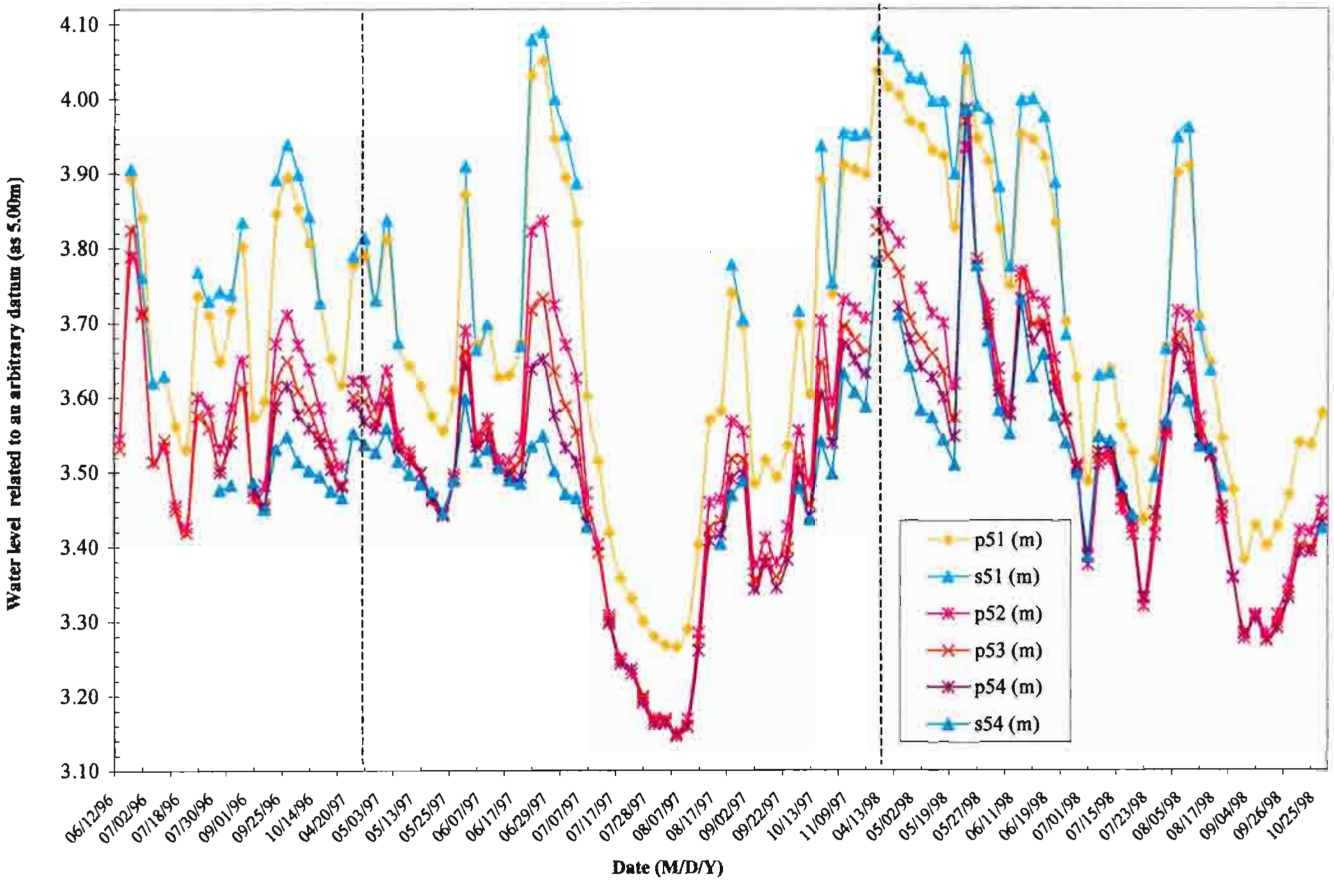

Figure C-22. Precipitation and water levels at site 29 along the transect 18 (T18-S29).

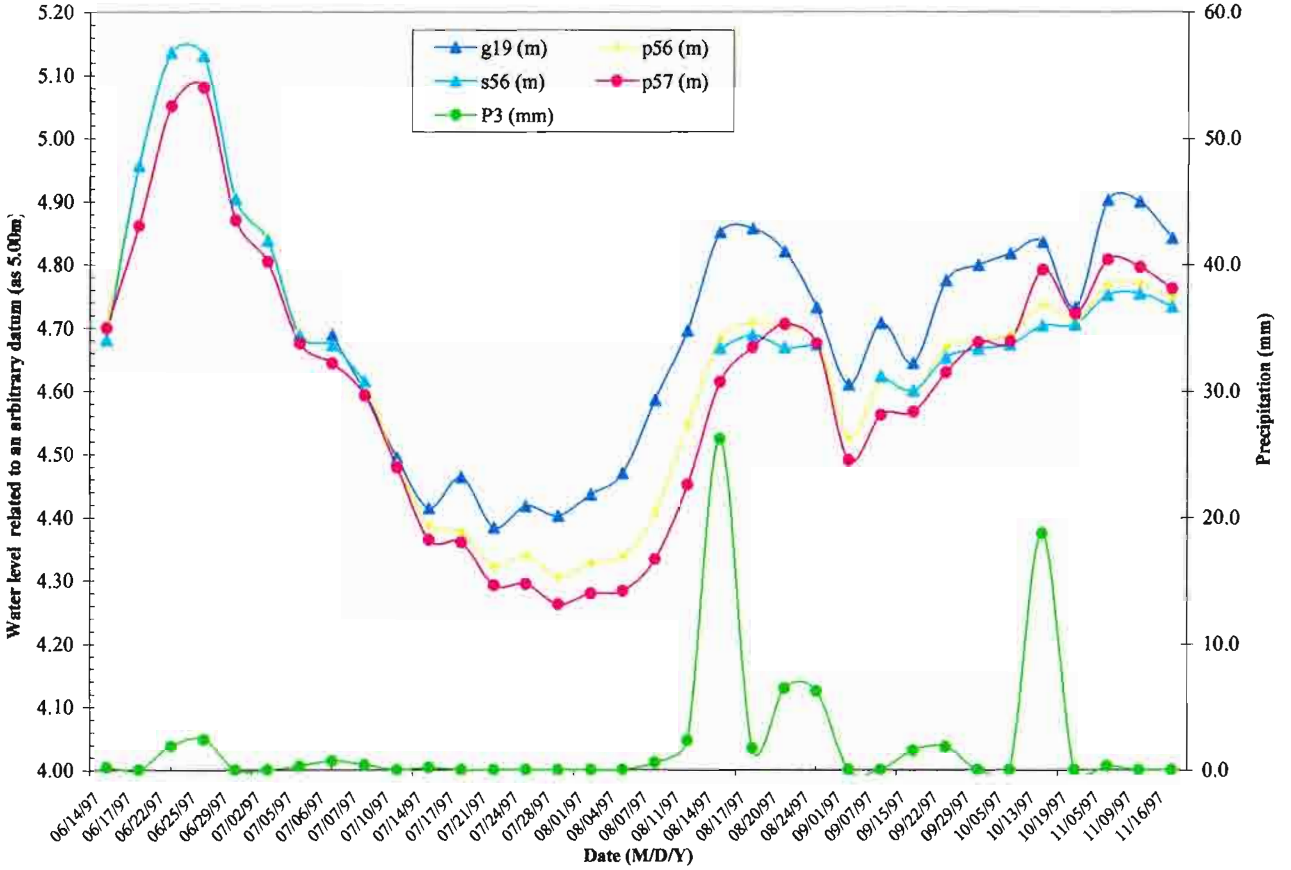

Figure C-23. Precipitation and water levels at site 30 along the transect 19 (T19-S30).

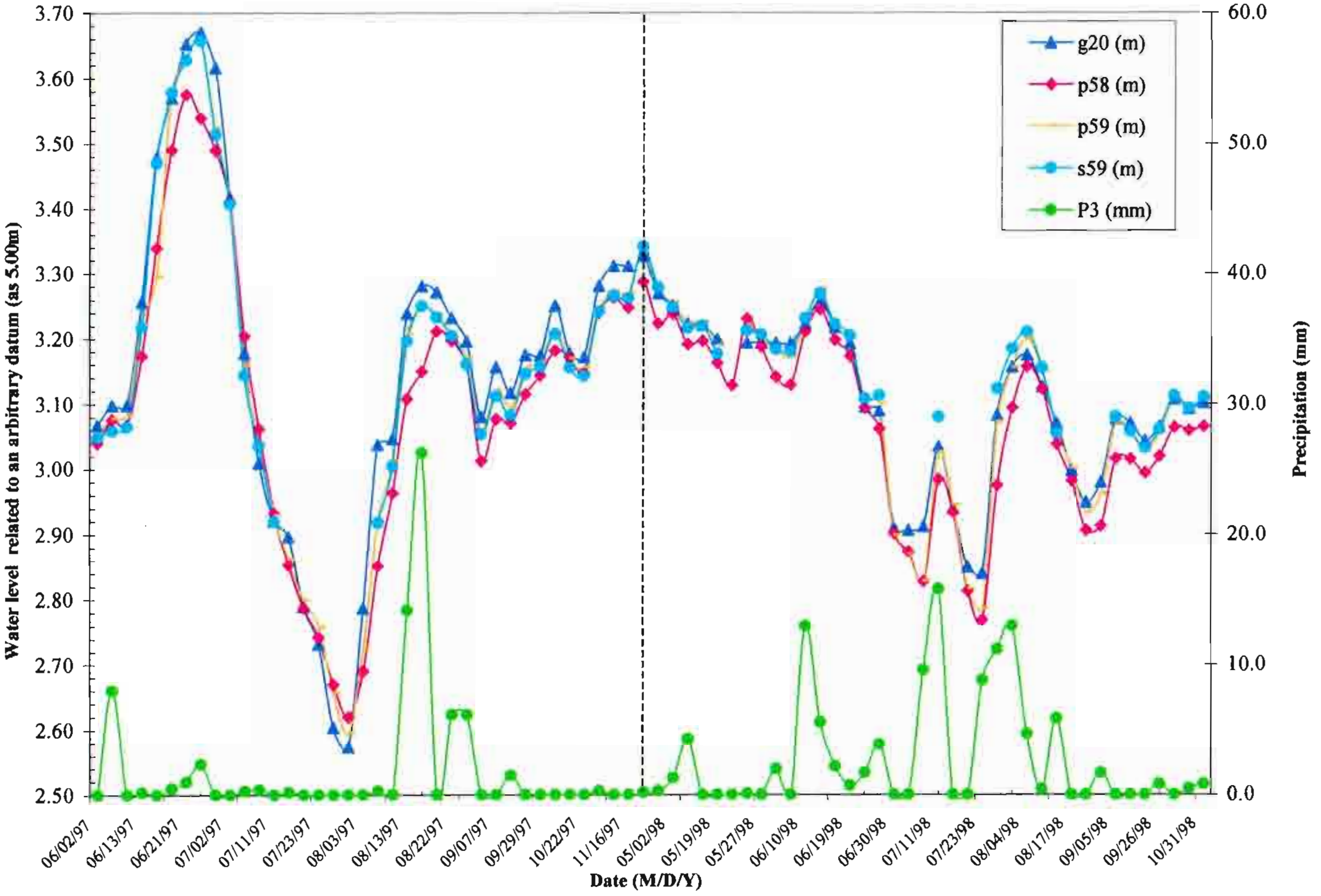

Figure C-24. Precipitation and water levels at site 31 along the transect 20 (T20-S31).

