AN ABSTRACT OF THE THESIS OF

Diana E. Sharps for the degree of Master of Science in Civil Engineering presented on December 6, 1996. Title: Spatial and Temporal Characteristics of Groundwater Levels Adjacent to Beaver Ponds in Oregon.

Abstract Approved: Signature redacted for privacy.

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This study was undertaken to evaluate the spatial and temporal characteristics of riparian groundwater tables adjacent to beaver ponds. The research was conducted in two parts; in the first portion a two-dimensional, finite-difference computer model was developed and utilized to simulate groundwater elevations through time in pond-adjacent aquifers. Two types of synthesized riparian settings, inhabited by beaver, were used as model sites: a stable, effluent stream reach located in the humid Coast Range in western Oregon and an incised, influent stream reach located in the semi-arid region east of the Cascade Range in central Oregon. Within the context of regional site parameters a range of input values were used to determine the effects of alternative hydrologic and hydraulic site conditions on groundwater tables. These input data included water level gradients, substrate hydraulic conductivity and storativity values and sources and magnitudes of recharge and discharge. The second part of the investigation was a case study in which groundwater levels next to a beaver pond located within a western Oregon stream reach were monitored from July 1991 through July 1992.

The results from both parts of the study indicated that beaver ponds cause elevated groundwater tables and increase the dimensions of the subsurface saturated soil zone in adjacent riparian areas. The simulation results included small, intermediate and large dimensions of the pond-adjacent saturated wedge per month throughout a one year period for each of the two synthesized riparian aquifer systems. The maximum vertical and lateral extents and the saturated soil and stored groundwater volumes were calculated for each pond-adjacent wedge. The quantitative bounds of the saturated wedge, including all sites and cases, ranged between 0.3 m high and 4 m wide to 1.7 m high and 90 m wide. Similarly, the volume of the pond adjacent saturated soil wedge ranged between 12 and 3500 m^3; the associated volumes of stored groundwater ranged from 0.6 to 700 m^3.

Beaver ponds were found to contribute to greater spatial and temporal hydrologic diversity for riparian groundwater conditions compared to those without pond influences. The magnitude and/or direction of groundwater flow between each pond and adjacent riparian aquifer was influenced by the presence of a pond. These changes occurred in response to a hydraulic differential created by the beaver pond within each groundwater system; the pond caused spreading of subsurface flow, acted as a hydraulic control or induced a combination of both of these conditions and created a localized flow cycling zone between the stream and riparian aquifer. Also, seasonal fluctuations in each pond-adjacent saturated wedge occurred due to climate dependent changes in inflow and outflow rates to and from the aquifer.

Sensitivity analysis indicated that the substrate hydraulic conductivity and the head difference between the pond surface and the stream surface below the dam had the greatest effect on the pond-adjacent groundwater levels. The expansion of the saturated zone was directly proportional to the dam height and to the aquifer transmissivity.

The pond and riparian aquifer interactions demonstrate a significant dimension in the ecology of beaver inhabited streams and should be included in holistic constructs of riverine ecosystems. Elevated pond-adjacent groundwater tables and greater exchange between surface and ground waters can promote vegetation growth and related sediment deposition and channel stability, increase nutrient transformations and biogeochemical pathways, influence soil genesis and morphology, increase biodiversity and create connectivity within the stream-riparian continuum.

Spatial and Temporal Characteristics of Groundwater Levels
Adjacent to Beaver Ponds in Oregon

by

Diana E. Sharps

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SPATIAL AND TEMPORAL CHARACTERISTICS OF GROUNDWATER LEVELS ADJACENT TO BEAVER PONDS IN OREGON

INTRODUCTION

Riparian zones are valuable for a variety of reasons; they can improve water quality, affect streamflow regimes and the extent of flooding, provide diverse habitat for wildlife and other organisms and enhance recreational opportunities. They have intrinsic worth as complex ecosystems and provide economic as well as social benefits. The recognition of the importance of streamside areas in recent years has resulted in increased riparian related research and protection efforts. Land use policy decisions and management activities intended to protect or improve riparian zone and stream conditions require justification and should be based on an understanding of riparian zone functions and processes; the hydrologic functions of riparian areas are an integral part of this understanding.

Beaver (Castor canadensis) are a source of natural alteration to stream systems; beaver activities influence stream hydrology, affording modification of instream processes as well as the ecological dynamics of adjacent riparian areas. Their effects pertain to many riparian resource issues including wetland establishment and protection, degraded channel rehabilitation, stream maintenance and buffer strip design. Thus, additional knowledge of how beaver ponds affect the temporal and spatial characteristics of riparian hydrology is needed.

Though several authors have reported that ground water table elevations adjacent to beaver ponds are increased, little quantitative data is available to substantiate these observations (Brayton, 1984; Apple, 1985; Parker et al., 1985; Gebhardt et al., 1989). Further information is needed on the relationships between the saturated zone dimensions, ground water table elevations and hydrologically significant pond and riparian zone factors in beaver inhabited stream reaches. Greater understanding and quantification of these relationships will help researchers and land managers to evaluate the role of beaver ponds in riparian zone function and in riparian management decision making and application.

OBJECTIVES

The intent of this research was to improve understanding of the stream-riparian area continuum within beaver inhabited stream reaches by evaluating spatial and temporal characteristics of groundwater tables in aquifers adjacent to beaver ponds. Two types of riparian areas representative of western and central Oregon stream systems were investigated. Stream, beaver pond and riparian aquifer characteristics which affect pond adjacent groundwater table flux and storage relationships were analyzed. Specific objectives were as follows:

1) Determine whether groundwater table elevations in riparian zones adjacent to beaver ponds are higher in comparison to those without beaver ponds, and if so;
2) Estimate the potential maximum increase in the groundwater table elevations and the lateral extents of the expanded saturated zones on a monthly basis over a one year period;
3) Quantify the increased saturated soil and stored groundwater volumes in pond adjacent aquifers;
4) Describe the effects of beaver ponds on riparian zone groundwater table configurations and flow dynamics in effluent and influent stream systems;
5) Describe the variation of the pond adjacent groundwater levels through time on a seasonal basis;

6) Conduct a sensitivity analysis to determine how variation of the riparian aquifer values for hydraulic conductivity, storativity, pond level relative to stream stage, lateral slope of the groundwater table and recharge rates affect pond adjacent groundwater table elevations.

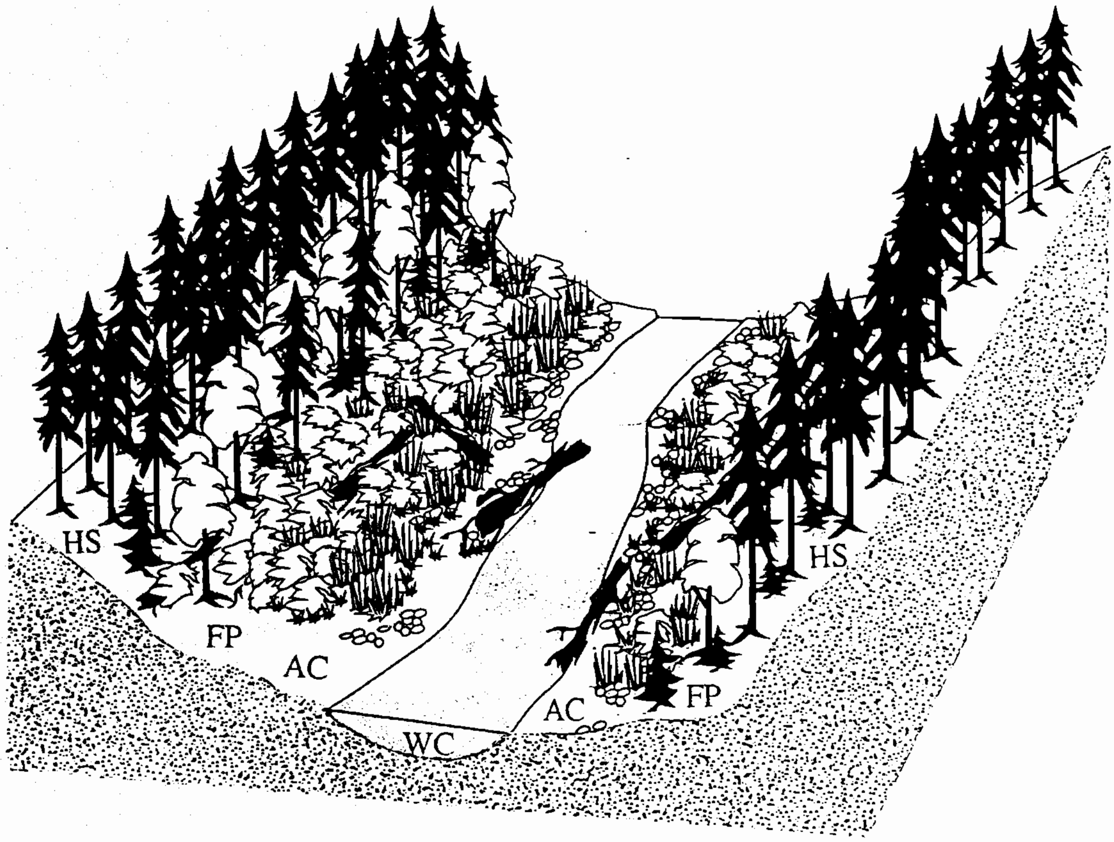
LITERATURE REVIEW

Riparian Zone Characteristics

Riparian zones are transition areas between aquatic and terrestrial ecosystems, and have distinct hydrologic, biologic and soil characteristics that interact to create and maintain their unique environmental conditions. These interfaces can be defined as areas that are proximal to rivers or streams and are supported by a high water table or periodic inundation (Skinner et al., 1988). The flux of materials, energy, nutrients and organisms between riparian zones and adjoining aquatic and upland areas is high. These ecosystems are also characterized by increased species diversity and productivity. Brinson, et al. (1981) list three characteristics that distinguish riparian ecosystems from other ecosystem types:

1) Riparian ecosystems have a linear form as a consequence of their proximity to rivers and streams;
2) Energy and material from the surrounding landscape converge and pass through riparian ecosystems in much greater amounts compared to any other ecosystem;
3) Riparian ecosystems are connected to upstream and downstream ecosystems.

Riparian zones are comprised of landforms, communities and environments within the larger landscape, as shown in Figure 1 (Gregory et al., 1991).



Vegetation communities associated with different geomorphic surfaces consist of scattered patches of grasses and herbs on exposed portions of the active channel (AC), and mosaics of herbs, shrubs and deciduous trees on the floodplain (FP). Conifers are intermixed on the lower floodplain and dominate the lower hillslopes (HS). Little terrestrial vegetation is found within the low flow wetted channel (WC). (Adapted from Gregory et al., 1991).

Figure 1. Riparian zone typical of river valleys in the Pacific Northwest.

Riparian Subsurface Hydrology

The hydrologic regime is an important factor influencing riparian ecosystem characteristics and processes (Mitsch and Gosselink, 1986). These systems exhibit hydrologic interactions between several types of incoming and outgoing water including precipitation, surface runoff, streamflow and subsurface flow. Evapotranspiration also affects soil moisture content and water transfer within riparian ecosystems. Each of these riparian zone hydrologic components may vary both in space and time with regard to flow occurrence, magnitude, frequency and rate of change.

Groundwater is an important creative component within riparian ecosystems and provides an influential hydrologic link in the stream-floodplain-hillslope continuum. Water below the free water table occurs as saturated flow and is usually referred to as groundwater; soil water that is above the water table occurs as vadose zone or tension held water (Freeze and Cherry, 1979).

Riparian groundwater table configurations are a function of groundwater energy gradients, aquifer hydraulic conductivity and storage characteristics and relative rates of aquifer recharge and discharge. Sources of inflow include surface infiltration, bank seepage and overbank flow from the channel, shallow subsurface flow and deep recharge from the surrounding aquifer. Outflow occurs as evapotranspiration, discharge to the channel, shallow subsurface seepage and recharge to the regional aquifer.

Streams are often described as being influent or effluent, depending upon the flow direction between the channel and the adjoining riparian groundwater table. Effluent streams gain water from the subsurface system in response to a groundwater energy gradient from the riparian aquifer to the channel. In contrast, influent stream systems supply water to the subsurface system and a hydraulic gradient from higher to lower potential exists between the channel and the riparian water table. Though these definitions can be useful in characterizing overall groundwater flow and distribution patterns, they are simplifications and may not represent more variant, localized groundwater table dynamics occurring within stream adjacent aquifers (Reiter, 1991).