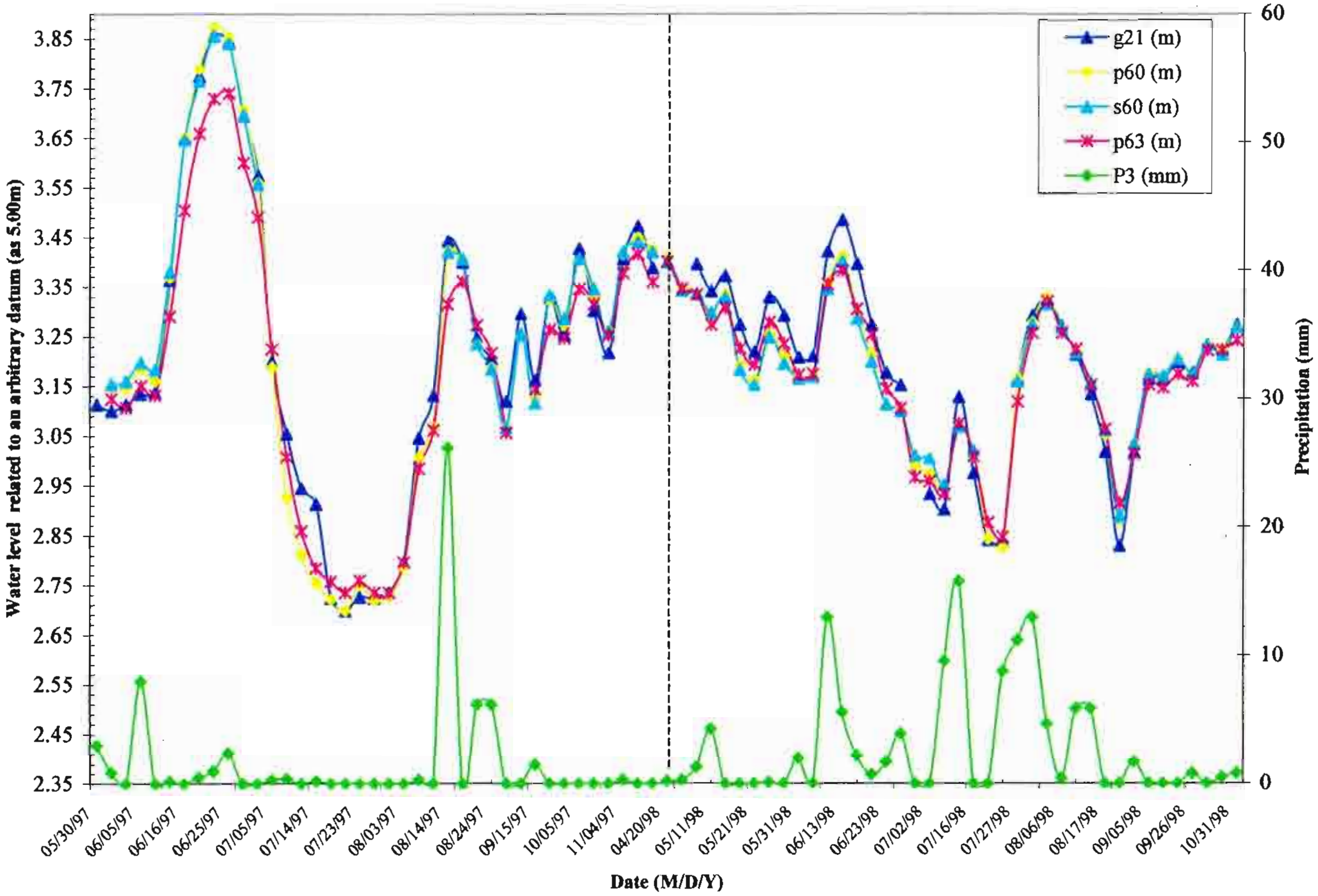

Figure C-25. Precipitation and water levels at site 32 along the transect 21 (T21-S32).

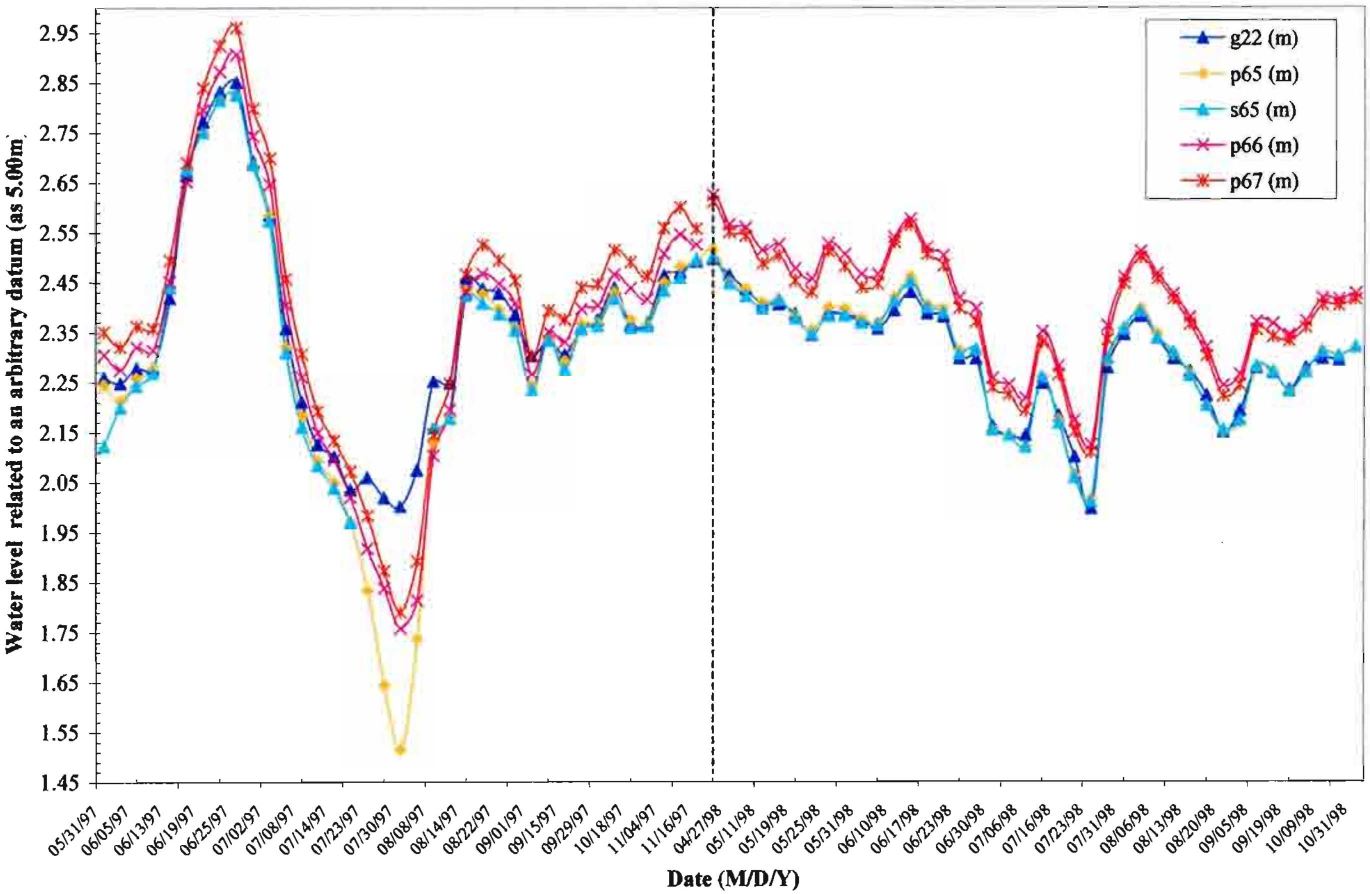

Figure C-26 (a). Water levels at site 33 along the transect 22a (T22a-S33).

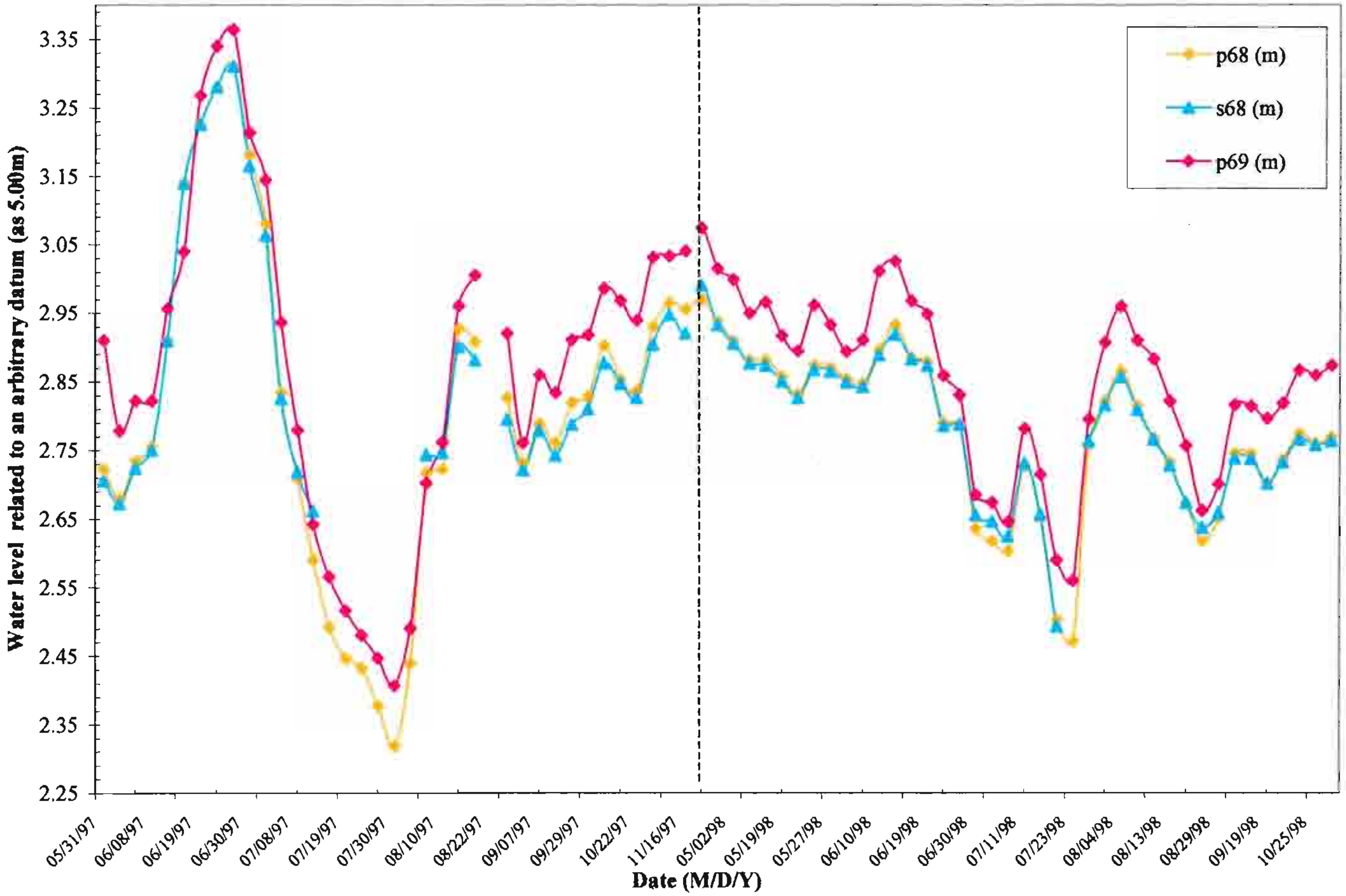

Figure C-26 (b). Water levels at site 33 along the transect 22b (T22b-S33).

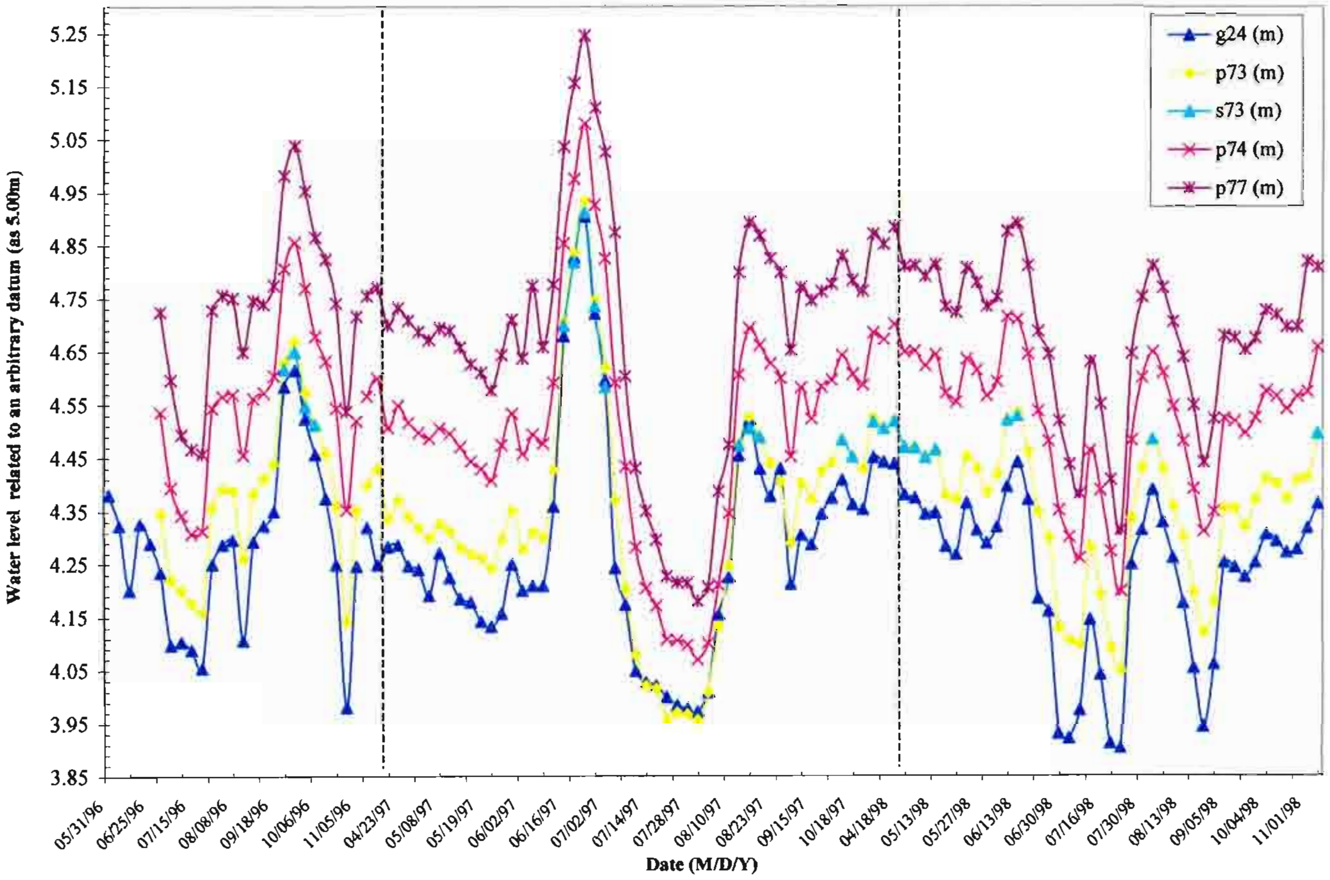

Figure C-28. Water levels at site 35 along the transect 24 (T24-S35).

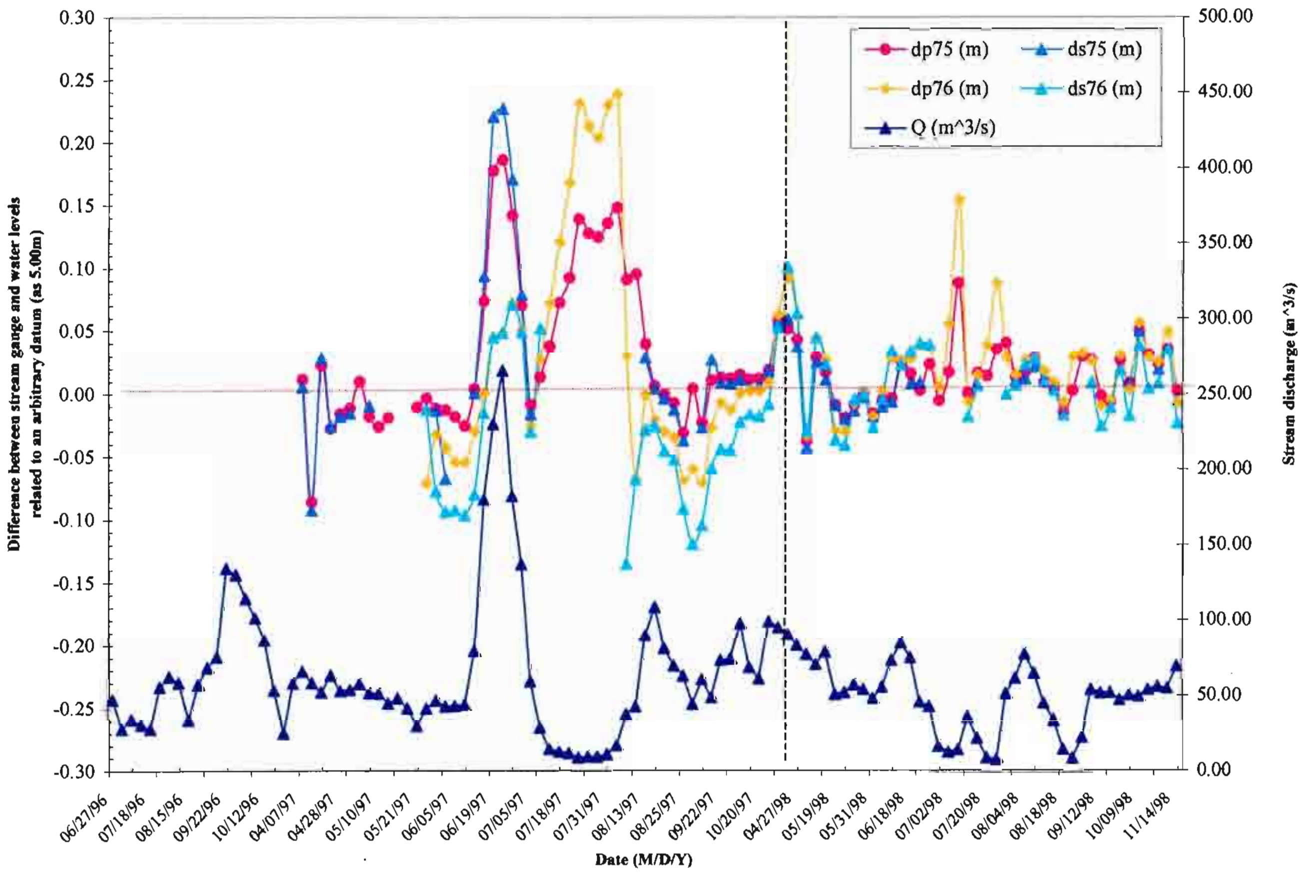

Figure C-29 (a). Differences between stream gauge and water levels at site 36 and site 37 along the transect 25 (T25-S36 & S37).

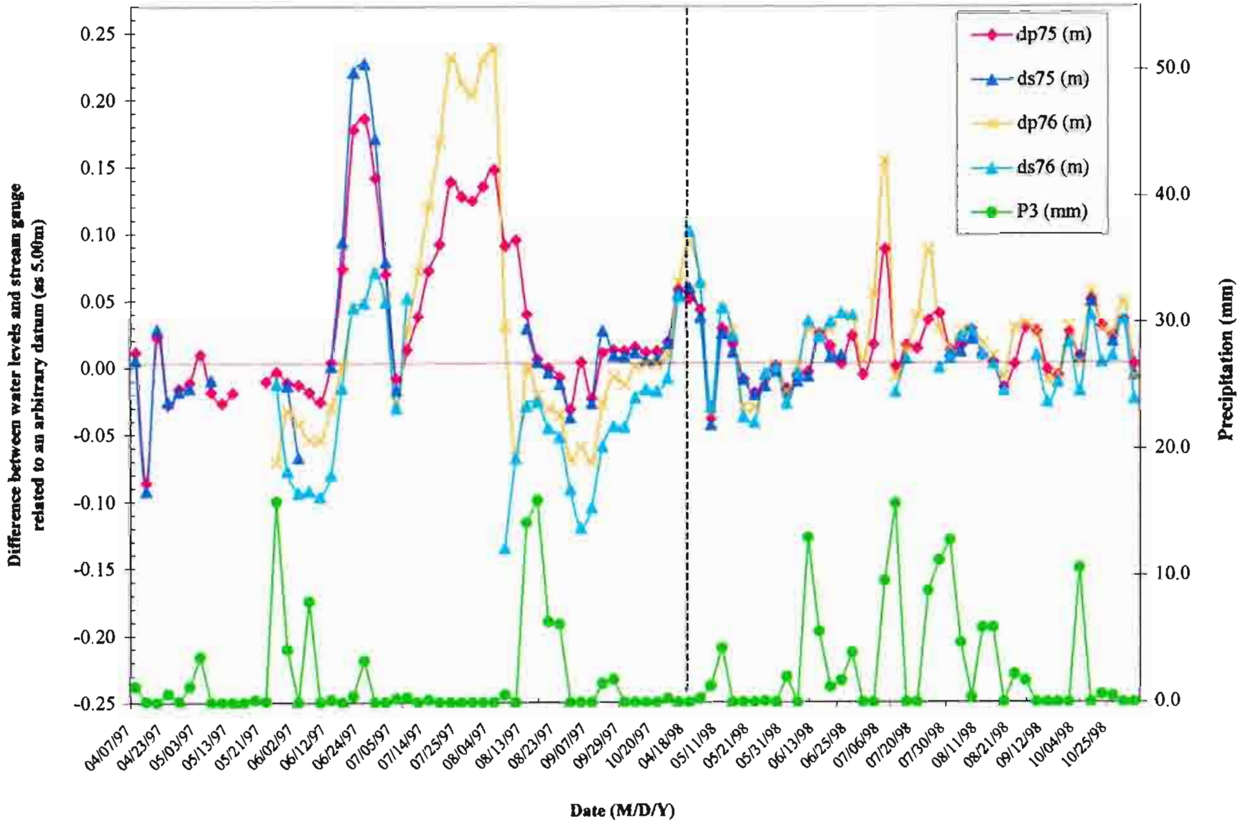

Figure C-29 (b). Precipitation and differences between stream gauge and water levels at site 36 and site 37 along the transect 25 (T25-S36 & S37).