Several authors report interactions between riparian groundwater table flux, saturated zone water storage and a wide range of stream system components and processes. For example, groundwater extraction resulted in the loss of riparian vegetation and bank erosion on the Carmel River, as found by Groenveld and Griepentrog (1985). Price and Fitzgibbon (1987) showed relationships between groundwater storage in various terrain types and winter streamflow in a Saskatchewan wetland. Jenkins (1989) evaluated connections between streamflow and groundwater to assess the effects of pumping on the Hassayampa River Preserve.

Groundwater Hydraulics

The behavior of groundwater flow through saturated porous media can be quantitatively described by Darcy's Law:

$$V = -K \frac{h_2 - h_1}{d}$$

where V = Darcy velocity or specific discharge

K = saturated hydraulic conductivity

d = linear distance along the direction of flow

H_2-H_1 = change in hydraulic head over distance d

Another form of Darcy's Law is:

$$Q = -AK \frac{h_2 - h_1}{d}$$

where Q = discharge

A = cross-sectional area perpendicular to the direction of flow

and other variables are as previously described.

Velocity (V) and discharge (Q) are given as macroscopically averaged descriptions of microscopic properties within the aquifer substrate. Soil is a complex porous media; the actual flow pathways and velocities within the pore spaces are highly variable and difficult to define. Therefore, the microscopic flow velocities are averaged over the total soil volume and macroscopic flow velocity (V) and volumetric flux (Q) vectors are used to represent flow through the substrate unit.

Saturated hydraulic conductivity (K) is a proportionality constant and is given as the ratio of groundwater flux to hydraulic gradient. The value of hydraulic conductivity can vary over several orders of magnitude and depends primarily on substrate properties including the mean size and distribution of soil grains, soil structure and pore geometry. In general, fine grained soils have a lower hydraulic conductivity than coarser materials. Hydraulic conductivity values for riparian soil can be relatively uniform to highly intermixed depending in part upon substrate depositional patterns, degree of subsequent reworking by fluvial action and soil genesis processes.

The hydraulic head (h) is given by Bernoulli's equation:

$$h = \frac{V^2}{2g} + \frac{P}{\gamma} + Z$$

where V = fluid velocity

g = acceleration due to gravity

P = pressure

γ = specific weight of fluid

Z = height above datum

The fluid velocity in most groundwater systems is usually so small that the velocity term is dropped and the hydraulic head is considered equal to the height of the water due to the pressure head plus the height above the datum. In unconfined aquifers the pressure head is close to zero at the free water surface, so the hydraulic head is considered to be equal to the elevation head. The continuous series of hydraulic head values throughout an unconfined aquifer defines a two-dimensional surface called the groundwater table, free water surface, or phreatic surface. The term h_2-h_1 represents the head differential between two locations along the same axis as the direction of flow. The flow distance is the length of the flow path between two points of hydraulic head measurement. The hydraulic gradient is defined as the hydraulic head difference divided by the flow distance.

The presented forms of Darcy's law can apply to groundwater flow in three dimensions, where V or Q, K and h_2-h_1/d become vector components. Thus flow analysis for an unconfined aquifer with either uniform conditions or variations in flux, hydraulic conductivity and/or hydraulic gradient is possible. These equations also indicate that saturated subsurface flow occurs in the direction of and at a rate proportional to the hydraulic gradient and the hydraulic conductivity. Hydraulic head may decrease non-linearly along the flow direction when unsteady flow, heterogenous or anisotropic (non-uniform) aquifer conditions exist.

Groundwater flow through riparian soils with a high degree of macroporosity or nonuniformity can be more difficult to characterize than flow through a more uniform matrix; Darcy's equation may only approximate flow parameters under these conditions. The application of Darcy's Law to groundwater analysis assumes that the flow through the soil matrix is laminar. This assumption is valid in soils with narrow pores; however, Darcy's law breaks down where there are continuous, connected large voids through which turbulent flow occurs (Cheng et al., 1975; Beasley, 1976). These soil macropores can be created by animal burrows, decomposed twigs and branches, and erosional fractures within the soil structure.

Effects of Beaver Ponds on Riparian Zone Characteristics

Historically, beaver have had an important influence on lotic ecosystems and landscape evolution throughout North America. According to estimates by Seton (1929) there were 60-400 million beaver inhabiting the continent at the beginning of the seventeenth century. Extensive reductions in beaver populations occurred due to beaver habitat destruction and fur trapping by European settlers. By the year 1900 beaver were almost extinct in the Pacific Northwest; however the population is currently rising due to predator reduction, lower pelt values, habitat improvement in localized areas and trapping regulations. The continental population is now thought to be between 6 and 12 million individuals (Naiman et al., 1988).

Riparian zones that are influenced by beaver can be substantially different when compared with unmodified reaches (Naiman et al., 1988). The beaver is a keystone species, one which affects ecosystem structure beyond its need for food and space. Initially beaver alter streams and riparian areas by cutting woody species and constructing dams. These activities have further effects on the character of stream systems and the quantity of materials stored and/or exchanged within riparian zones. For example, sediment deposition within beaver impoundments in conjunction with stream migration can extend floodplains over a number of years and affect valley floor morphology (Ringer, 1994). Organic matter can also be retained, modifying nutrient cycling and decomposition. Riparian vegetation structure, community composition and productivity are influenced as well. Beaver selectively cut certain plant species for food and dam construction, and ponds help create favorable conditions for hydrophytic plant establishment and growth due to associated changes in soil moisture and nutrient availability. Furthermore, the hydrologic and hydraulic characteristics of channels are altered. Beaver dams form stepped reservoirs; streamflow is routed through these ponds, over and around dams, thereby reducing effective stream gradient and spreading flows. Long term channel and bank stability can be improved because of the reduction in erosive stream power and increased sediment retention and entrapment. Also, beaver dams are comprised of woody debris which, in conjunction with their associated ponds, helps to improve habitat for fish and other aquatic organisms. However, beaver ponds do fail and the catastrophic release of water and sediment can create a significant disturbance.

Beaver Pond and Riparian Groundwater Relationships

Beaver ponds are thought to have important effects on riparian groundwater levels and flow dynamics. Several authors suggest that subsurface water table elevations can increase and the saturated zone can extend further in riparian areas surrounding beaver ponds when compared to unmodified stream reaches (Brayton, 1984; Apple, 1985; Stabler, 1985). Lowry (1993) observed an increase in aquifer recharge adjacent to a beaver pond in central Oregon. These phenomena are due to hydrologic interactions between the stored water behind the dam, the channel flow, the stream banks and the floodplain.

One mechanism by which beaver ponds can contribute to locally elevated riparian groundwater levels is by affecting the lateral flow of water between the pond and the adjacent channel banks. Riparian water table responses and an increase in the spread of the saturated zone depend on pond and aquifer characteristics including the water level energy gradient between the pond and streambanks, and the substrate permeability and water storage capacity. Kondolf et al. (1987) list three necessary conditions for subsurface water flux between a stream and a riparian aquifer and also for significant bank storage to occur:

1) There must be a relative stage increase within the channel;
2) The bank material must have a high enough hydraulic conductivity to allow for water exchange;
3) There must be a sufficient volume of permeable bank material to provide for water storage relative to stream flow.

Although beaver ponds exist in a wide variety of fluvial geomorphic settings with differing stream, pond and riparian substrate characteristics, the conditions stipulated by Kondolf et al. (1987) may be met for many beaver inhabited stream reaches. Condition one is represented by the increased elevation of the stored water in the beaver pond relative to the stream water level below the dam. The dam height provides a rough estimate of the stage increase within the channel, though seasonally variable pond and streamflow levels regulate the actual hydraulic head difference. During the summer dry season both the pond water stage and the below dam stream stage are decreased, while during wetter seasons the pond and downstream stages are increased.

The hydraulic conductivity and water storage volume of the riparian substrate (conditions two and three) are influenced by the type and extent of the alluvial floodplain deposit adjacent to the beaver pond. Many fluvial/geomorphic factors influence the form of a stream channel and associated floodplain; these include flow magnitudes and frequencies, stream gradient, channel geometry and sediment source areas and types (Schumm, 1977). In general, streams that have higher velocities or steeper gradients and that carry a larger proportion of coarse sand and gravel have more permeable floodplain deposits and associated greater hydraulic conductivities. Lower gradient, meandering streams dominated by silt and clay are more likely to have riparian aquifers with lower permeabilities and hydraulic conductivities. Downstream reaches generally have greater alluvial deposits than headwater stream reaches that are constrained by bedrock. The potential spread of the pond adjacent saturated zone is greater in riparian aquifers with increased permeabilities and storage volumes.

An additional mechanism that can cause relatively elevated groundwater levels near beaver ponds is increased surface infiltration and associated groundwater recharge. As water spills out of the pond the flow is spread over a greater distance through and along the length of the dam, creating a wider channel relative to a narrower, undammed channel. The overdam flow can be slowed and spread over the valley floor deposits below the dam. This can result in greater infiltration amounts directly downstream of beaver ponds and recharged groundwater levels.

Though various processes can be influential in causing saturation zone spreading near beaver ponds, the scope of this research is limited to addressing the groundwater table elevation alterations that occur due to the subsurface flux of water between beaver ponds and adjacent riparian aquifers.

METHODS

A two part investigation was conducted in order to obtain more information about the spatial and temporal characteristics of groundwater tables adjacent to beaver ponds. In the first portion of the study, a computer model that simulated groundwater level dynamics and incorporated alternative hydrologic and hydraulic characteristics representative of two types of beaver pond-riparian reaches located in western and central Oregon was developed. The second part of the investigation was a case study in which groundwater levels in a riparian aquifer adjacent to a beaver pond located on Oak Creek in western Oregon were monitored.

Part I: Computer Model

In the first study phase a horizontal, two-dimensional, finite-difference computer model was developed and used as a tool to provide quantitative examples of the potential groundwater table configurations in riparian aquifers near beaver ponds. The model results help determine whether groundwater levels adjacent to beaver ponds are increased compared to those without pond influences, as well as provide information needed to address the additional objectives of this study. The water table elevations were related to several variables that influence groundwater distribution including water level energy gradients, substrate hydraulic conductivity, transmissivity and storativity values, and sources and magnitudes of recharge and discharge.

The intent of this study phase was to simulate the simplified behavior of groundwater levels adjacent to two hypothetical beaver ponds based on a range of averaged and estimated hydraulic and hydrologic parameters, rather than to model specific pond-riparian sites with highly detailed aquifer conditions and hydrologic behavior. The model simulations provide prefatory information about the quantitative bounds and behavior of the subsurface water table elevations and saturated zone dimensions associated with beaver ponds, information that is undefined in the scientific literature and has been referred to only qualitatively. The results include estimated small, intermediate and large dimensions of the pond adjacent saturated wedge for each of two hypothetical pond-riparian aquifer systems for each month throughout a one year period.

Model Sites

Two types of synthesized beaver inhabited riparian settings were used as model sites: a stable, effluent stream reach located in the humid Coast Range of western Oregon and an incised, influent stream reach located in the semi-arid region east of the Cascade Range in central Oregon. Representative geomorphic, climatic and vegetative characteristics found within each region were used to create the two example riparian reaches.

Though beaver can occupy a wide range of habitat types, studies show that sites most habitable by beaver have several factors in common; the synthesized model sites also incorporate these findings. Colonies generally exist in areas that have low valley and stream gradients (less than 5 percent), valley widths greater than channel widths, soils with very slow to moderate permeabilities and vegetation types and quantities sufficient for food and dam construction material (Denny, 1952; Retzer et al., 1956; Brenner, 1962; Howard and Larson, 1985; Mccomb et al., 1990).

Western Site Description

The Western Site represents a beaver pond-riparian area within a stable third order stream in the Oregon Coast Range physiographic region. The stream is effluent and has an average annual flow of 0.15 cubic meters per second (cms), draining a watershed area of approximately 3 km^2. The channel lies in the middle of an alluvium filled valley ranging from 100 to 180 m wide that is bounded by moderately steep hillsides. The stream-riparian-hillslope aquifer components are hydrologically connected and the groundwater system within the upper aquifer is unconfined. The channel has an average longitudinal gradient of 3 percent. The floodplain adjacent to the pond has a 5 percent lateral slope and a 3 percent slope parallel to the channel.