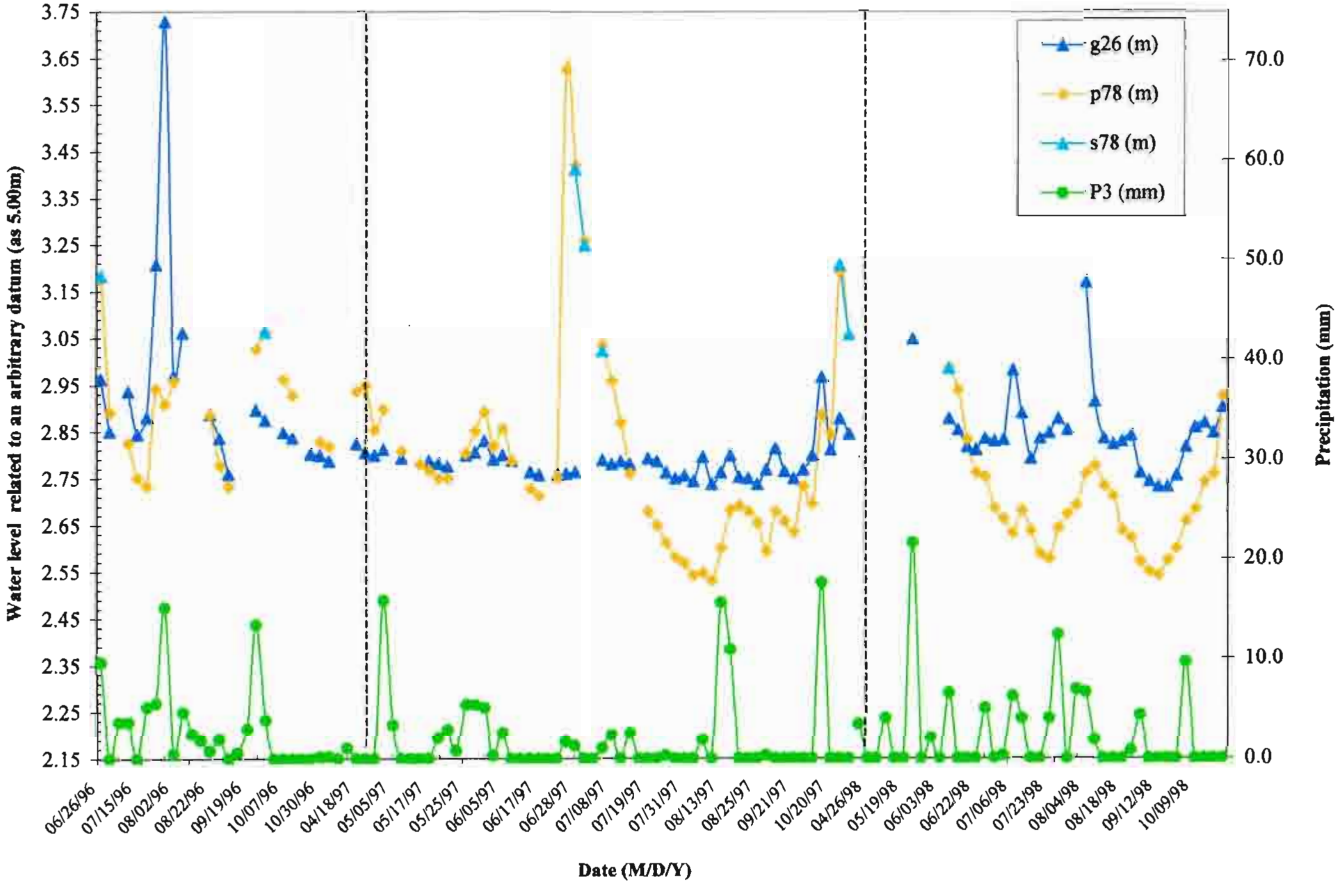

Figure C-30. Precipitation and water levels at site 38 and site 39 along the transect 26 (T26-S38 & S39).

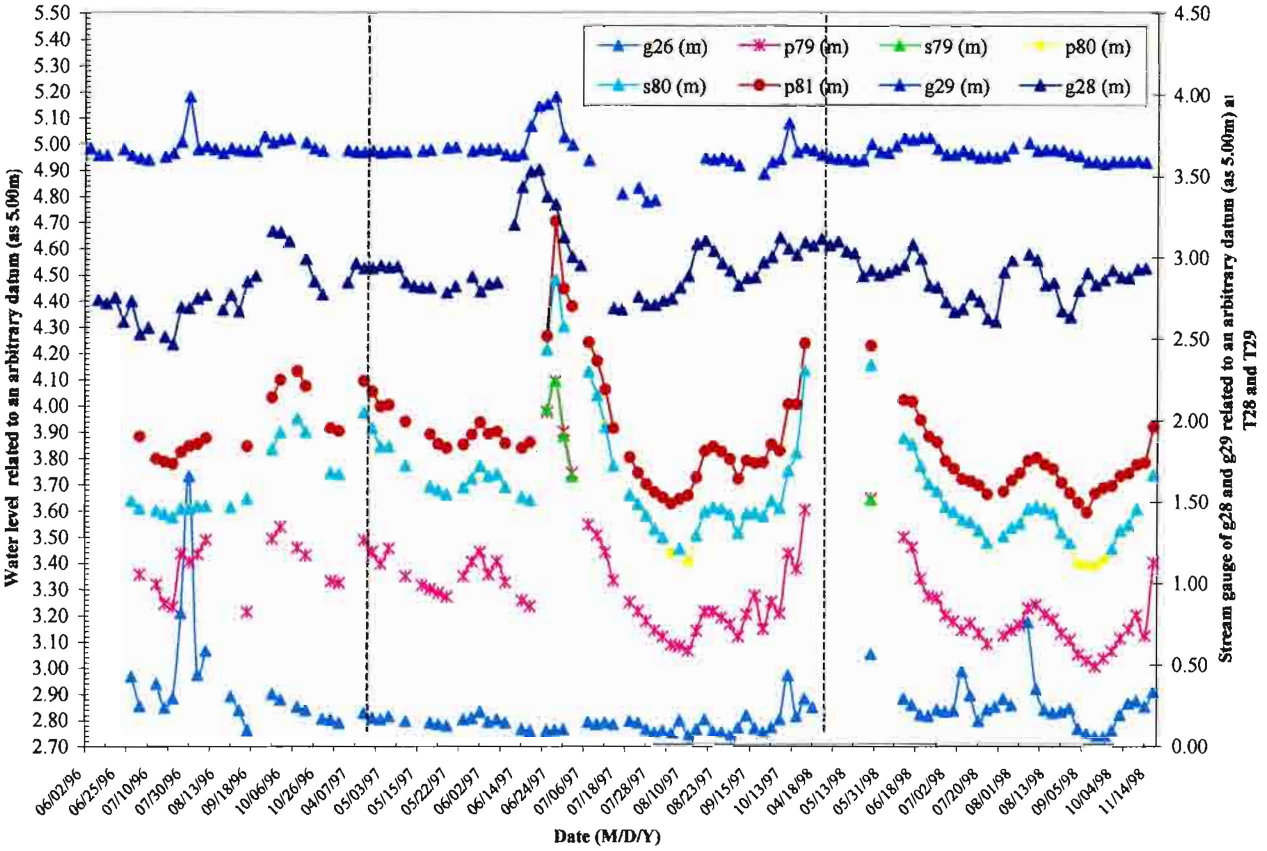

Figure C-31. Water levels at site 40 along the transect 27 (T27-S40), and comparing with stream gauge changes at transect 28 and 29.

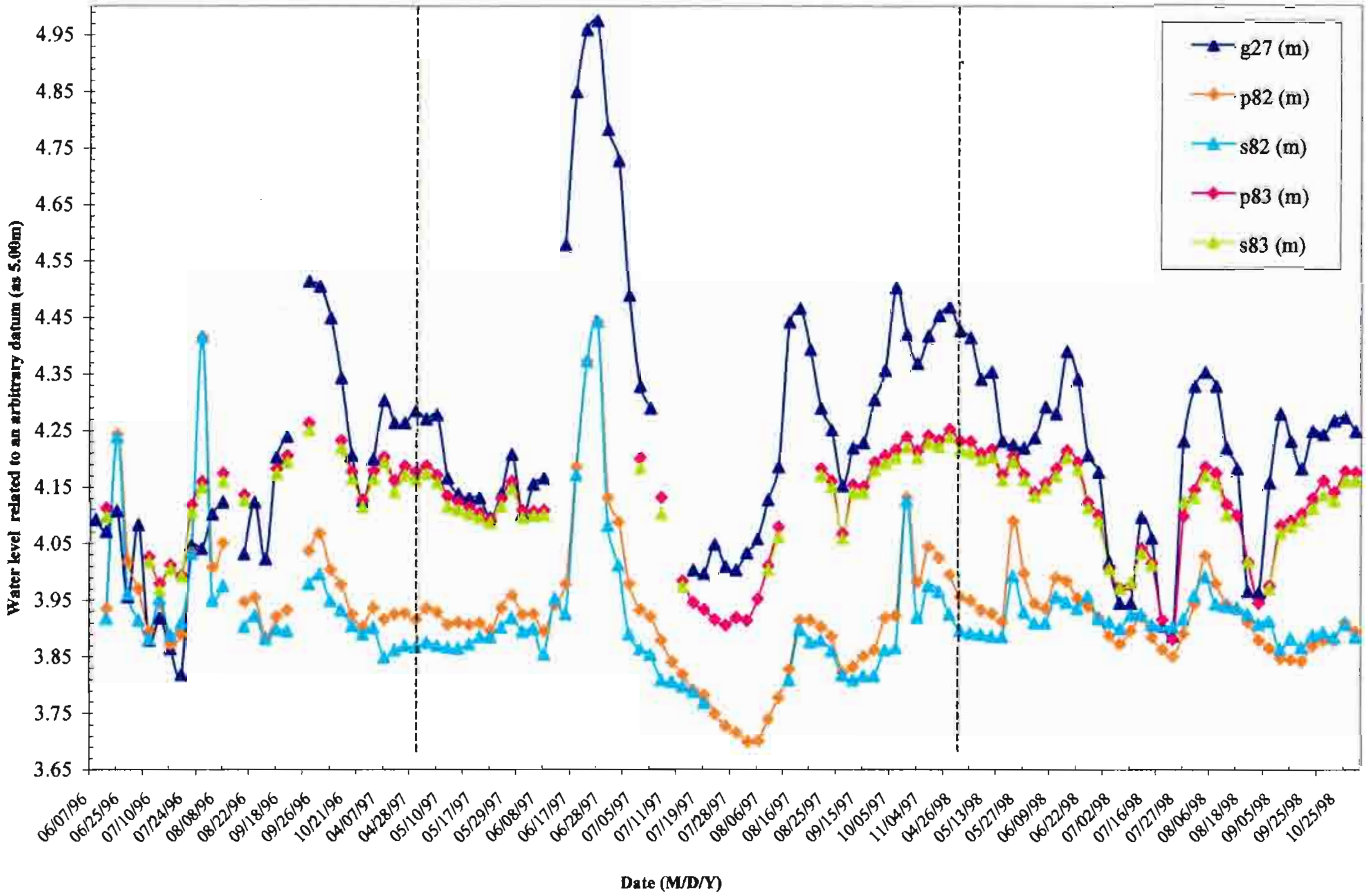

Figure C-32. Water levels at site 41 and site 42 along the transect 28 (T28-S41 & S42).

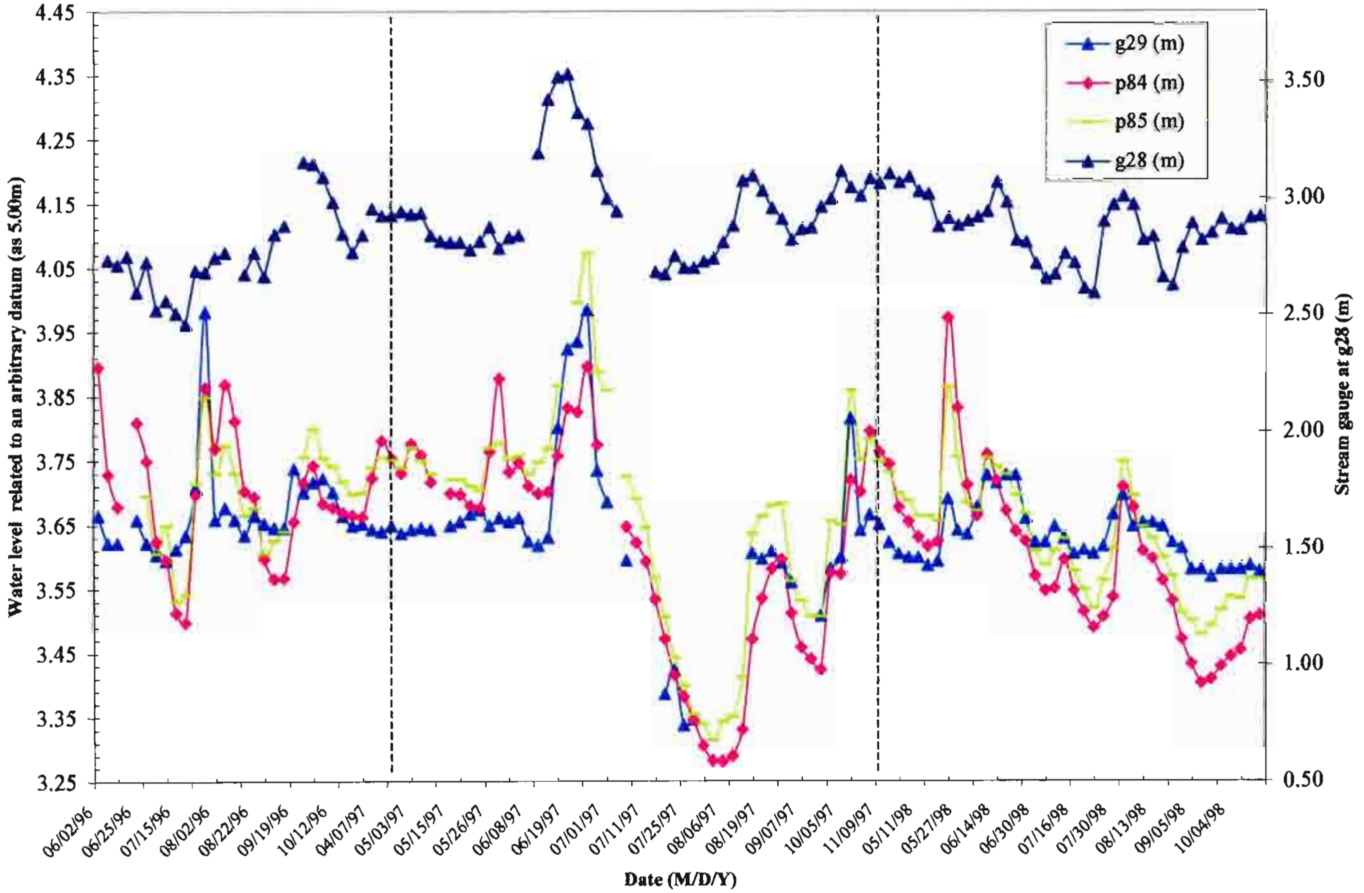

Figure C-33 (a). Water levels at site 43 along the transect 29 (T29-S43), and comparing with main channel water level changes at transect 28.