The alluvial deposits in the site area average 6 m deep and are underlain by the Tyee sandstone formation. Textures vary from silty clays to sandy loams, permeabilities range from very slow to moderate.

The regional climate is humid; precipitation typically occurs in winter as low intensity, long duration rainfall and averages 230 cm annually. Summers are usually dry. The highest and lowest average monthly precipitation values are approximately 40 and 2 cm for December and July, respectively. Average monthly temperatures vary from a high of 18 °C in August to a low of 6 °C in January. Table 1 contains average monthly precipitation and temperature values for the site.

The vegetation in the area is dominated by dense stands of hardwoods and conifers; shrubs, herbs and grasses are also present. The overstory is composed of conifer species including Douglas fir (Pseudotsuga menziesii), western red cedar (Thuja plicata), Sitka spruce (Picea sitchensis) and western hemlock (Tsuga heterophylla). In addition, hardwoods such as red alder (Alnus rubra) and bigleaf maple (Acer macrophyllum) are common. The understory vegetation is predominantly vine maple (Acer circinatum), salmonberry (Rubus) and swordfern (Polystichum munitum). The basal cover of live plants and litter varies between 90 and 100 percent; very little bare ground is exposed.

Any logging in the surrounding watershed has not significantly affected riparian zone structure and function.

Central Site Description

The Central Site is representative of a beaver pond-riparian reach within a stream system in the western portion of the Blue Mountains physiographic region, located within north central Oregon. The stream flows through a broad, flat bottomed alluvial valley that is surrounded by plateaus and hog-back ridges. The stream is predominantly influent throughout the lower valley, however recharge

Table 1. Average monthly precipitation and temperature values for the Western and Central sites.

Month	Western Site		Central Site	
	Precipitation cm	Temperature °C	Precipitation cm	Temperature °C
Aug	3.3	17.9	1.8	19.8
Sep	7.4	16.9	1.8	15.2
Oct	15.9	13.6	2.1	9.9
Nov	35.6	9.2	3.6	4.1
Dec	39.7	6.4	3.3	1.9
Jan	38.0	6.4	2.8	1.8
Feb	29.0	8.1	1.8	2.9
Mar	29.0	8.9	2.6	5.4
Apr	17.2	10.2	3.1	8.1
May	10.5	12.7	3.9	12.1
Jun	6.7	15.3	3.3	16.6
Jul	2.1	17.3	1.5	20.2
Total	234.4	-----	31.6	-----
Average	-----	11.9	-----	9.8

and discharge reaches are interspersed along some channel segments. The reach containing the pond is influent. The middle and upper portions of the 300 km^2 watershed provide the major source areas for the streamflow; the mean annual discharge is 0.40 cms.

The stream is incised along most of its length and the present active channel is isolated below historic floodplain deposits by a vertical distance ranging between 1.4 and 2.4 m. Floodplains are developing adjacent to the downcut channel but are confined within oversteepened, nearly vertical cutbanks. The pond is contained within the lower channel; the adjacent floodplain or lower terrace is undergoing aggradation due to pond associated effects. The lateral distance between the edge of the beaver pond and the slope break between the incised channel floodplain and upper terrace is approximately 10 m. The upper terrace has a mean lateral slope of 5 percent and extends for 0.5 km to the valley walls. The average longitudinal channel gradient within the vicinity of the site is 3 percent.

The geology of the area is dominated by alluvial valley deposits which form a complex of clay, silt, sand and gravel characteristic of recent Quaternary alluvium. These alluvial strata are bounded below by the John Day formation, which consists of tuffaceous claystones with intercalated vitric tuffs. The uppermost alluvial deposits form an unconfined aquifer and consist of fine grained material averaging 11 m in depth; these deposits are underlain by an aquitard composed of fine clay. Soils range in texture from silty clay to loamy sand and have very slow to moderate permeabilities.

The region has a semi-arid climate with an average annual precipitation of 30 cm; most of the precipitation falls during extensive, lower intensity storms from November through April. Although summer months are usually drier than the rest of the year, short duration, localized thunderstorms occasionally occur due to convective fronts. The greatest average monthly precipitation (3.9 cm) occurs during May and the least average monthly precipitation (0.6 cm) falls during July. Average monthly temperatures range from approximately 0.1 °C to 20 °C and are lowest in January and highest in July. Average monthly precipitation and temperature values for the site are listed in Table 1.

The plant species in the site vicinity are primarily composed of mesic and xeric varieties. The upper terrace and drier areas on the lower floodplain are dominated by short grasses and shrubs adapted to moisture depletion and greater disturbance levels. These include big sagebrush (Artemesia tridentata), cheatgrass (Bromus tectorum), greasewood (Sarcobatus vermiculatus) and knapweed (Centaurea repens). A few hydric varieties grow in stream adjacent areas that have higher moisture levels, these species include rushes (Juncus balticus, Scirpus validus), saltgrass (Distichlis stricta) and willow (Salix exigua). Cottonwood (Populus) species are also present in small numbers.

The area was formerly grazed by cattle at moderate stocking levels. Consequently the soil is disturbed, the structure is broken down due to animal compaction and vegetative cover is reduced. Basal cover averages 20, 15, 20 and 45 percent for live plants, litter, rock and bare ground, respectively.

Numerical Aquifer Model

A two-dimensional, horizontal, finite-difference numerical model was developed to simulate the spatial and temporal characteristics of water tables in riparian aquifers adjacent to beaver ponds. The model is comprised of finite-difference equations together with boundary conditions and initial water level distributions that represent the groundwater behavior within synthesized riparian areas.

The groundwater model generated in this study is based on hydrologic processes and physical laws that affect groundwater levels and flow dynamics. The processes that affect the distribution of water levels in riparian zones surrounding beaver ponds can be viewed in terms of a water balance equation, incorporating volume rates of inflow and outflow and changes in storage over time ($I - O = \Delta S/\Delta t$). The process components that were included in the model to generate groundwater head elevations were rates of precipitation, infiltration, evapotranspiration, groundwater inflow and outflow and changes in storage volume. The continuity principle and Darcy's Law, the force equation describing flow through porous media, were incorporated.

Numerical expressions of these hydrologic processes and laws that apply to the aquifer systems were used to create the groundwater model (Wang and Anderson, 1982; Kinzelbach, 1986). The continuity equation for steady state groundwater flow through a horizontal aquifer is:

$$\frac{\partial q_x}{\partial x}\Delta x(b\Delta y) + \frac{\partial q_y}{\partial y}\Delta y(b\Delta x) = R(x,y)\Delta x\Delta y$$

where b = thickness of the horizontal aquifer, perpendicular to the xy plane

$\Delta x, \Delta y$ = distance increments along the coordinate directions x and y

$\frac{\partial q_x}{\partial x}, \frac{\partial q_y}{\partial y}$ = flow rate through an aquifer unit area along the coordinate directions x and y

$R(x,y)\Delta x\Delta y$ = volume of water added per unit time per unit aquifer area

The form of the continuity equation used to describe groundwater flow through an unconfined aquifer for transient conditions includes the rate of release from storage and is written as:

$$\frac{\partial q_x}{\partial x}\Delta x(b\Delta y) + \frac{\partial q_y}{\partial y}\Delta y(b\Delta x) = R(x,y)\Delta x\Delta y - S\frac{\partial h}{\partial t}(\Delta x\Delta y)$$

where S = storativity coefficient

$\frac{\partial h}{\partial t}$ = change in hydraulic head over time

and the other variables are as previously defined. The term $-S\frac{\partial h}{\partial t}(\Delta x\Delta y)$ represents the volume of water released from storage over time per unit aquifer area with thickness b.

Substituting Darcy's Law for q_x and q_y and dividing through by $-Kb\Delta x\Delta y$ yields the transient flow equation:

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} = \frac{S}{Kb}\frac{\partial h}{\partial t} - \frac{R(x,y,t)}{Kb}$$

The analytical solution for this equation is only applicable for very simple systems; however, the finite difference method can be used to obtain an approximate solution. In this method the aquifer domain is discretized into a set of points in space (nodes) and time, and the continuous partial differential equation is replaced with a set of linear algebraic differential equations. Their solution gives values of head at specific points. The head values are computed over the spatial domain at a specified time step; recursive computations yield head values for future times after the heads at some initial time have been given. The finite difference form of the transient flow equation is:

$$\frac{h^n_{i+1,j} - 2h^n_{ij} + h^n_{i-1,j}}{(\Delta x)^2} + \frac{h^n_{i,j+1} - 2h^n_{ij} + h^n_{i,j-1}}{(\Delta y)^2}$$

$$= \frac{S}{Kb}\frac{h^{n+1}_{ij} - h^n_{ij}}{\Delta t} - \frac{R^n_{ij}}{Kb}$$

where h^n_{ij} = hydraulic head at node ij at time step n

Δt = time increment

R^n_{ij} = depth of water added at node ij at time step n

and other variables are as previously defined.

If Δx and Δy are set equal to "a" and h_{ij}^{n+1} is solved for, the equation is expressed as:

$$h_{ij}^{n+1} = \left(1 - \frac{4Kb\Delta t}{Sa^2}\right) h_{ij}^{n}$$

$$+ \left(\frac{4Kb\Delta t}{Sa^2}\right)\left(\frac{h_{i+1,j}^{n} + h_{i-1,j}^{n} + h_{i,j+1}^{n} + h_{i,j-1}^{n}}{4}\right) + \frac{R_{ij}^{n}\Delta t}{S}$$

This form of the equation is called an explicit or forward difference approximation because h_{ij}^{n+1} is expressed explicitly in terms of known values of head at node ij found in the previous time step. The "new" values of head (h_{ij}^{n+1}) are used in the head calculation for the next time step as "old" head values (h_{ij}^{n}). In other words, h_{ij}^{n+1} values replace h_{ij}^{n} values through each successive calculation throughout the simulation time period.

For each modeled aquifer, a horizontal grid system was used to represent the pond-riparian reach so that the areal distribution of the aquifer and boundary characteristics used as model input parameters could be defined; a node was associated with each grid cell. Figure 2 contains a typical grid overlay used to represent each synthesized site.

Next, a system of finite difference equations that performed water balance calculations and defined water levels for each node through a series of time steps was generated for each modeled pond-riparian site. A range of alternative hydraulic

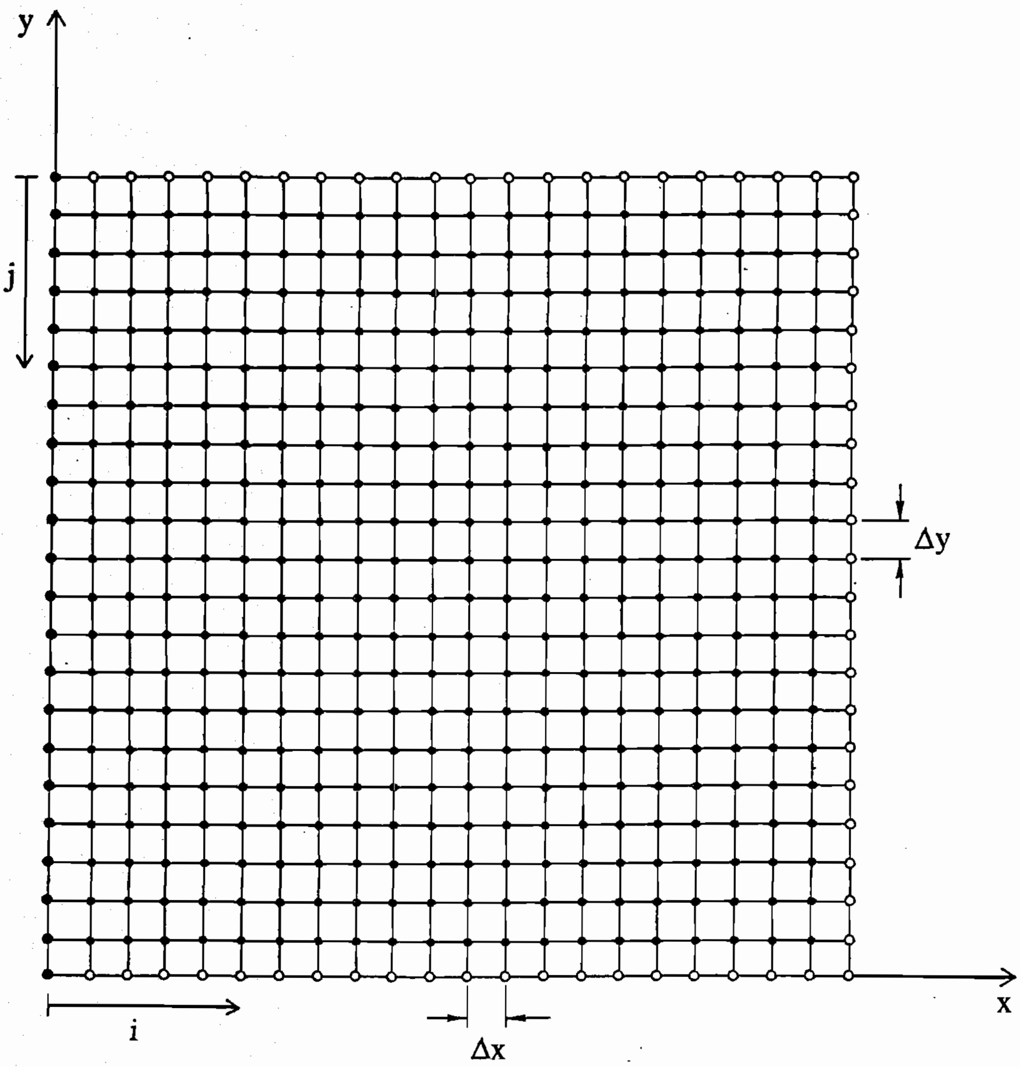


Figure 2. Finite difference grid. Circles represent nodes. Darkened circles along the y-axis represent the constant head channel boundary, open circles along the remaining perimeter represent 'semi-infinite' boundaries of the riparian aquifer face.