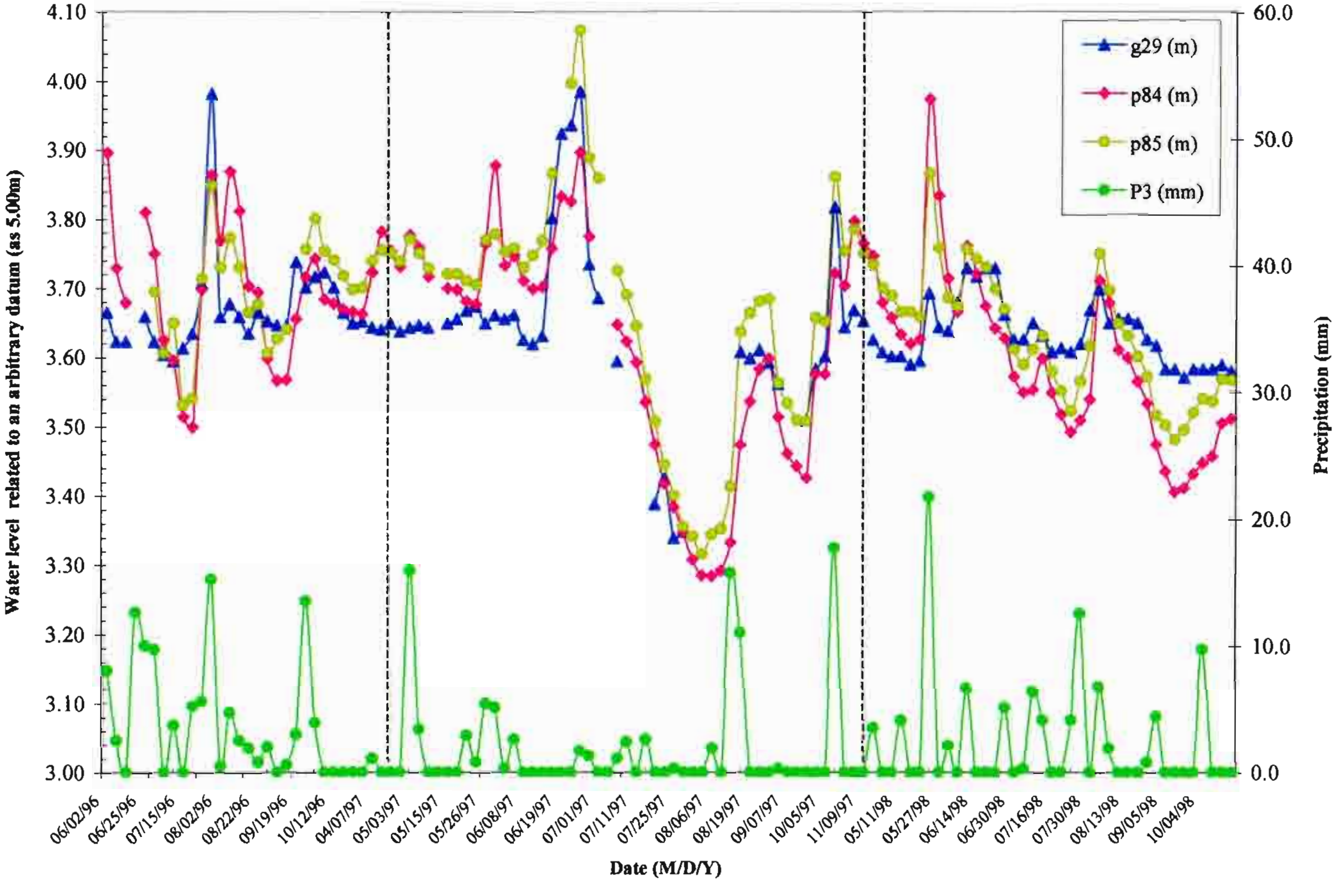

Figure C-33 (b). Precipitation and water levels at site 43 along the transect 29 (T29-S43).

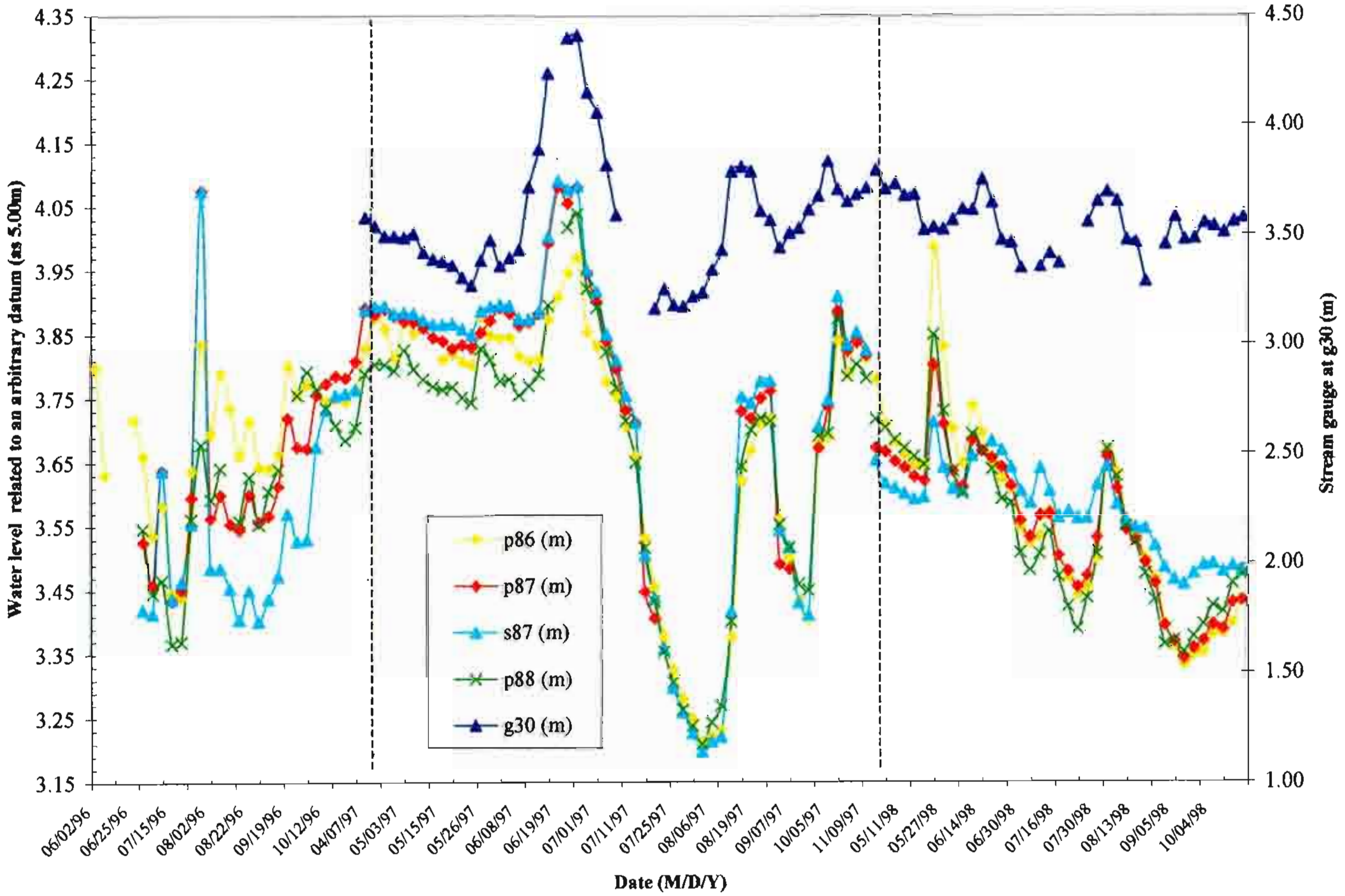

Figure C-34 (a). Water levels at site 44 along the transect 30 (T30-S44), and comparing with stream water level changes at transect 30.

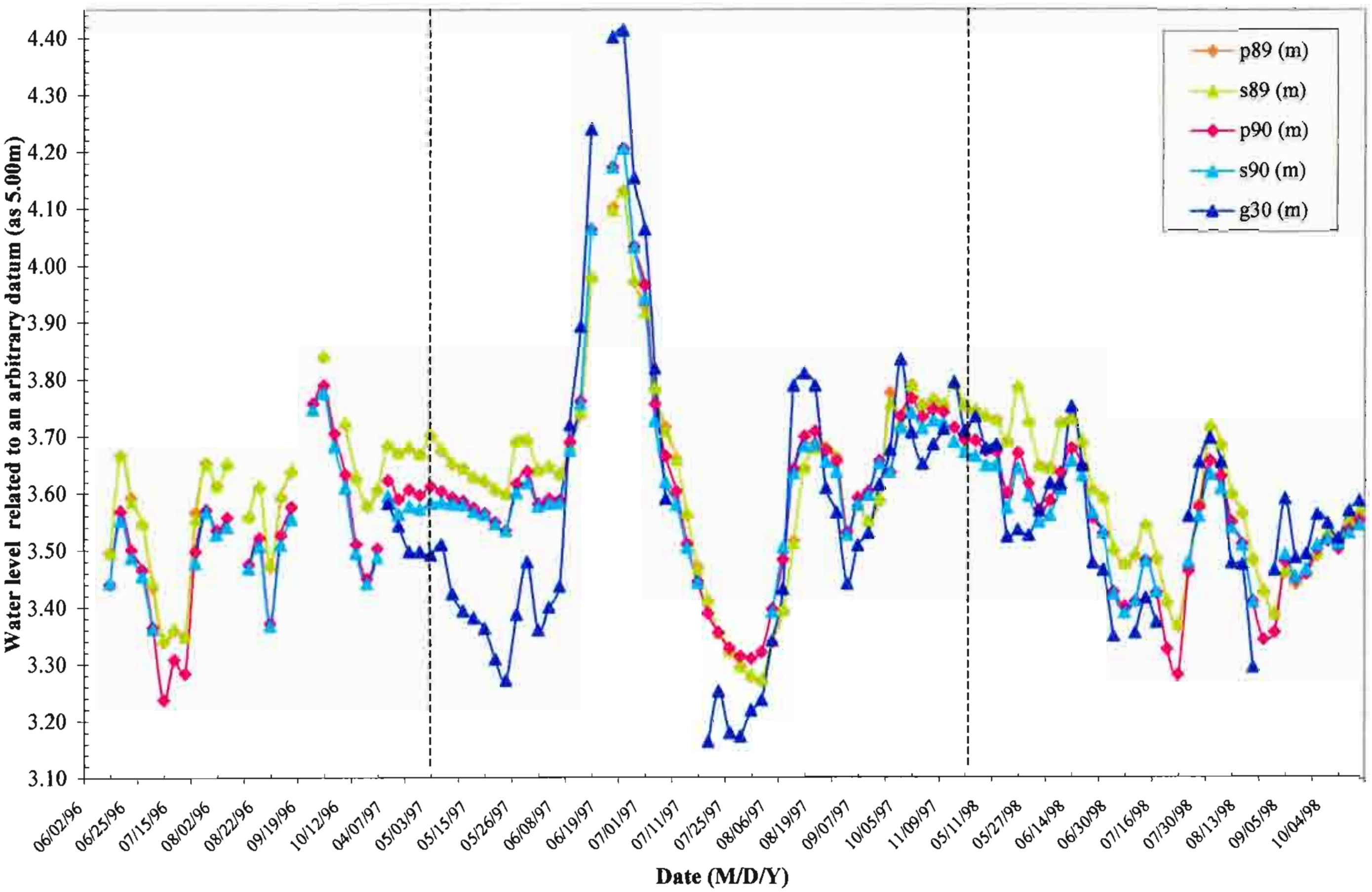

Figure C-34 (b). Water levels at site 45, 46, and 47 along the transect 30 (T30-S45, S46, and S47), and comparing with stream water level changes at transect 30.

Appendix D:

Results of Statistical Analyses

Habitat Class Type and ID

Habitat Type	**ID**	**Habitat Subtype**	**ID**
Main channel (MC)	0	Sandbar; braided stream	0
Side-channel (SC)	1	Side-channel (SC)	11
		Tributary (TB)	12
Backwater (BW)	2	Connected Backwater (CB)	21
		Disconnected Backwater (DB)	22
Slough (SL)	3	Permanent Slough (PS)	31
		Intermittent Slough (IS)	32
Pond (PN)	4	Riparian Pond (RP)	41
		Wet Meadow Pond (WP)	42

Table D-1. Correlation analyses between monitoring sites and stream gauges

Habitat Class	Transect Site ID	Obsv. Well ID	by Variable	Kendall's (*t*)	Prob>|*t*|
31	T01-S01	**p01 (m)**	**g01 (m)**	0.4471	<.0001
31	T01-S01	**s01 (m)**	**g01 (m)**	0.1871	0.0194
22	T01-S03	**p06 (m)**	**g02 (m)**	0.8089	0.0000
22	T01-S03	**s06 (m)**	**g02 (m)**	0.7156	<.0001
21	T02-S04	**p09 (m)**	**g03 (m)**	0.8788	0.0000
21	T02-S04	**s09 (m)**	**g03 (m)**	0.7981	<.0001
21	T02-S05	**p10 (m)**	**g04 (m)**	0.8918	0.0000
21	T02-S05	**s10 (m)**	**g04 (m)**	0.8348	<.0001
32	T31-S06	**p11 (m)**	**g04 (m)**	0.5856	<.0001
32	T31-S06	**s11 (m)**	**g04 (m)**	*0.0741*	*0.8016*
32	T31-S06	**p12 (m)**	**g04 (m)**	0.3588	0.0046
32	T31-S06	**s12 (m)**	**g04 (m)**	0.4021	0.0445
42	T32-S49	**p13 (m)**	**g04 (m)**	0.7893	<.0001
42	T32-S49	**s13 (m)**	**g04 (m)**	*0.2029*	*0.4582*
21	T32-S50	**p14 (m)**	**g04 (m)**	0.7204	<.0001
21	T32-S50	**s14 (m)**	**g04 (m)**	0.8377	<.0001
31	T03-S07	**p16 (m)**	**g06 (m)**	0.3054	<.0001
31	T03-S07	**s16 (m)**	**g06 (m)**	*0.0873*	*0.1940*
22	T04-S08	**p19 (m)**	**g08 (m)**	0.8926	0.0000
22	T04-S08	**s19 (m)**	**g08 (m)**	0.7908	0.0000
32	T04-S09	**p20 (m)**	**g08 (m)**	0.5659	0.0000
32	T04-S09	**s20 (m)**	**g08 (m)**	0.3807	0.0004
31	T05-S10	**p22 (m)**	**g08 (m)**	0.4303	<.0001
31	T05-S10	**s22 (m)**	**g08 (m)**	0.3450	<.0001
41	T06-S12	**p24 (m)**	**g08 (m)**	0.3263	<.0001
41	T06-S12	**s24 (m)**	**g08 (m)**	0.4058	0.0370
21	T07-S13	**p26 (m)**	**g10 (m)**	0.8187	0.0000
21	T07-S13	**s26 (m)**	**g10 (m)**	0.7575	0.0000
21	T07-S14	**p27 (m)**	**g10 (m)**	0.7127	0.0000
21	T07-S14	**s27 (m)**	**g10 (m)**	0.6671	0.0000
22	T08-S15	**p29 (m)**	**g11 (m)**	0.8257	0.0000
22	T08-S15	**s29 (m)**	**g11 (m)**	0.6274	<.0001
21	T09-S16	**p31 (m)**	**g12 (m)**	0.8361	0.0000
21	T09-S16	**s31 (m)**	**g12 (m)**	0.6982	0.0000
21	T10-S17	**p32 (m)**	**g13 (m)**	0.7774	0.0000
21	T10-S17	**s32 (m)**	**g13 (m)**	0.6469	<.0001
21	T10-S18	**p33(m)**	**g13 (m)**	0.8919	0.0000
21	T10-S18	**s33 (m)**	**g13 (m)**	0.8422	0.0000
12	T11-S19	**p34 (m)**	**g14 (m)**	0.7703	0.0000
12	T11-S19	**s34 (m)**	**g14 (m)**	0.7522	0.0000
42	T11-S20	**p36 (m)**	**g14 (m)**	0.5811	0.0000
42	T11-S20	**s36 (m)**	**g14 (m)**	0.5742	0.0002
11	T12-S21	**p39 (m)**	**g15 (m)**	0.7806	<.0001
11	T12-S21	**s39 (m)**	**g15 (m)**	0.6626	<.0001
41	T12-S22	**p38 (m)**	**g15 (m)**	0.3075	0.0080
41	T12-S22	**s38 (m)**	**g15 (m)**	0.2471	0.0342

Table D-1. Correlation analyses between monitoring sites and stream gauges (continuous)

41	T12-S23	**p37 (m)**	**g15 (m)**	0.5796	<.0001
41	T12-S23	**s37 (m)**	**g15 (m)**	*0.2094*	*0.3162*
11	T13-S24	**p40 (m)**	**g16 (m)**	0.6682	<.0001
11	T13-S24	**s40 (m)**	**g16 (m)**	0.8044	<.0001
22	T14-S25	**p41 (m)**	**g17 (m)**	0.8213	0.0000
22	T14-S25	**s41 (m)**	**g17 (m)**	0.6819	<.0001
22	T15-S26	**p42 (m)**	**g17 (m)**	0.7484	0.0000
22	T15-S26	**s42 (m)**	**g17 (m)**	0.7004	<.0001
32	T17-S28	**p51 (m)**	**g17 (m)**	0.6761	<.0001
32	T17-S28	**s51 (m)**	**g17 (m)**	0.5482	<.0001
31	T18-S29	**p54 (m)**	**g17 (m)**	0.5617	<.0001
31	T18-S29	**s54 (m)**	**g17 (m)**	0.2518	<.0001
21	T19-S30	**p56 (m)**	**g19 (m)**	0.8365	<.0001
21	T19-S30	**s56 (m)**	**g19 (m)**	0.6495	0.0009
21	T20-S31	**p59 (m)**	**g20 (m)**	0.9344	0.0000
21	T20-S31	**s59 (m)**	**g20 (m)**	0.8640	0.0000
11	T21-S32	**p60 (m)**	**g21 (m)**	0.8831	0.0000
11	T21-S32	**s60 (m)**	**g21 (m)**	0.8459	0.0000
11	T21-S32	**p61 (m)**	**g21 (m)**	0.6943	0.0000
11	T21-S32	**s61 (m)**	**g21 (m)**	0.8617	0.0000
11	T21-S32	**p62 (m)**	**g21 (m)**	0.7313	0.0000
11	T21-S32	**s62 (m)**	**g21 (m)**	0.7548	0.0000
11	T22-S33	**p65 (m)**	**g22 (m)**	0.9400	0.0000
11	T22-S33	**s65 (m)**	**g22 (m)**	0.9212	0.0000
11	T22-S33	**p68 (m)**	**g22 (m)**	0.9511	0.0000
11	T22-S33	**s68 (m)**	**g22 (m)**	0.8995	0.0000
21	T23-S34	**p71 (m)**	**g23 (m)**	0.9070	0.0000
21	T23-S34	**s71 (m)**	**g23 (m)**	0.6888	<.0001
21	T24-S35	**p73 (m)**	**g24 (m)**	0.8978	0.0000
21	T24-S35	**s73 (m)**	**g24 (m)**	0.7918	<.0001
22	T25-S36	**p75 (m)**	**g25 (m)**	0.9104	0.0000
22	T25-S36	**s75 (m)**	**g25 (m)**	0.8561	0.0000
11	T25-S37	**p76 (m)**	**g25 (m)**	0.8729	0.0000
11	T25-S37	**s76 (m)**	**g25 (m)**	0.7515	0.0000
32	T26-S39	**p78 (m)**	**g29 (m)**	0.4754	<.0001
32	T26-S39	**s78 (m)**	**g29 (m)**	*0.2546*	*0.3828*
42	T27-S40	**p80 (m)**	**g29 (m)**	0.4486	<.0001
42	T27-S40	**s80 (m)**	**g29 (m)**	0.4156	<.0001
12	T28-S41	**p82 (m)**	**g28 (m)**	0.5087	<.0001
12	T28-S41	**s82 (m)**	**g28 (m)**	0.1658	0.0343
21	T28-S42	**p83 (m)**	**g27 (m)**	0.7027	0.0000
21	T28-S42	**s83 (m)**	**g27 (m)**	0.6852	0.0000
12	T30-S44	**p87 (m)**	**g30 (m)**	0.2046	0.0110
12	T30-S44	**s87 (m)**	**g30 (m)**	0.2575	0.0007
41	T30-S45	**p89 (m)**	**g30 (m)**	0.5635	<.0001
41	T30-S45	**s89 (m)**	**g30 (m)**	0.5609	<.0001
21	T30-S46	**p90 (m)**	**g30 (m)**	0.6877	0.0000
21	T30-S46	**s90 (m)**	**g30 (m)**	0.6366	<.0001

Table D-2. Simple linear regression models for riverine habitats by discharge of main channel (listed by transect-site)