aquifer properties, recharge rates and boundary conditions were utilized as input parameters. During the model simulations, water was allowed to move horizontally between, and vertically within, grid cells in response to hydraulic gradients and varying rates and distributions of inflow and outflow. A computer program using ThinkPascal version 3.1 was written to implement the numerical model. The program listing can be found in Appendix A.

Computed results consisted of water levels at each of the grid cells throughout each pond adjacent aquifer. These spatial distributions of water levels were determined at the first of each month, extending through one year. Finally, the computed water levels were used to create water table elevation graphs and to evaluate several associated hydrological characteristics and processes within riparian zones.

Input Data

The input data necessary to solve the groundwater flow model for each setting consisted of the following types of aquifer and riparian zone information:

1) Values for hydraulic conductivity (K) and storativity (S) coefficients;
2) Values defining the aquifer bottom (ab_{ij}) and ground surface (gs_{ij}) elevations at each node throughout the model aquifer;
3) Values for the initial ground water elevations at each node (h_{ij});

4) Definition of the aquifer boundary conditions, including the channel boundary head difference (ΔDH) between the above and below dam water levels;

5) Selections for time step (Δt) and distance increment (Δx) values;

6) Values for net areal recharge rates (R), based on precipitation, infiltration and evapotranspiration rates.

To determine the effect of alternative hydrologic and hydraulic site conditions on the synthesized groundwater levels occurring adjacent to beaver ponds, three model simulations were performed for each western and central site (for a total of six simulations). The input parameters were selected from a range of possible values so that the simulation results included estimated small, intermediate and large dimensions of the pond adjacent saturated zone within the riparian aquifer for each of the two synthesized sites. The simulation cases were termed western small (WS), western intermediate (WM), western large (WL), central small (CS), central intermediate (CM) and central large (CL).

Each simulation execution began on August first (at $t=0$) when the beaver dam construction was assumed to occur. Model runs were made over consecutive months for time periods corresponding to the number of days in each month. The total time for each simulation was twelve months or 365 days.

The values used for the input parameters were governed by the hydrologic, geomorphic, climatic and vegetative characteristics associated with each type of stream-riparian aquifer system. The potential monthly recharge rates, the ground surface and aquifer bottom elevations, the initial groundwater head values and the boundary conditions except for the pond node elevations along the channel boundary remained the same for all three simulations carried out for each site. However, the parameters for hydraulic conductivity, storativity, pond level relative to stream stage, lower floodplain elevation for the central site, time and distance increments, and actual monthly recharge rate varied between the simulations. These variations were utilized to produce the small, intermediate and large dimensions of the pond adjacent saturated wedge for each site. For this simplified model analysis, the areal input parameters for the hydraulic conductivity, storativity and potential monthly recharge terms for each simulation were assumed to be uniform for each node throughout the grid and the aquifer material in all configurations was assumed to be everywhere homogenous and isotropic.

In order to compare the groundwater table elevations in riparian aquifers with beaver ponds to those without beaver ponds, an additional six simulations were run without beaver ponds present in the channel (ie. with $\Delta DH=0$). These simulations were paired with those described above.

A discussion of each type of input data follows. The input values for hydraulic conductivity, storativity, head difference between the stream and pond stages, time and distance increments, precipitation rates, infiltration factors and evapotranspiration rates that were used for each riparian aquifer simulation are included in Tables 2 through 7.

Table 2. Data input values for K, S, ΔDH, Δt, Δx, P, I and PET for Case WS. (See text for discussion of input variables).

Month	K m/day	S	ΔDH m	Δt days	Δx m	P m/day	I	PET m/day
Aug	0.01	0.05	0.3	0.5	2.0	0.0011	1.0	0.0042
Sep	"	"	"	"	"	0.0025	1.0	0.0031
Oct	"	"	"	"	"	0.0051	1.0	0.0018
Nov	"	"	"	"	"	0.0119	1.0	0.0009
Dec	"	"	"	"	"	0.0128	1.0	0.0005
Jan	"	"	"	"	"	0.0123	1.0	0.0005
Feb	"	"	"	"	"	0.0104	1.0	0.0008
Mar	"	"	"	"	"	0.0094	1.0	0.0013
Apr	"	"	"	"	"	0.0057	1.0	0.0020
May	"	"	"	"	"	0.0034	1.0	0.0031
Jun	"	"	"	"	"	0.0022	1.0	0.0042
Jul	"	"	"	"	"	0.0007	1.0	0.0047
Total						234 cm/yr		83 cm/yr

Table 3. Data input values for K, S, ΔDH, Δt, Δx, P, I and PET for Case WM. (See text for discussion of input variables).

Month	K m/day	S	ΔDH m	Δt days	Δx m	P m/day	I	PET m/day
Aug	0.10	0.13	1.0	0.5	5.0	0.0011	1.0	0.0042
Sep	"	"	"	"	"	0.0025	1.0	0.0031
Oct	"	"	"	"	"	0.0051	1.0	0.0018
Nov	"	"	"	"	"	0.0119	1.0	0.0009
Dec	"	"	"	"	"	0.0128	1.0	0.0005
Jan	"	"	"	"	"	0.0123	1.0	0.0005
Feb	"	"	"	"	"	0.0104	1.0	0.0008
Mar	"	"	"	"	"	0.0094	1.0	0.0013
Apr	"	"	"	"	"	0.0057	1.0	0.0020
May	"	"	"	"	"	0.0034	1.0	0.0031
Jun	"	"	"	"	"	0.0022	1.0	0.0042
Jul	"	"	"	"	"	0.0007	1.0	0.0047
Total						234 cm/yr		83 cm/yr

Table 4. Data input values for K, S, ΔDH, Δt, Δx, P, I and PET for Case WL. (See text for discussion of input variables).

Month	K m/day	S	ΔDH m	Δt days	Δx m	P m/day	I	PET m/day
Aug	1.00	0.20	1.7	0.5	10.0	0.0011	1.0	0.0042
Sep	"	"	"	"	"	0.0025	1.0	0.0031
Oct	"	"	"	"	"	0.0051	1.0	0.0018
Nov	"	"	"	"	"	0.0119	1.0	0.0009
Dec	"	"	"	"	"	0.0128	1.0	0.0005
Jan	"	"	"	"	"	0.0123	1.0	0.0005
Feb	"	"	"	"	"	0.0104	1.0	0.0008
Mar	"	"	"	"	"	0.0094	1.0	0.0013
Apr	"	"	"	"	"	0.0057	1.0	0.0020
May	"	"	"	"	"	0.0034	1.0	0.0031
Jun	"	"	"	"	"	0.0022	1.0	0.0042
Jul	"	"	"	"	"	0.0007	1.0	0.0047
Total						234 cm/yr		83 cm/yr

Table 5. Data input values for K, S, ΔDH, Δt, Δx, P, I and PET for Case CS. (See text for discussion of input variables).

Month	K m/day	S	ΔDH m	Δt days	Δx m	P m/day	I	PET m/day
Aug	0.01	0.05	0.3	0.25	2.0	0.0006	0.75	0.0042
Sep	"	"	"	"	"	0.0006	1.0	0.0026
Oct	"	"	"	"	"	0.0007	1.0	0.0014
Nov	"	"	"	"	"	0.0012	1.0	0.0005
Dec	"	"	"	"	"	0.0011	1.0	0.0003
Jan	"	"	"	"	"	0.0009	1.0	0.0003
Feb	"	"	"	"	"	0.0006	1.0	0.0004
Mar	"	"	"	"	"	0.0008	1.0	0.0008
Apr	"	"	"	"	"	0.0010	1.0	0.0015
May	"	"	"	"	"	0.0013	0.75	0.0025
Jun	"	"	"	"	"	0.0011	0.75	0.0038
Jul	"	"	"	"	"	0.0005	0.75	0.0047
Total						32 cm/yr		71 cm/yr

Table 6. Data input values for K, S, ΔDH, Δt, Δx, P, I and PET for Case CM. (See text for discussion of input variables).

Month	K m/day	S	ΔDH m	Δt days	Δx m	P m/day	I	PET m/day
Aug	0.10	0.13	0.8	0.10	2.0	0.0006	0.80	0.0042
Sep	"	"	"	"	"	0.0006	1.0	0.0026
Oct	"	"	"	"	"	0.0007	1.0	0.0014
Nov	"	"	"	"	"	0.0012	1.0	0.0005
Dec	"	"	"	"	"	0.0011	1.0	0.0003
Jan	"	"	"	"	"	0.0009	1.0	0.0003
Feb	"	"	"	"	"	0.0006	1.0	0.0004
Mar	"	"	"	"	"	0.0008	1.0	0.0008
Apr	"	"	"	"	"	0.0010	1.0	0.0015
May	"	"	"	"	"	0.0013	0.80	0.0025
Jun	"	"	"	"	"	0.0011	0.80	0.0038
Jul	"	"	"	"	"	0.0005	0.80	0.0047
Total						32 cm/yr		71 cm/yr

Table 7. Data input values for K, S, ΔDH, Δt, Δx, P, I and PET for Case CL. (See text for discussion of input variables).

Month	K m/day	S	ΔDH m	Δt days	Δx m	P m/day	I	PET m/day
Aug	1.00	0.20	1.3	0.10	5.0	0.0006	0.85	0.0042
Sep	"	"	"	"	"	0.0006	1.0	0.0026
Oct	"	"	"	"	"	0.0007	1.0	0.0014
Nov	"	"	"	"	"	0.0012	1.0	0.0005
Dec	"	"	"	"	"	0.0011	1.0	0.0003
Jan	"	"	"	"	"	0.0009	1.0	0.0003
Feb	"	"	"	"	"	0.0006	1.0	0.0004
Mar	"	"	"	"	"	0.0008	1.0	0.0008
Apr	"	"	"	"	"	0.0010	1.0	0.0015
May	"	"	"	"	"	0.0013	0.85	0.0025
Jun	"	"	"	"	"	0.0011	0.85	0.0038
Jul	"	"	"	"	"	0.0005	0.85	0.0047
Total						32 cm/yr		71 cm/yr

Hydraulic Conductivity Coefficients

As previously discussed, saturated hydraulic conductivity is the capacity of a substrate to transmit water. The hydraulic conductivity values were necessary for the transmissivity calculations incorporated within the program. Transmissivity is a measure of the ability of an aquifer to transmit water and is equal to the product of the hydraulic conductivity (K) and the saturated thickness (b) of the aquifer:

$$T = Kb$$

Saturated hydraulic conductivity estimates for the hypothetical sites were based in part on K values associated with soil textural classes found within beaver inhabited areas as reported in the literature. Soil textures within riparian zones conducive to beaver generally range from fine to medium grained and have classifications including silty clay, loam and loamy sand (Howard and Larson, 1985). The approximate K values associated with each of these soil textural classes are 0.01, 0.1 and 1.0 m/day, respectively (Dunne and Leopold, 1978; Freeze and Cherry, 1979).