Transect-Site	y	b_0	b_1	x	R^2	Adj. R^2	p	n	*Type*
T01-S02	**s01**	3.6033	0.0212	**Sqrt (Q)**	0.1452	0.1364	<.0001	99	31
T01-S02	**p01**	3.2551	0.0584	**Sqrt (Q)**	0.4401	0.4358	<.0001	132	31
T01-S03	**Exp (s06)**	22.4126	2.7660	**Sqrt (Q)**	0.6144	0.6070	<.0001	54	22
T01-S03	**p06**	3.2218	0.0655	**Sqrt (Q)**	0.8059	0.8043	<.0001	124	22
T02-S04	**s09**	2.9772	0.0024	**Q**	0.8391	0.8365	<.0001	63	21
T02-S04	**Exp (p09)**	11.8065	1.3868	**Sqrt (Q)**	0.8904	0.8894	<.0001	114	21
T02-S05	**s10**	3.6644	0.0024	**Q**	0.9234	0.9204	<.0001	27	21
T02-S05	**p10**	3.3898	0.0527	**Sqrt (Q)**	0.9233	0.9222	<.0001	73	21
T02-S48	**g05**			**Q**			>.0500	46	42
T31-S06	**s12**			**Q**			>.0500	56	32
T31-S06	**Exp (p12)**	17.6190	1.0225	**Sqrt (Q)**	0.1715	0.1632	<.0001	102	32
T32-S49	**s13**	2.8937	0.0000	Q^2	0.4334	0.4098	0.0003	26	42
T32-S49	**Exp (p13)**	8.5931	0.8289	**Sqrt (Q)**	0.8627	0.8611	<.0001	85	42
T32-S50	**s14**	2.5050	0.0027	**Q**	0.9125	0.9112	<.0001	73	21
T32-S50	**Exp (p14)**	7.3702	0.8797	**Sqrt (Q)**	0.8327	0.8306	<.0001	85	21
T03-S07	**s16**	3.2496	0.0005	**Q**	0.1088	0.1012	0.0002	120	31
T03-S07	**p16**	3.3124	0.0007	**Q**	0.3205	0.3147	<.0001	120	31
T04-S08	**s19**	3.6248	0.0537	**Sqrt (Q)**	0.7547	0.7524	<.0001	109	22
T04-S08	**p19**	3.5267	0.0622	**Sqrt (Q)**	0.8922	0.8913	<.0001	131	22
T04-S09	**s20**			**Q**			>.0500	44	32
T04-S09	**p20**	3.6568	0.0028	**Q**	0.2896	0.2834	<.0001	117	32
T05-S10	**s22**	3.4100	0.0006	**Q**	0.1433	0.1341	0.0002	96	31
T05-S10	**p22**	3.4373	0.0008	**Q**	0.2249	0.2167	<.0001	96	31
T06-S11	**g09**	3.7407	0.0005	**Q**	0.1400	0.1336	<.0001	137	31
T06-S11	**p23**	3.7207	0.0006	**Q**	0.1533	0.1474	<.0001	144	31
T06-S12	**s24**			**Q**			>.0500	15	41
T06-S12	**p24**	3.7426	0.0014	**Q**	0.1458	0.1390	<.0001	127	41
T07-S13	**Exp (s26)**	26.7572	1.4650	**Sqrt (Q)**	0.8430	0.8417	<.0001	116	21
T07-S13	**Exp (p26)**	20.5221	1.9974	**Sqrt (Q)**	0.9146	0.9139	<.0001	125	21
T07-S14	**Exp (s27)**	21.5042	1.7440	**Sqrt (Q)**	0.7468	0.7445	<.0001	113	22
T07-S14	**Exp (p27)**	19.7142	1.9215	**Sqrt (Q)**	0.8019	0.8003	<.0001	125	22
T08-S15	**s29**	4.2244	0.0549	**Sqrt (Q)**	0.6923	0.6840	<.0001	39	22
T08-S15	**p29**	4.0572	0.0651	**Sqrt (Q)**	0.8928	0.8919	<.0001	117	22
T09-S16	**Exp (s31)**	29.5634	5.8459	**Sqrt (Q)**	0.8220	0.8200	<.0001	91	21
T09-S16	**p31**	3.6315	0.0808	**Sqrt (Q)**	0.8733	0.8722	<.0001	125	21
T10-S17	**s32**	4.4785	0.0030	**Q**	0.7767	0.7737	<.0001	77	21
T10-S17	**p32**	4.5316	0.0025	**Q**	0.6864	0.6838	<.0001	120	21
T10-S18	**s33**	4.6384	0.0031	**Q**	0.8683	0.8670	<.0001	106	21
T10-S18	**p33**	4.2600	0.0674	**Sqrt (Q)**	0.9089	0.9081	<.0001	121	21
T11-S19	**s34**						>.0500	85	12
T11-S19	**p34**						>.0500	126	12
T11-S20	**s35**						>.0500	6	42
T11-S20	**p35**						>.0500	113	42
T12-S21	**Exp (s39)**	67.7281	7.1160	**Sqrt (Q)**	0.8263	0.8237	<.0001	69	11
T12-S21	**Exp (p39)**	68.3999	6.9668	**Sqrt (Q)**	0.8435	0.8416	<.0001	82	11

Table D-2. Simple linear regression models for riverine habitats by discharge of main channel (listed by transect-site) (continuous)

T12-S22 (1997)	**s38**	4.2715	0.0120	**Sqrt (Q)**	0.6367	0.6249	<.0001	33	91
T12-S22 (1997)	**p38**	4.2412	0.0142	**Sqrt (Q)**	0.6954	0.6856	<.0001	33	91
T12-S22 (1998)	**s38**	4.1151	0.0004	**Q**	0.1175	0.0948	0.0283	41	91
T12-S22 (1998)	**p38**	4.1204	0.0005	**Q**	0.1889	0.1681	0.0045	41	91
T12-S23	**s37**						>.0500	38	41
T12-S23	**p37**	4.2073	0.0300	**Sqrt (Q)**	0.2103	0.2030	<.0001	109	41
T13-S24	**s40**	4.1957	0.0519	**Sqrt (Q)**	0.8955	0.8914	<.0001	28	11
T13-S24	**p40**	4.3653	0.0029	**Q**	0.9122	0.9108	<.0001	66	11
T14-S25	**s41**	4.6481	0.0372	**Sqrt (Q)**	0.6688	0.6625	<.0001	55	22
T14-S25	**Exp (p41)**	81.5174	6.4944	**Sqrt (Q)**	0.7840	0.7811	<.0001	77	22
T15-S26	**Exp (s42)**	41.0972	2.2279	**Sqrt (Q)**	0.6465	0.6431	<.0001	106	22
T15-S26	**Exp (p42)**	40.5207	2.3996	**Sqrt (Q)**	0.6569	0.6538	<.0001	113	22
T17-S28	**Exp (s51)**	32.8971	1.7194	**Sqrt (Q)**	0.3425	0.3313	<.0001	61	31
T17-S28	**Exp (p51)**	23.8867	2.2115	**Sqrt (Q)**	0.4799	0.4749	<.0001	108	31
T18-S29	**S54**						>.0500	74	31
T18-S29	**p54**						>.0500	97	31
T19-S30	**s56**	4.4980	0.0023	**Q**	0.9292	0.9258	<.0001	23	21
T19-S30	**p56**	4.1610	0.0586	**Sqrt (Q)**	0.9454	0.9437	<.0001	34	21
T20-S31	**Exp (s59)**	10.6161	1.6441	**Sqrt (Q)**	0.9251	0.9238	<.0001	60	21
T20-S31	**Exp (p59)**	11.1100	1.5802	**Sqrt (Q)**	0.9182	0.9171	<.0001	75	21
T21-S32	**s60**	2.6702	0.0739	**Sqrt (Q)**	0.9592	0.9585	<.0001	64	11
T21-S32	**Exp (p60)**	8.1016	2.3006	**Sqrt (Q)**	0.9595	0.9590	<.0001	78	11
T22-S33	**s68**	2.3947	0.0547	**Sqrt (Q)**	0.9271	0.9260	<.0001	69	11
T22-S33	**Exp (p68)**	8.2805	1.1154	**Sqrt (Q)**	0.9437	0.9429	<.0001	76	11
T23-S34 (1997)	**s71**	3.9038	0.0000	Q^2	0.9419	0.9401	<.0001	33	21
T23-S34 (1997)	**p71**	3.4180	0.0612	**Sqrt (Q)**	0.9489	0.9482	<.0001	75	21
T23-S34 (1998)	**s71**	3.8644	0.0034	**Q**	0.7931	0.7867	<.0001	34	21
T23-S34 (1998)	**p71**	3.6282	0.0575	**Sqrt (Q)**	0.9271	0.9253	<.0001	42	21
T24-S35	**s73**	4.2969	0.0023	**Q**	0.9548	0.9528	<.0001	25	21
T24-S35	**Exp (p73)**	36.7697	5.7178	**Sqrt (Q)**	0.9518	0.9514	<.0001	113	21
T25-S36	**s75**	4.5804	0.0459	**Sqrt (Q)**	0.8560	0.8538	<.0001	68	21
T25-S36	**Exp (p75)**	65.7949	9.0704	**Sqrt (Q)**	0.9379	0.9373	<.0001	111	21
T25-S37	**Exp (s76)**	67.0184	9.6238	**Sqrt (Q)**	0.9467	0.9458	<.0001	65	11
T25-S37	**Exp (p76)**	56.7872	10.5410	**Sqrt (Q)**	0.9589	0.9584	<.0001	80	11
T26-S38	**g26**						>.0500	96	12
T26-S39	**s78**						>.0500	8	32
T26-S39	**p78**	2.6761	0.0018	**Q**	0.2217	0.2134	<.0001	96	32
T27-S40	**Exp (s80)**	34.6330	0.1095	**Q**	0.3131	0.3050	<.0001	86	42
T27-S40	**Exp (p80)**	33.6353	0.1133	**Q**	0.3087	0.3010	<.0001	92	42
T28-S41	**Exp (s82)**	48.5163	0.0004	Q^2	0.4533	0.4482	<.0001	109	12
T28-S41	**p82**	3.8276	0.0017	**Q**	0.4390	0.4341	<.0001	116	12
T28-S42	**Exp (s83)**	45.5189	2.2966	**Sqrt (Q)**	0.7410	0.7378	<.0001	84	21
T28-S42	**Exp (p83)**	42.1458	2.8114	**Sqrt (Q)**	0.7952	0.7930	<.0001	95	21
T29-S43	**g29**	3.5738	0.0011	**Q**	0.3518	0.3456	<.0001	107	12
T30-S44	**Exp (s87)**	28.2943	1.4580	**Sqrt (Q)**	0.2281	0.2212	<.0001	114	12

Table D-3. Multiple linear regression models for water levels in riverine habitats (listed by transect-site)

Transect-Site	*y*	b_0	b_1	x_1	b_2	x_2	b_3	x_3	R^2	*Adj.* R^2	*p*	*n*	***Type***
T01-S02	**s01**	3.7517	0.0141	**Sqrt (Q)**	-0.0071	$\mathbf{T_4}$	0.0107	$\mathbf{P_4}$	0.4636	0.4467	<.0001	99	31
T01-S02	**p01**	3.6088	0.0400	**Sqrt (Q)**	-0.0131	$\mathbf{T_4}$	0.0144	$\mathbf{P_4}$	0.6454	0.6371	<.0001	132	31
T01-S03	**Exp (s06)**	23.5686	3.1386	**Sqrt (Q)**	-0.3015	$\mathbf{T_4}$			0.7120	0.7007	<.0001	54	22
T01-S03	**p06**	3.3691	0.0612	**Sqrt (Q)**	-0.0060	$\mathbf{T_4}$			0.8528	0.8503	<.0001	124	22
T02-S04	**s09**	2.9794	0.0025	**Q**	-0.0029	$\mathbf{P_3}$			0.8612	0.8566	<.0001	63	21
T02-S04	**Exp (p09)**	11.6783	1.4293	**Sqrt (Q)**	-0.0828	$\mathbf{P_4}$			0.9002	0.8984	<.0001	114	21
T02-S05	**s10**	3.6898	0.0026	**Q**	-0.0028	$\mathbf{T_3}$			0.9428	0.9380	<.0001	27	21
T02-S05	**p10**	3.6796	0.0028	**Q**	-0.0033	$\mathbf{T_4}$	-0.0022	$\mathbf{P_4}$	0.9407	0.9381	<.0001	73	21
T02-S48	**g05**			**Q**							>.0500	46	42
T31-S06	**s12**	2.3975	0.3847	**p12**					0.4816	0.4720	<.0001	56	32
T31-S06	**Exp (p12)**	18.1848	0.7592	**Sqrt (Q)**	0.6098	$\mathbf{P_4}$			0.3305	0.3170	<.0001	102	32
T32-S49	**s13**	2.8937	0.0000	$\mathbf{Q^2}$					0.4334	0.4098	0.0003	26	42
T32-S49	**Exp (p13)**	7.7056	0.8305	**Sqrt (Q)**	0.1585	$\mathbf{ET_4}$			0.8794	0.8765	<.0001	85	42
T32-S50	**s14**	2.5050	0.0027	**Q**					0.9125	0.9112	<.0001	73	21
T32-S50	**Exp (p14)**	6.3533	0.8816	**Sqrt (Q)**	0.1818	**ET4**			0.8515	0.8479	<.0001	85	21
T03-S07	**s16**	3.2496	0.0005	**Q**					0.1088	0.1012	0.0002	120	31
T03-S07	**p16**	3.3417	0.0007	**Q**	-0.0014	**T**			0.3498	0.3387	<.0001	120	31
T04-S08	**s19**	3.6829	0.0544	**Sqrt (Q)**	-0.0037	$\mathbf{T_3}$			0.7948	0.7909	<.0001	109	22
T04-S08	**p19**	3.6096	0.0597	**Sqrt (Q)**	-0.0034	**T**			0.9129	0.9116	<.0001	131	22
T04-S09	**s20**	4.3287	-0.0128	**T**					0.3343	0.3185	<.0001	44	32
T04-S09	**p20**	3.9793	0.0019	**Q**	-0.0163	$\mathbf{T_4}$	0.0149	$\mathbf{P_4}$	0.5591	0.5474	<.0001	117	32
T05-S10	**s22**	3.5093	0.0005	**Q**	-0.0046	$\mathbf{T_4}$			0.2841	0.2688	<.0001	96	31
T05-S10	**p22**	3.5661	0.0006	**Q**	-0.0059	$\mathbf{T_4}$			0.4588	0.4471	<.0001	96	31
T06-S11	**g09**	3.7353	0.0004	**Q**	0.0051	$\mathbf{P_4}$			0.2616	0.2506	<.0001	137	31
T06-S11	**p23**	3.7508	0.0004	**Q**	-0.0018	$\mathbf{T_4}$	0.0059	$\mathbf{P_4}$	0.2766	0.2611	<.0001	144	31

Table D-3. Multiple linear regression models for water levels in riverine habitats (listed by transect-site) (Continuous)

T06-S12	**s24**										>.0500	15	41
T06-S12	**p24**	3.9958	-0.0101	**T_4**	0.0133	**P_4**			0.2631	0.2512	<.0001	127	41
T07-S13	**Exp (s26)**	28.4952	1.4208	**Sqrt (Q)**	-0.0758	**T_4**			0.8614	0.8589	<.0001	116	21
T07-S13	**Exp (p26)**	22.3388	1.9405	**Sqrt (Q)**	-0.0735	**T_4**			0.9227	0.9214	<.0001	125	21
T07-S14	**Exp (s27)**	24.6089	1.6726	**Sqrt (Q)**	-0.1384	**T_4**			0.7834	0.7795	<.0001	113	22
T07-S14	**Exp (p27)**	23.1596	1.8127	**Sqrt (Q)**	-0.1376	**T_4**			0.8258	0.8229	<.0001	125	22
T08-S15	**s29**	4.2339	0.0593	**Sqrt (Q)**	-0.0034	**T**			0.7324	0.7175	<.0001	39	22
T08-S15	**p29**	4.1093	0.0635	**Sqrt (Q)**	-0.0018	**T**	-0.0027	**P**	0.9056	0.9031	<.0001	117	22
T09-S16	**Exp (s31)**	28.2653	6.1459	**Sqrt (Q)**	-0.4800	**P_4**			0.8393	0.8357	<.0001	91	21
T09-S16	**p31**	3.7074	0.0812	**Sqrt (Q)**	-0.0034	**T**	-0.0051	**P_4**	0.8959	0.8933	<.0001	125	21
T10-S17	**s32**	4.5681	0.0030	**Q**	-0.0047	**T**	-0.0038	**P_3**	0.8359	0.8292	<.0001	77	21
T10-S17	**p32**	4.5941	0.0026	**Q**	-0.0029	**T**	-0.0038	**P_4**	0.7229	0.7158	<.0001	120	21
T10-S18	**s33**	4.7052	0.0032	**Q**	-0.0036	**T**	-0.0029	**P_4**	0.9130	0.9104	<.0001	106	21
T10-S18	**p33**	4.3084	0.0679	**Sqrt (Q)**	-0.0022	**T**	-0.0039	**P_4**	0.9242	0.9223	<.0001	121	21
T11-S19	**s34**										>.0500	85	12
T11-S19	**p34**										>.0500	126	12
T11-S20	**s35**										>.0500	6	42
T11-S20	**p35**										>.0500	113	42
T12-S21	**Exp (s39)**	58.4352	6.9952	**Sqrt (Q)**	0.6114	**P_4**	1.5214	**ET_4**	0.8610	0.8545	<.0001	69	11
T12-S21	**Exp (p39)**	57.6750	6.8471	**Sqrt (Q)**	0.6475	**P_4**	1.7696	**ET_4**	0.8769	0.8722	<.0001	82	11
T12-S22 (1997)	**s38**	4.3343	0.0109	**Sqrt (Q)**	-0.0028	**T**			0.8145	0.8021	<.0001	33	91
T12-S22 (1997)	**p38**	4.3050	0.0131	**Sqrt (Q)**	0.0028	**T**			0.8390	0.8283	<.0001	33	91
T12-S22 (1998)	**s38**	4.1906	-0.0027	**T**					0.3688	0.3527	<.0001	41	91
T12-S22 (1998)	**p38**	4.1956	-0.0026	**T**	0.0010	**P_4**			0.4130	0.3821	<.0001	41	91

Table D-3. Multiple linear regression models for water levels in riverine habitats (listed by transect-site) (Continuous)

T12-S23	**s37**	4.5247	0.0141	**P_4**					0.3013	0.2819	0.0004	38	41
T12-S23	**p37**	4.0929	0.0281	**Sqrt (Q)**	0.0156	**P_4**	0.0155	**ET_4**	0.3870	0.3695	<.0001	109	41
T13-S24	**s40**	4.1957	0.0519	**Sqrt (Q)**					0.8955	0.8914	<.0001	28	11
T13-S24	**p40**	4.3653	0.0029	**Q**					0.9122	0.9108	<.0001	66	11
T14-S25	**s41**	4.6481	0.0372	**Sqrt (Q)**					0.6688	0.6625	<.0001	55	22
T14-S25	**Exp (p41)**	80.3737	6.4039	**Sqrt (Q)**	0.6201	**P_4**			0.8042	0.7989	<.0001	77	22
T15-S26	**Exp (s42)**	45.1162	2.1355	**Sqrt (Q)**	-0.1728	**T**			0.6717	0.6654	<.0001	106	22
T15-S26	**Exp (p42)**	44.9836	2.2821	**Sqrt (Q)**	-0.1848	**T**			0.6793	0.6735	<.0001	113	22
T17-S28	**Exp (s51)**	35.4979	1.8539	**Sqrt (Q)**	-0.3085	**T_4**	0.4598	**P_4**	0.5022	0.4760	<.0001	61	31
T17-S28	**Exp (p51)**	29.4555	1.9447	**Sqrt (Q)**	-0.2569	**T_4**	0.4724	**P_4**	0.5748	0.5625	<.0001	108	31
T18-S29	**S54**	3.5796	-0.0045	**T_4**	0.0126	**P_4**			0.4046	0.3878	<.0001	74	31
T18-S29	**p54**	3.6441	-0.0099	**T_4**	0.0143	**P_4**			0.3299	0.3156	<.0001	97	31
T19-S30	**s56**	4.5077	0.0023	**Q**	-0.0031	**P_4**			0.9426	0.9368	<.0001	23	21
T19-S30	**p56**	4.1610	0.0586	**Sqrt (Q)**					0.9454	0.9437	<.0001	34	21
T20-S31	**Exp (s59)**	10.6161	1.6441	**Sqrt (Q)**					0.9251	0.9238	<.0001	60	21
T20-S31	**Exp (p59)**	11.1100	1.5802	**Sqrt (Q)**					0.9182	0.9171	<.0001	75	21
T21-S32	**s60**	2.7242	0.0730	**Sqrt (Q)**	-0.0024	**T**			0.9655	0.9644	<.0001	64	11
T21-S32	**Exp (p60)**	8.1016	2.3006	**Sqrt (Q)**					0.9595	0.9590	<.0001	78	11
T22-S33	**s68**	2.3947	0.0547	**Sqrt (Q)**					0.9271	0.9260	<.0001	69	11
T22-S33	**Exp (p68)**	8.2805	1.1154	**Sqrt (Q)**					0.9437	0.9429	<.0001	76	11
T23-S34 (1997)	**s71**	3.9038	0.0000	**Q^2**					0.9419	0.9401	<.0001	33	21
T23-S34 (1997)	**p71**	3.4180	0.0612	**Sqrt (Q)**					0.9489	0.9482	<.0001	75	21
T23-S34 (1998)	**s71**	3.9329	0.0030	**Q**	-0.0025	**T_4**			0.8286	0.8175	<.0001	34	21
T23-S34 (1998)	**p71**	3.6975	0.0533	**Sqrt (Q)**	-0.0021	**T_4**			0.9341	0.9307	<.0001	42	21

Table D-3. Multiple linear regression models for water levels in riverine habitats (listed by transect-site) (Continuous)

T24-S35	**s73**	4.2969	0.0023	**Q**					0.9548	0.9528	<.0001	25	21
T24-S35	**Exp (p73)**	36.7697	5.7178	**Sqrt (Q)**					0.9518	0.9514	<.0001	113	21
T25-S36	**s75**	4.5804	0.0459	**Sqrt (Q)**					0.8560	0.8538	<.0001	68	21
T25-S36	**Exp (p75)**	65.7949	9.0704	**Sqrt (Q)**					0.9379	0.9373	<.0001	111	21
T25-S37	**Exp (s76)**	67.0184	9.6238	**Sqrt (Q)**					0.9467	0.9458	<.0001	65	11
T25-S37	**Exp (p76)**	56.7872	10.5410	**Sqrt (Q)**					0.9589	0.9584	<.0001	80	11
T26-S38	**g26**										>.0500	96	12
T26-S39	**s78**										>.0500	8	32
T26-S39	**p78**	2.7636	0.0018	**Q**	-0.0050	**T_4**			0.2663	0.2505	<.0001	96	32
T27-S40	**Exp (s80)**	34.6330	0.1095	**Q**					0.3131	0.3050	<.0001	86	42
T27-S40	**Exp (p80)**	33.6353	0.1133	**Q**					0.3087	0.3010	<.0001	92	42
T28-S41	**Exp (s82)**	47.0490	0.0004	**Q^2**	0.6181	**P_4**			0.5696	0.5615	<.0001	109	12
T28-S41	**p82**	3.8276	0.0017	**Q**					0.4390	0.4341	<.0001	116	12
T28-S42	**Exp (s83)**	48.2730	2.1882	**Sqrt (Q)**	-0.1241	**T_4**			0.7828	0.7775	<.0001	84	21
T28-S42	**Exp (p83)**	46.8555	2.5552	**Sqrt (Q)**	-0.1750	**T_4**			0.8392	0.8357	<.0001	95	21
T29-S43	**g29**	3.5738	0.0011	**Q**					0.3518	0.3456	<.0001	107	12
T30-S44	**Exp (s87)**	22.8970	1.4896	**Sqrt (Q)**	0.8759	**ET_3**			0.2875	0.2747	<.0001	114	12
T30-S44	**Exp (p87)**	23.8785	1.4851	**Sqrt (Q)**	0.7299	**ET_3**	0.3071	**P_3**	0.3370	0.3173	<.0001	105	12
T30-S45	**Exp (s89)**	25.5208	2.1387	**Sqrt (Q)**	-1.6446	**log (P)**			0.8081	0.7879	<.0001	22	81
T30-S45	**Exp (p89)**	25.4898	2.1389	**Sqrt (Q)**	-1.6198	**log (P)**			0.8108	0.7909	<.0001	22	81
T30-S46	**s90**	3.5058	0.0026	**Q**	-0.0375	**log (P)**			0.8894	0.8764	<.0001	20	21
T30-S46	**Exp (p90)**	14.9481	2.4909	**Sqrt (Q)**	0.4721	**ET_4**			0.8324	0.8294	<.0001	115	21
T30-S47	**g30**	2.8463	0.0938	**Sqrt (Q)**					0.9302	0.9294	<.0001	84	11