In addition, saturated hydraulic conductivity values were estimated in the field at riparian sites in western and central Oregon that are currently or were previously inhabited by beavers. A commonly used field method for estimating hydraulic conductivity is the slug test, such as the one used in this study for unconfined aquifers with partially penetrating wells (Dawson and Istok, 1989). The test involved causing an abrupt change in well water level then monitoring the water level recovery through time.

Slug tests were performed at 10 pond-riparian locations in western Oregon stream systems and at 10 locations in central Oregon during the summers of 1991 and 1992. Five well sites were randomly selected at each location; wells were placed lateral to the pond and within 40 m of the channel. Each well was constructed of meshed steel piping 2.54 cm in diameter and 2.5 m long. The wells were installed by boring vertical holes that had the same diameter as the pipes into the ground; the pipes were then fit into the holes.

The initial step in conducting the test was to record the static water level in a given well. Next, a closed end PVC pipe (a "slug") was inserted into the well and the water level was allowed to return to its equilibrium height; the pipe was then removed. Water from the surrounding aquifer then began to flow back into the well at a rate dependent upon the local hydraulic conductivity. The well water elevation and the time passed since the slug was removed were simultaneously recorded. These data along with other aquifer and well information were used to calculate hydraulic conductivity by using the following equation:

$$K = \frac{r_c^2 \ln(R/r_w)}{2(l-d)t_l}$$

where K = aquifer hydraulic conductivity

r_c = effective radius of the well casing over which the water level in the well changes

R = radius of influence of the injection well or the distance from the well at which the drawdown is zero

r_w = effective radius of the well bore

l = vertical distance from the static water table to the bottom of the well screen

d = distance from the static water table to the top of the well screen

t_l = time lag

given

$$t_l = \frac{t}{\ln(H_w/H_o)}$$

where t = time since withdrawal

H_w = height of water in the well above the static water table at $t > 0$

H_o = instantaneous change in head in the well casing due to an withdrawal of a known volume V at time $t = 0$

The value of t can be conveniently found as the time where $H_w/H_o = 0.37$ on a log H_w/H_o vs. time graph.

Five hydraulic conductivity tests were conducted in the pond-adjacent area at each of the ten pond-riparian locations in western Oregon and the ten locations in central Oregon. The mean value of the five hydraulic conductivity tests performed at each site was calculated. The mean K values for the western sites ranged from 0.005 to 0.85 m/day with an overall average of 0.118 m/day; the mean K values for the central sites ranged from 0.009 to 1.01 m/day with an overall average of 0.137 m/day. These hydraulic conductivity values and stream locations are given in

Appendix B. The values fall within the range of estimated K values for soil types within beaver inhabited stream reaches as derived from the literature (Howard and Larson, 1985).

Hydraulic conductivity values of 0.01, 0.1 and 1.0 m/day were assigned as input values for each of the three simulation pairs WS and CS, WM and CM, and WL and CL, respectively, representing the range of texture classifications from silty clays to loamy sands for each synthesized site. The K values were uniform for all cells per each case and remained constant through each simulation.

The saturated thickness (b) for each cell was represented by the groundwater table elevation minus the aquifer bottom elevation at each corresponding node. Transmissivity values were calculated for each cell as each of the model simulations progressed since the water level and associated saturated thickness of the aquifer varied with cell location and through time.

Storativity Coefficients

The storativity coefficient (S) is a dimensionless quantity that represents the volume of water an aquifer releases from storage per unit surface area per unit decline in hydraulic head (Freeze and Cherry, 1979). The most reliable means of estimating storativity is by using aquifer testing methods requiring pumping. However, this was impractical due to the difficulty in getting generator equipment into many of the remote field areas and due to the lengthy response time of return flow to wells in fine textured soils.

The storativity coefficients for the unconfined aquifers represented in this study were assumed to be equal to the specific yield of the aquifer material (Freeze and Cherry, 1979). The specific yield is the volume of water that a unit volume of aquifer releases from storage by gravity drainage. Water holding and release capacities of soil are strongly affected by differences in texture; specific yield estimates for the soil textural classes representing the western and central sites were 0.05, 0.13 and 0.20 for silty clays, loams and loamy sands, respectively (Dunne and Leopold, 1978). An S value of 0.05 was assigned to Cases WS and CS, 0.13 was used for Cases WM and CM, and 0.20 was input for Cases WL and CL. The storativity value used in each case was uniform for all nodes.

Aquifer Bottom and Ground Surface Elevations

The aquifer bottom and ground surface configurations for each synthesized site matched the described site conditions and were defined with distributions of nodal elevations for AB_{ij} and GS_{ij}. The aquifer bottom in all simulations carried out for the Western Site had a 3 percent gradient parallel to the channel and a 5 percent slope perpendicular to the channel. The ground surface slope and orientation were similar to those of the aquifer bottom; the distance between the two planes was 6 m. The aquifer bottom for the Central Site had a 3 percent gradient parallel to the channel and a 0 percent lateral slope to the extent of the model aquifer boundary. The ground surface or upper terrace had a 3 percent slope parallel to the stream and a 5 percent gradient in the upslope direction perpendicular to the channel. The height of the upper terrace nearest to the channel was 11 m above the aquifer bottom; this distance gradually increased since the ground surface sloped upward relative to the aquifer bottom. The elevation of the lower terrace relative to the aquifer bottom varied since the stream was undergoing aggradation within the lower floodplain near the pond. The lower terrace was 0.3 m higher than the elevation of the pond surface at the dam location for each case. The lower terrace had a 5 percent lateral slope and a 3 percent longitudinal slope, similar to the upper terrace.

Initial Groundwater Head Values

A set of head values that defined the water level throughout the model aquifer was required to begin each model simulation; these initial conditions were used as h_{ij}^{n} values for each node during the first time step. The synthesized pond-riparian aquifer system used in the model as the Western Site had an effluent ground water table; groundwater flowed into the channel from the adjacent hillslope and riparian aquifer. The initial head values for this site simulated a water table with a uniform 5 percent gradient toward and perpendicular to the channel and with a uniform 3 percent gradient in the downslope direction parallel to the stream. The initial head values along the channel were 4 m above the nodal elevations defining the aquifer bottom for the Western Site.

The riparian aquifer system of the synthesized Central Site had an influent groundwater table; the stream recharged the adjacent riparian aquifer. The initial conditions defined a water table with a uniform negative 5 percent gradient away from and perpendicular to the channel and a uniform 3 percent gradient in the downslope direction parallel to the stream. The initial head values along the channel were 8 m above the nodal elevations defining the aquifer bottom for the Central Site. Profiles of the initial groundwater table, the aquifer bottom and the ground surface lateral to the stream at the dam location for each site are shown in Figure 3.

Boundary Conditions

Model boundaries coincided with the aquifer limits defined by the geohydrologic character of the synthesized riparian sites. Channel boundary conditions were defined by channel water slope and elevation characteristics. Each channel boundary was comprised of constant head grid cells along the y-axis of the model; the assigned head values for each pond and stream node established representative channel water profiles. For each simulation the stream water profile both above and below the pond had a 3 percent slope and the pond water level had a 0 percent slope. The nodal elevations defining the stream sections intersected the initial groundwater head values along the channel, described in the previous section. For each of the 'small', 'medium' and 'large' simulation cases, the elevations of the channel boundary grid cells representing the pond equaled the stream stage immediately below the dam location plus the associated low, medium and high values of ΔDH. The ΔDH term was defined as the head difference between the pond level and the stream stage just below the dam. The ΔDH input values were

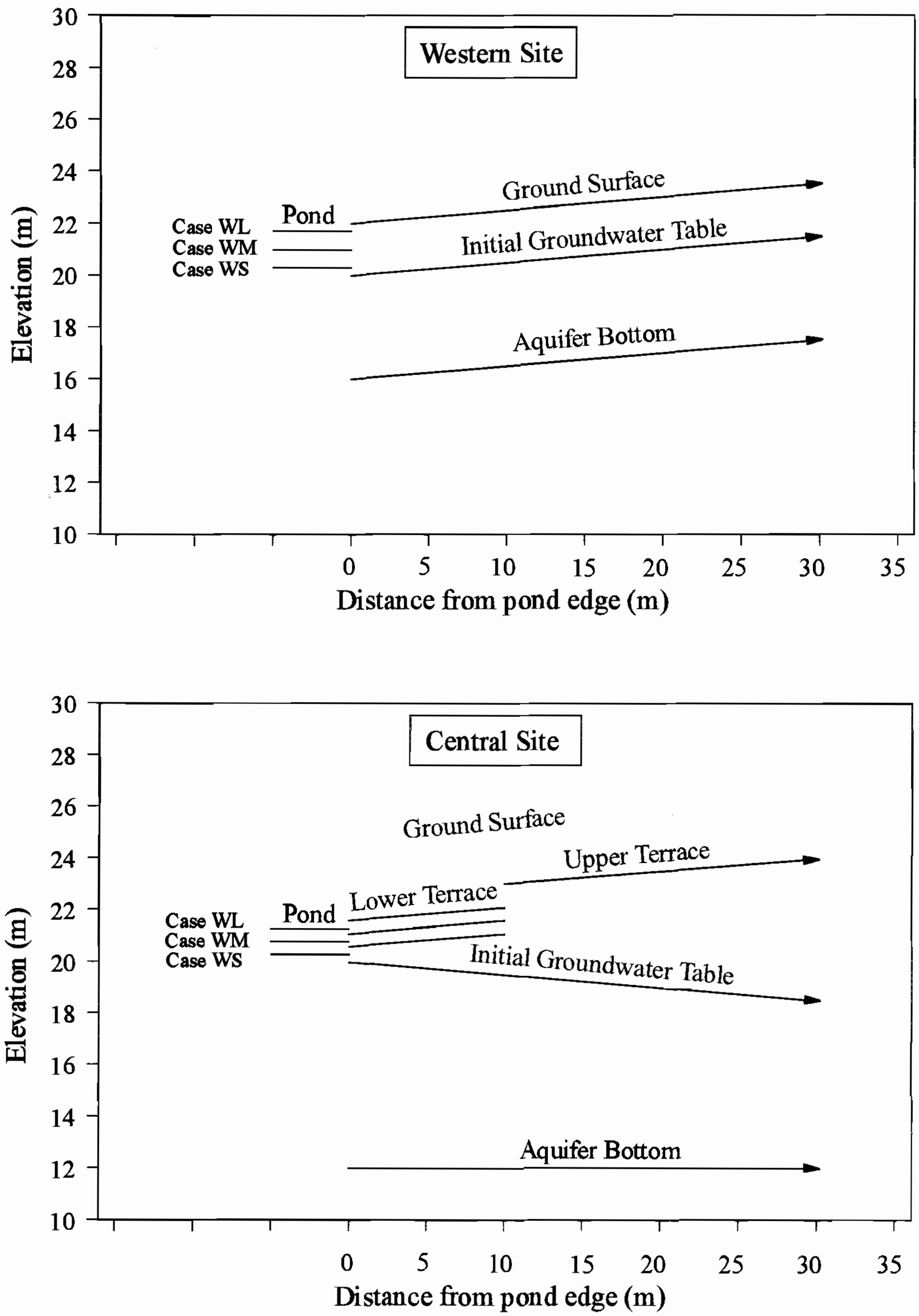


Figure 3. Lateral profiles of the initial groundwater table, the aquifer bottom and the ground surface for the Western and Central Sites.

based on field measurements and dam height data reported in previous studies (Morgan, 1868; Scheffer, 1938; Bryant, 1983; McComb, Sedell and Buschholz, 1990; Beedle, 1992).

Field determinations of ΔDH were carried out using a device that indicated the elevation difference between the pond level and the stream stage. A survey rod was placed vertically in the stream just below the dam. A flexible clear plastic hose was filled with water and plugged on each end. One end of the hose was then attached to and vertically aligned with the measuring rod; the end of the hose was placed higher than the level of the pond water. The remaining part of the hose was draped over the dam and positioned so that the end was held below the pond surface; the plugs were then removed. The pond and the tubing attached to the rod were hydraulically connected, thus the water level in the tubing equalled the elevation of the pond surface. The ΔDH value was determined by subtracting the stream stage from the pond equivalent stage measured on the survey rod.

The ΔDH values for the western field sites ranged from 0.3 to 1.7 m with an average of 1.0 m; the values for the central field sites ranged from 0.3 to 1.3 m with an average of 0.8 m. These values were comparable to the ranges and averages of dam heights within beaver inhabited streams as found by other researchers and were used as input data values. Appendix B includes ΔDH values determined from the field data.

The pond lengths and associated number of pond nodes along the channel boundary varied according to dam height; Cases WS, WM and WL had pond lengths of 10, 33 and 57 m, and Cases CS, CM and CL had pond lengths of 10, 27 and 43 m, respectively.

Boundaries along the remainder of the model perimeter (the upstream and downstream sides parallel to the x-axis and the upslope side parallel to the y-axis) were treated as 'semi-infinite'. These boundaries were achieved by linearly extrapolating the gradient from the nodes adjacent to the boundary to imaginary nodes across the boundary. This type of boundary condition allowed for lateral inflow and outflow along the groundwater seepage face and represented a hydrologic continuum between the modeled riparian area and the adjacent aquifer.

Time and Distance Increments

The choices for time step (Δt) and distance increment or cell length (Δx) values were important model considerations and were adjusted according to the rate of the aquifer water level response to flow between grid cells and net recharge in order to avoid model instability. The Δt and Δx values for each simulation were selected so that the parameter $Kb\Delta t/S\Delta x^2$ was kept less than or equal to 0.25 (Rushton and Redshaw, 1979). If this parameter had been exceeded, mass balance errors would have amplified as the model simulations progressed and the solutions would have been unstable. The companion Δt and Δx values were different for each case and ranged from 0.1 day and 2.0 m to 0.5 day and 10.0 m.

Recharge Terms

The recharge term (R) was used to simulate areally distributed net recharge that contributed to an increase or decrease of the groundwater table elevation and was primarily dependent upon precipitation, infiltration and evapotranspiration rates. The recharge term was defined as:

$$R = P I - AET$$

where R = areally distributed net recharge that contributed to an increase or decrease in groundwater table elevation

P = precipitation rate

I = percentage of precipitation that infiltrated the soil surface

AET = actual evapotranspiration rate

The R value was calculated for each node on a month by month basis and expressed in terms of an incremental rate for each time step during the model simulations. Descriptions of the equation components follow.

The precipitation value multiplied by the infiltration factor represented the effective amount of precipitation available for recharge through time. The amount of precipitation incident over a given time period was the maximum amount of water available for areal recharge. The precipitation rates used to represent precipitation occurring at the Western and Central Sites are listed in Tables 2 through 7.

Infiltration is the movement of water through the soil surface and into the soil. The infiltration term was a proportionality factor that could range between zero and one, depending upon the difference between the precipitation intensity or rate of water arrival at the soil surface and the soil infiltration capacity. Soil infiltrability is most affected by soil porosity, percent bare soil surface, soil texture and vegetation type and crown cover (Johnson, 1979). In the undisturbed, well vegetated forest soils in western Oregon, soil infiltration capacities usually exceed the rainfall rates (Harr, 1976; Johnson, 1979). Therefore, the I value for the Western Site was set equal to 1.0 for each month throughout each simulation. The Central Site represented a moderately disturbed area with reduced vegetation, compacted soils and a greater percentage of bare ground and thus had lower soil infiltration capacities. The precipitation rates of the summer thunderstorms exceeded the infiltration capacities of the soil; during the summer months the I value was set equal to 0.75, 0.80 and 0.85 for Cases CS, CM and CL, respectively. The I value was assumed to increase slightly from Case CS to CL since soil textures specified for each case were increasingly coarser, with associated increases in infiltration capacities. Other research supports these infiltration/precipitation ratios. For example, Heffner (1987) found that during the summer approximately 80 percent of incident precipitation infiltrated the soil surface at grazed areas within a disturbed rangeland with climate and site characteristics similar to those of the synthesized central Oregon site. Precipitation that did not infiltrate was assumed to be routed to the channel as surface runoff. The I value for the remaining months was set equal to 1.0 since the precipitation intensities for the rest of the year were much lower and assumed to be less than the soil infiltration capacity. The monthly values of I used during the recharge calculation for each site are listed in Tables 2 through 7.

Evapotranspiration is defined as the process by which water is removed from the land surface through evaporation and transpiration; potential evapotranspiration (PET) is the rate of evapotranspiration that occurs if sufficient water is available to meet the demand of a well-vegetated surface. Actual evapotranspiration (AET) is the proportion of PET that is evapotranspired under the existing water supply and is affected by soil moisture levels, vegetative factors including plant type and growing season, and climatic factors such as air temperature and solar radiation.

Since there is little quantitative information about the use of water through evapotranspiration in riparian zones, rough estimates of the potential evapotranspiration values required for modeling each synthesized riparian zone were calculated using the Blaney-Criddle method (Dunne and Leopold, 1978). The data requirements were air temperature, site location and vegetation type. Potential evapotranspiration values were calculated for each case by using the synthesized site characteristics and are given in Tables 2 through 7.

Actual evapotranspiration losses were estimated within the model by summing two types of evapotranspiration components, that amount of water lost from the saturated groundwater regime (GWET) plus that amount of water lost at the ground surface through the upper soil layer (SET). The actual evapotranspiration values associated with each node varied for each model simulation and/or through time since evapotranspiration rates differed according to month, site conditions and climate, and changing groundwater head values at each node.

The groundwater evapotranspiration component simulated water that was evapotranspired from below the water table. When the groundwater table was at the ground surface, evapotranspiration occurred at the potential evapotranspiration rate. When the depth of the water table exceeded a specified interval termed the limiting depth, groundwater evapotranspiration was set equal to zero. The limiting depth was correlated with the plant rooting depth. Between these limits, the groundwater evapotranspiration component varied linearly with the water table elevation.

The surface evapotranspiration component varied according to the relative rates of potential evapotranspiration and infiltrating precipitation. If the rate at which precipitation was infiltrating was greater than or equal to the potential evapotranspiration rate, soil moisture was not limiting and the surface evapotranspiration rate was set equal to the potential evapotranspiration rate. Just a portion of the precipitation that was infiltrating into the soil was evapotranspired from the surface component, the remainder of the water was assumed to percolate to the groundwater table. If the rate at which precipitation was infiltrating was less than the potential evapotranspiration rate, the soil moisture content was limiting and the surface evapotranspiration rate was set equal to the infiltrating precipitation rate.

The total amount of precipitation infiltrating the soil was evapotranspired from the surface component.

The sum of the two evapotranspiration components (GWET plus SET) could not exceed the potential evapotranspiration rate (PET); this constraint was incorporated into the model.

During model simulation, the value of the groundwater elevation was not allowed to exceed the ground surface elevation if the available storage capacity was filled and the groundwater table had risen to the ground surface; the excess water was considered to be surface runoff. For this condition effective recharge was equal to zero. In addition the value of the groundwater elevation could not fall below the value of the aquifer bottom at each node; this constraint was also incorporated into the model.

Sensitivity Analysis

A sensitivity analysis was conducted to provide insights about the input parameters relative influence on the model results and the simulated riparian water table response. The procedure involved keeping all input parameters constant at a selected standard level except for the one being analyzed and to vary that parameter through a range of possible values. Simulations with variation of the model input parameters for the hydraulic conductivity (K) and storativity (S) values, the head difference between the pond and stream stages (ΔDH), and the lateral gradient of the initial water table (SL) were performed. In addition, two sets of evapotranspiration and precipitation rates were selected to illustrate how relative levels of net recharge (R) affected the model results. The low, high and standard set of input parameters were chosen to represent the range of data input values used in this study, encompassing beaver pond sites in both western and central Oregon. This approach provided broader, more useful information for future modeling attempts. The standard set of input parameters used as constants for the sensitivity analysis were K = 0.10 m/day, S = 0.13, ΔDH = 1.0 m and SL = 0.0 percent. The R standard value was set equal to 0 m/day. This condition was chosen in order to better evaluate differences in the ground water table response due to variation of a single parameter. If the R standard value had not been 0 m/day, the outcome of the sensitivity analysis would have been masked by more than one fluctuating variable (the influence of the R on the groundwater table was not uniform over the modeled area, but varied from cell to cell because it was partly dependent upon the elevation of the groundwater table). The K value was varied from 0.01 to 1.00 m/day for evaluation, the S value was varied from 0.05 to 0.20, the ΔDH term was varied from 0.3 to 1.7 m and the SL parameter was varied from - 5 to 5 percent. The R value was varied by using companion input values of 0.0017 m/day PI and 0.0008 m/day PET, and 0.0033 m/day PI and 0.0017 m/day PET.

Parameters held constant throughout each sensitivity analysis simulation included those defining the ground surface, aquifer bottom and initial groundwater table. The ground surface in each case had a 5 percent slope perpendicular to and upwards from the channel and a 3 percent longitudinal slope parallel to the channel.

The aquifer bottom had a 0 percent lateral slope and a 3 percent slope parallel to the channel. The slope and orientation of the initial water table was similar to the aquifer bottom. The vertical distance between the aquifer bottom and the ground surface was 10 m; the initial water table was 8 m above the aquifer bottom. The total simulation time period for each case was 30 days.

Assumptions and Limitations

The main assumptions used in the model portion of the study are as follows (Wang and Anderson, 1982):

1) The aquifer was homogenous and isotropic;
2) Flow was horizontal and uniform everywhere in a vertical section;
3) The slope of the water table was mild, so that the flow velocity could be assumed proportional to the tangent of the angle of slope of the water table instead of the sine;
4) The stream was hydraulically connected to the groundwater aquifer and acted as a boundary of known head;
5) Groundwater flow through the riparian aquifer could be described by Darcy's Law;
6) The potential surface flux or R values were uniform over a time interval in a vertical section.

The model was limited since field conditions exist for which some or all of the above assumptions are not valid. The simulation results approximated the groundwater table configurations within natural aquifers, however the developed model lacked the detailed reality of the complex hydrologic interactions that occur within riparian systems. An important feature of lotic ecosystems is a high level of spatio-temporal heterogeneity. A signature of this heterogeneity is found in the extent, pattern and composition of the alluvial deposits. One of the greatest limitations may have been in assuming the aquifer was homogenous and isotropic. Also, using time-averaged data reduced variation in groundwater table response. Future research should include the effects of substrate variation and temporal fluctuations in recharge on water table dynamics within riparian aquifers. In addition, possible errors associated with the field measurements used to determine input data values may have introduced model inaccuracies.

Part II: Case Study

Site Description

The Oak Creek study site is within McDonald-Dunn Forest near the eastern foothills of the Coast Range, approximately 3 km northwest of Corvallis, Oregon. The Forest is managed by Oregon State University College of Forestry and consists of 4500 ha of predominately forested land. The site is located along a portion of Oak Creek in Township 11 South, Range 5 West, Section 17, as shown in Figure 4. Oak Creek drains a 1.75 km^2 watershed above the study site and is a first-order stream at this point. The creek joins with other tributaries downstream and flows

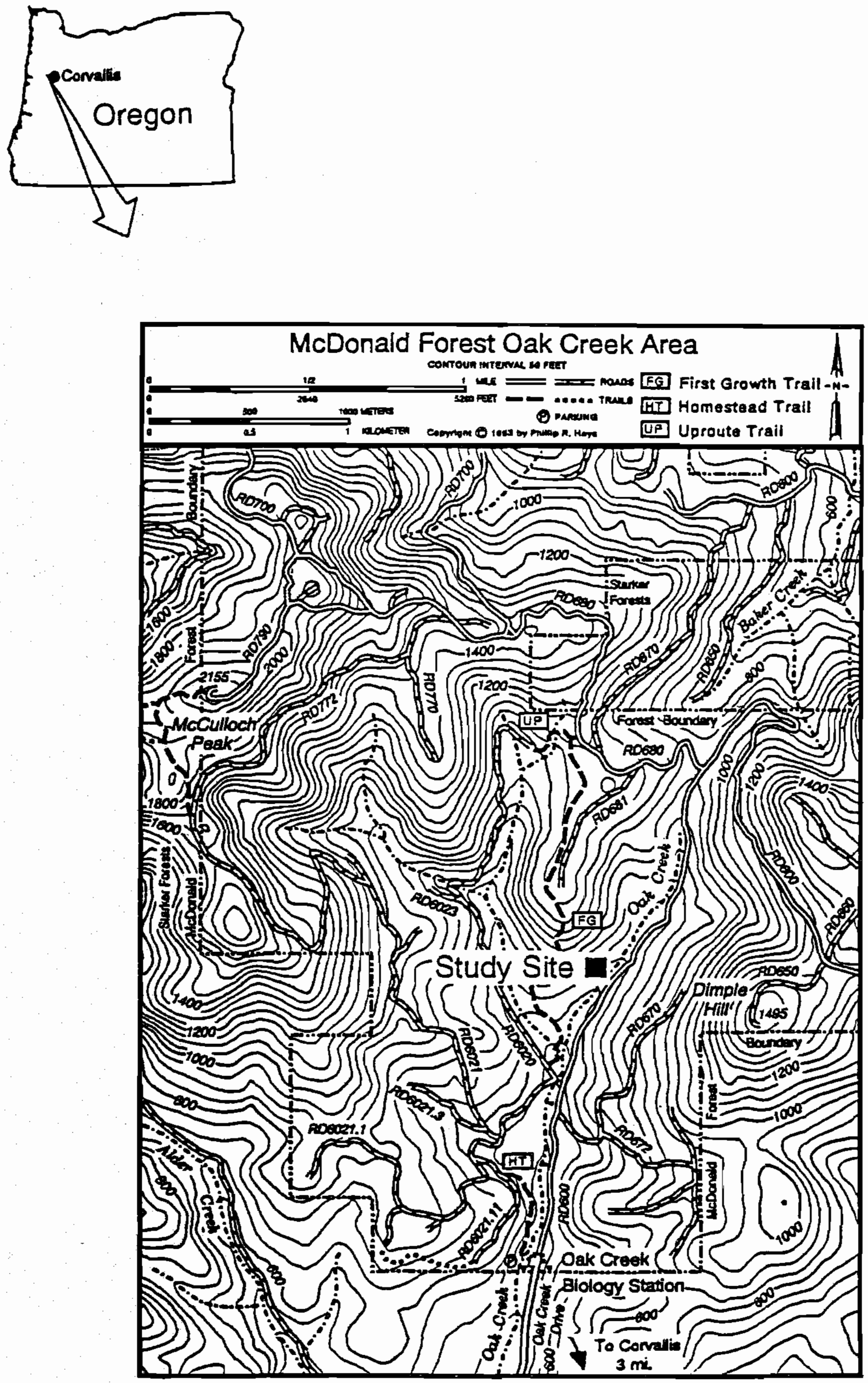


Figure 4. Location of the Oak Creek study site within McDonald Forest near Corvallis, Oregon.

into Marys River; the main channel is approximately 12 km long. The landscape position of the study site is adjacent to the current channel and on a relict alluvial fan deposit. The channel within the vicinity of the study reach is composed of a series of beaver ponds forming pools, falls and glides. A single pond-riparian area-downstream reach was chosen from the local pond complex for the monitoring site. The pool has a surface area of approximately 150 m^2 and the dam height ranges between 0.8 and 1.0 m high. Tree ring analysis indicates the pond area has been flooded for at least 8-10 years. A series of small rivulets and two larger streams flow out of and below the beaver dam. The average stream gradient within the vicinity of the study site is 3 percent and the lateral slope of the ground surface adjacent to the pond is 7 percent.

The parent material underlying most of McDonald Forest is the Siletz River Volcanics, a basalt formation. Recent alluvium derived from this rock forms the basis for the Waldo soil series at the study site (Rowly and Jorgensen, 1983). This series consists of deep, poorly drained clayey soils with low permeabilities and fine textures. Low chroma mottles and grey-black coloration at lower profile depths indicate long periods of saturation and a reducing environment. The depth to underlying bedrock at the site is greater than 2.5 m.

The climate in the Oak Creek area is characterized as "winter wet and summer dry". The Forest is in the rain shadow of the Oregon Coast Range and receives 100 to 150 cm of precipitation annually; nearly all occurs as low to moderate intensity rainfall. Typically, 80 percent of the annual precipitation occurs

Table 8. Monthly precipitation and temperature values for the Oak Creek site (Taylor, 1992).

Month	Monthly Normals 1961-1990		Month	Monthly Values July 1991-July 1992	
	Ppt. cm	Mean Temp. °C		Ppt. cm	Mean Temp. °C
			Jul 91	1.0	19.6
Aug	2.2	19.0	Aug	1.8	19.7
Sep	3.8	16.4	Sep	0.5	18.8
Oct	7.9	11.7	Oct	6.5	12.7
Nov	17.3	7.5	Nov	13.0	8.5
Dec	19.6	4.3	Dec	11.1	5.1
Jan	17.3	4.1	Jan 92	11.5	6.3
Feb	12.8	6.0	Feb	11.5	8.6
Mar	11.6	7.8	Mar	2.6	10.3
Apr	6.5	9.6	Apr	10.4	12.1
May	5.0	12.6	May	0.0	15.8
Jun	3.1	16.1	Jun	3.0	18.6
Jul	1.3	18.7	Jul	3.0	20.1
Total	108	-----	Total	75.9	-----
Average	-----	11.2	Average	-----	14.7

during October through March. Precipitation is routed to the channel primarily as subsurface flow. Mean monthly precipitation varies between 19.6 cm in December and 1.3 cm in August; mean monthly temperature ranges between 3 °C in January to 18 °C in August, as given in Table 8 (Taylor, 1992). Monthly precipitation and average temperature values during the study period from July 1991 to July 1992 are also listed in Table 8.

A mixed vegetation community occurs at the site. The dominant overstory species is second growth Douglas fir. In addition, Oregon ash (Fraxinus latifolia), bigleaf maple and red alder are present. The understory is primarily composed of scattered tall shrubs and brush; species include blackberry (Rhubus sp.), California hazel (Corylus cornuta), snowberry (Symphoricarbos albus), vinemaple (Acer circinatum) and wildrose (Rosa gymnocarpa). Also common within the understory are mixed forbes, bracken and the grass species false brome (Brachypodium sylvaticum).

Most of the plants at the site are classed as upland or transitional species. However, wetland indicators were common within a marginal strip 1 to 2 m wide along the border of the pond; these species include the forbes water-parsley (Oenanthe sarmentosa), nettle (Urtica dioica) and solomon-plume (Smilacina stellata). A distinct assemblage of bulrush (Scirpus microcarpus) and horsetail (Equisetum telmateia) begins directly adjacent to the beaver dam and spreads into an approximately 4 m wide band within the riparian zone downstream of the pond.

Data Collection Methods and Facilities

The depth to the free water surface in the groundwater observation wells at the study site was measured with a water level sounder and recorded on a weekly basis from July 4, 1991 to July 30, 1992. Also, pond and stream stages were measured during each site visit so that comparisons to riparian aquifer water levels could be made. A total of 37 observation wells were placed on the northwest side of the pond and channel to allow measurement of groundwater levels and the saturated zone dimensions throughout the study area, as shown in Figure 5. Stilling wells were placed at the edge of the beaver pond and in the stream below the dam. The wells were arranged in transects that were perpendicular to the channel; transects A through C were next to the beaver pond, D was adjacent to the dam and E through H were downstream of the beaver pond. The wells were spaced closest together near the channel and dam where the greatest hydraulic head difference and associated groundwater flux existed. Transects A through D were placed 13 m apart, D through G were 3 m apart and the distance between transects G and H was 7 m. The distance between the wells within the transects was variable. Wells closest to the dam were located at 2 m intervals, wells further away were spaced 6 m apart.

The wells used for the study site were open standpipe type, typically used for measuring the free water surface in an unconfined aquifer. The wells were constructed from 2.54 cm diameter polyvinyl chloride (PVC) pipes that were screened by drilling circumferential sets of 6 holes, 3 mm in diameter, at 1.2 cm

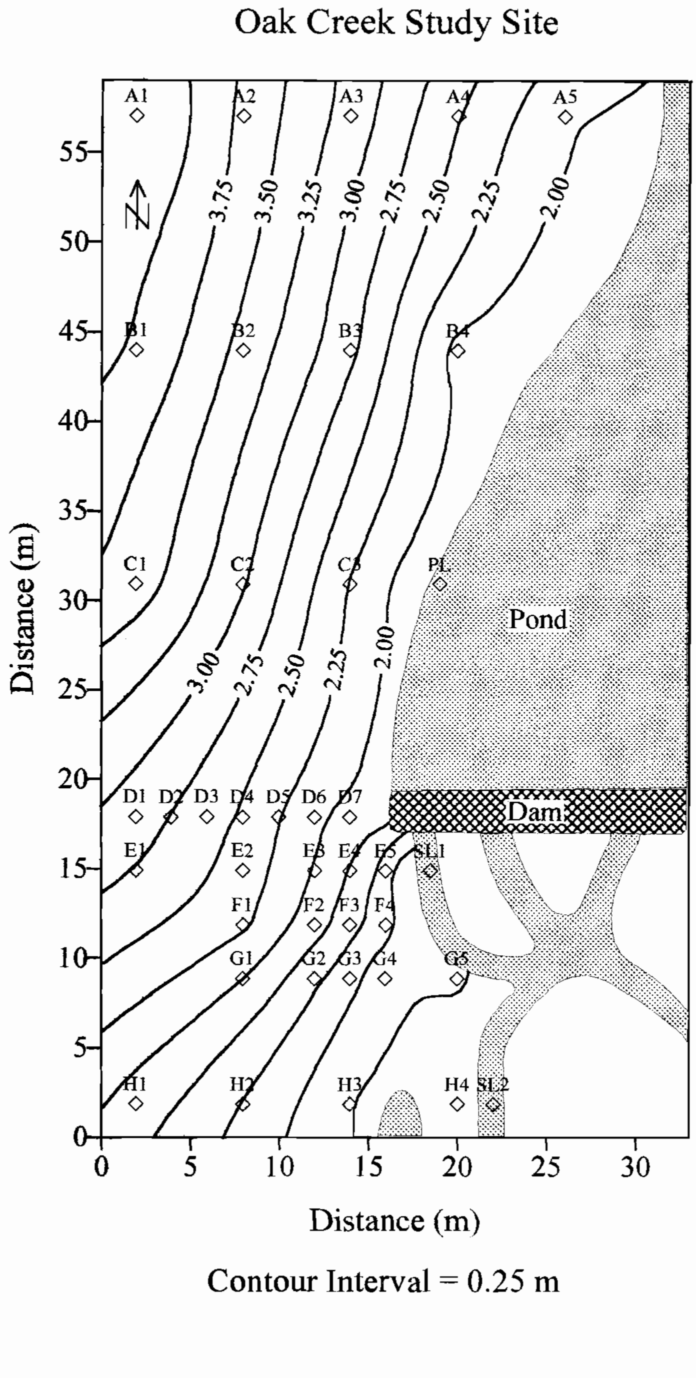


Figure 5. Topography of the Oak Creek study site including the location of the monitoring wells.

intervals along the length of each pipe from the base to approximately 10 cm from the top. The inside of each well was lined with meshed geotextile fabric to prevent sediment from entering the well interior. The lower end of each well was closed off with a conical wooden plug.

The wells were installed by boring vertical holes into the ground with a soil probe that had a slightly smaller diameter than the well pipes; the pipes were then fit into the holes. The soil cores were collected from the probe, stored in troughs and then later used to determine soil textural classes at each well location. A bentonite seal was placed around the upper 10 cm of each pipe to prevent surface water from flowing down the pipe wall; also, each pipe was covered with a loose-fitting PVC cap.

The pond stilling well was constructed with an L-shaped section of PVC pipe that was attached to a post located adjacent to the pond edge. The lower portion of the pipe was placed below the pond surface and extended horizontally into the pond, allowing water to flow in. Pond stage (ie. the level of the water within the pipe) was measured in the upper, vertical pipe section. Similar stilling wells were constructed adjacent to the stream at two locations below the dam.

The well depths were variable and were determined by the estimated depth to saturation during the drier summer months when the groundwater table was lowest. Well depths ranged from 1.0 to 2.0 m; depths increased with distance from the pond and stream since groundwater levels were assumed to be deeper relative to the ground surface when further away from the channel.

Topographic measurements of the ground surface, wells and relative groundwater levels were made in order to create graphics of the ground surface and the water table at the study site. The wells were surveyed to determine their elevation and horizontal distance relative to a datum. The measured distance between the top of each well and the free water surface was converted to the height of the water surface relative to the datum.

Hydraulic conductivity tests were performed at each well location to estimate the anticipated rate and direction of groundwater flow by using Darcy's Law. This information was used to determine well placement and to provide information necessary for interpretation of field groundwater monitoring results. Hydraulic conductivity tests were performed as described in the model input data section. The estimated hydraulic conductivity values at the study site ranged from 0.004 to 0.035 m/day with a weighted average of 0.011 m/day. Appendix C includes the K values for each well. The K values were relatively high for clayey soils; this may be attributed to the presence of macropores commonly found within forest soils.

Storativity values were also estimated for the Oak Creek site and were estimated from the soil textures of the core samples (Dunne and Leopold, 1978) and from laboratory analysis rather than from pump tests due to equipment limitations. Portions of intact soil samples were collected from the mid-section of each well core. They were then saturated and extracted to field moisture capacity in order to determine water availability; the values for each well are given in Appendix C. The weighted average of the core sample storativity values was 0.06.

RESULTS AND DISCUSSION

This chapter contains the presentation of results obtained during the model and case study portions of this research; the potential effects of the subsurface flux of water between beaver ponds and adjacent riparian aquifers on groundwater table configurations, storage volumes and flow patterns are included. The previously outlined objectives provide the basis for discussion. In addition, the effect of pond adjacent groundwater regimes on several riparian zone ecological processes and characteristics are addressed.

Pond Effects on Riparian Groundwater Elevations

Objective Number One: Determine whether groundwater table elevations in riparian aquifers adjacent to beaver ponds are higher in comparison to those without beaver ponds.

Analysis of the riparian groundwater table configurations indicated that water table elevations in riparian aquifers adjacent to beaver ponds are higher in comparison to those without beaver ponds. An increase in pond adjacent groundwater levels was observed throughout the year in all simulated aquifers for the synthesized western and central Oregon sites as well as at the Oak Creek case study site. Supporting data are included in the following sections.

Pond Adjacent Saturated Wedge Dimensions

Objective Number Two: Estimate the potential maximum increase in the groundwater table elevations and the lateral extents of the expanded saturated zones on a monthly basis over a one year period.

The potential increase in the ground water table elevations and in the dimensions of the expanded saturated zone varied with each riparian aquifer system. The expanded saturated zone due to the effect of the beaver pond can be viewed as a wedge shaped lense that extended into the floodplain adjacent to and downstream of each pond. This lense was bounded above by the ground water table when the beaver pond was present and below by the ground water table when the beaver pond was not present in the riparian aquifer. These 'with pond' and 'without pond' groundwater table configurations were produced during the riparian aquifer simulations of the synthesized Western and Central Sites. The 'with pond' groundwater tables for the Oak Creek site were determined from the well monitoring data. The 'without pond' groundwater tables at Oak Creek were estimated by extrapolating the above pond and downstream groundwater profiles to the pond adjacent aquifer location. Results indicated that the maximum increase in the vertical and lateral extent of the expanded saturated zone occurred adjacent to the dam; the lense was thickest where the water elevation increase between the stream stage and the pond stage was the greatest. The thickness of the lense decreased radially away from the pond as the effect of the pond on the riparian groundwater table elevations diminished.

For each simulated riparian system, cross-sectional groundwater table profiles were generated using the computed values of water table elevations that were lateral to the dam location. Profiles representing winter and summer groundwater configurations for the Western and Central Site simulations are shown in Figures 6 through 9. Groundwater table profiles for consecutive monthly intervals are presented in Figures D1 through D24, found in Appendix D. Results of simulations with beaver ponds and associated simulations without ponds are paired on the same graph to allow for comparison. The maximum increase in the ground water table elevation that occurred adjacent to each beaver pond was measured as the vertical difference between paired profiles. The maximum lateral extent of the elevated ground water table was the distance from the dam edge to where the ponded and unponded groundwater table profiles converged. Monthly values of the maximum vertical and lateral dimensions of the increased saturated zone associated with each beaver pond-riparian aquifer system are given in Tables 9 and 10.

Results of the model simulations for the Western Site are included in the following section. The groundwater table results from Case WS showed the smallest increase in the spread of the saturated zone. This simulated aquifer had the lowest dam height and the finest textured soil (K=0.001 m/day). The maximum increase in the groundwater table elevation of 0.3 m occurred directly adjacent to the dam

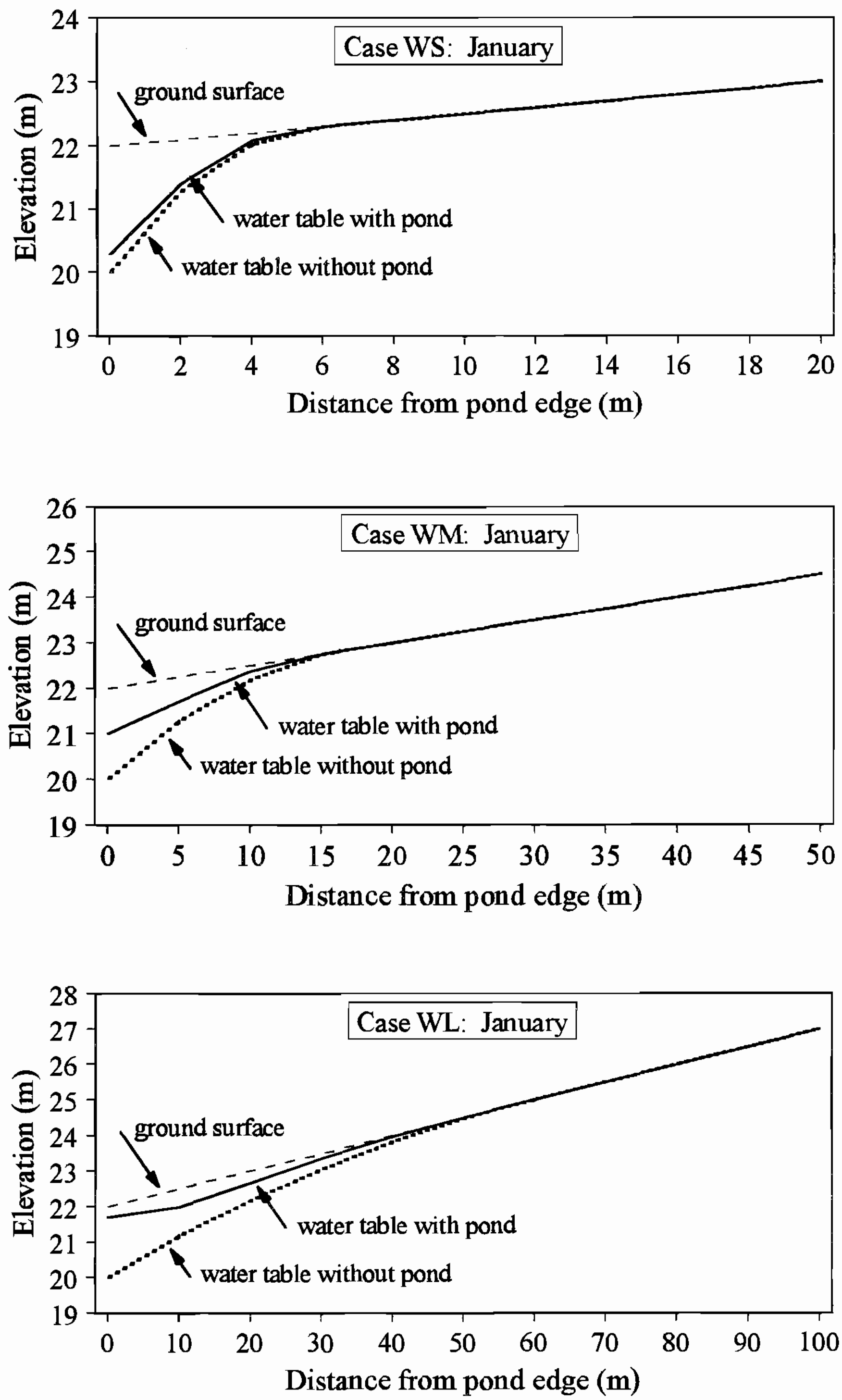


Figure 6. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Cases WS, WM and WL during January.

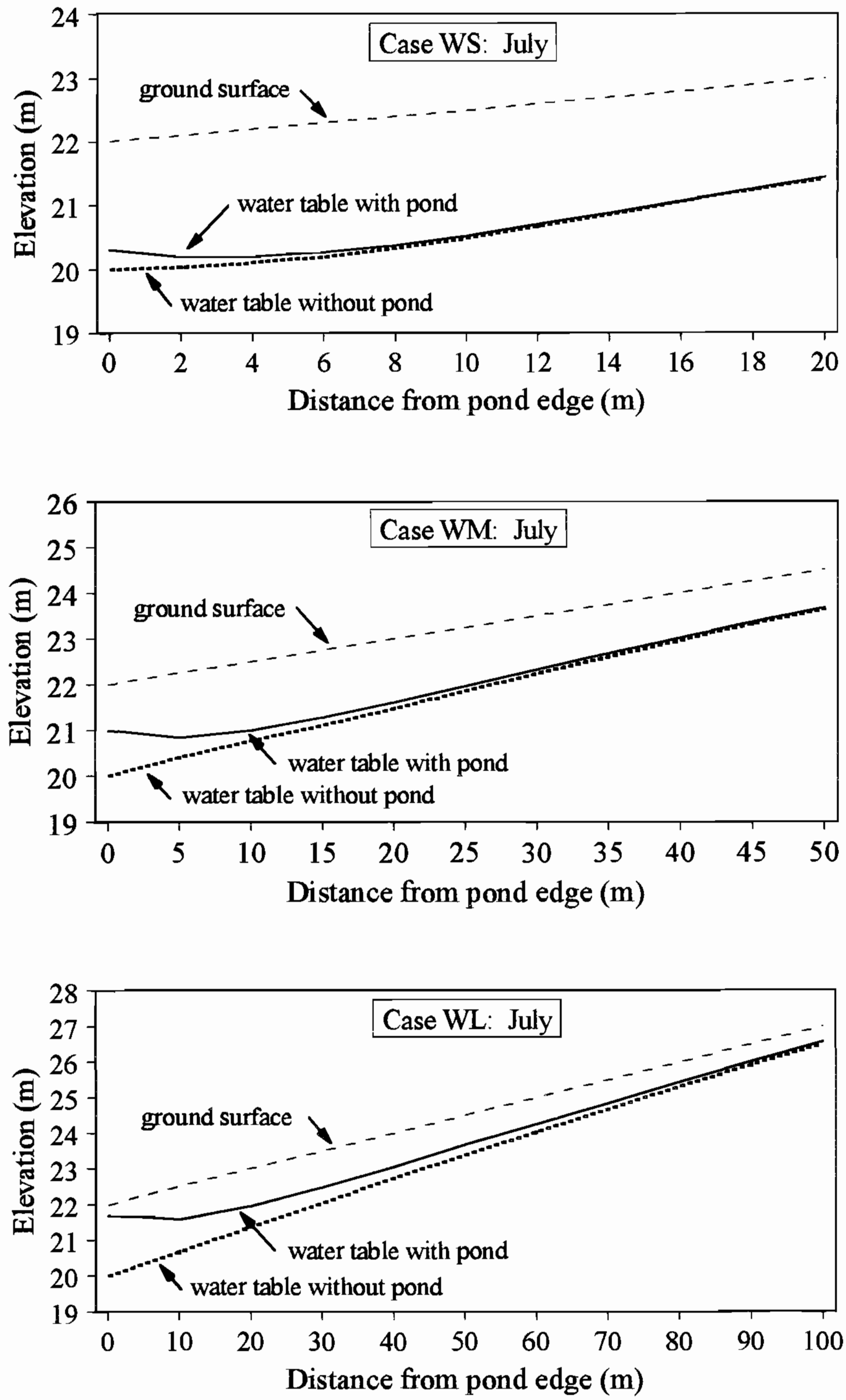


Figure 7. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Cases WS, WM and WL during July.

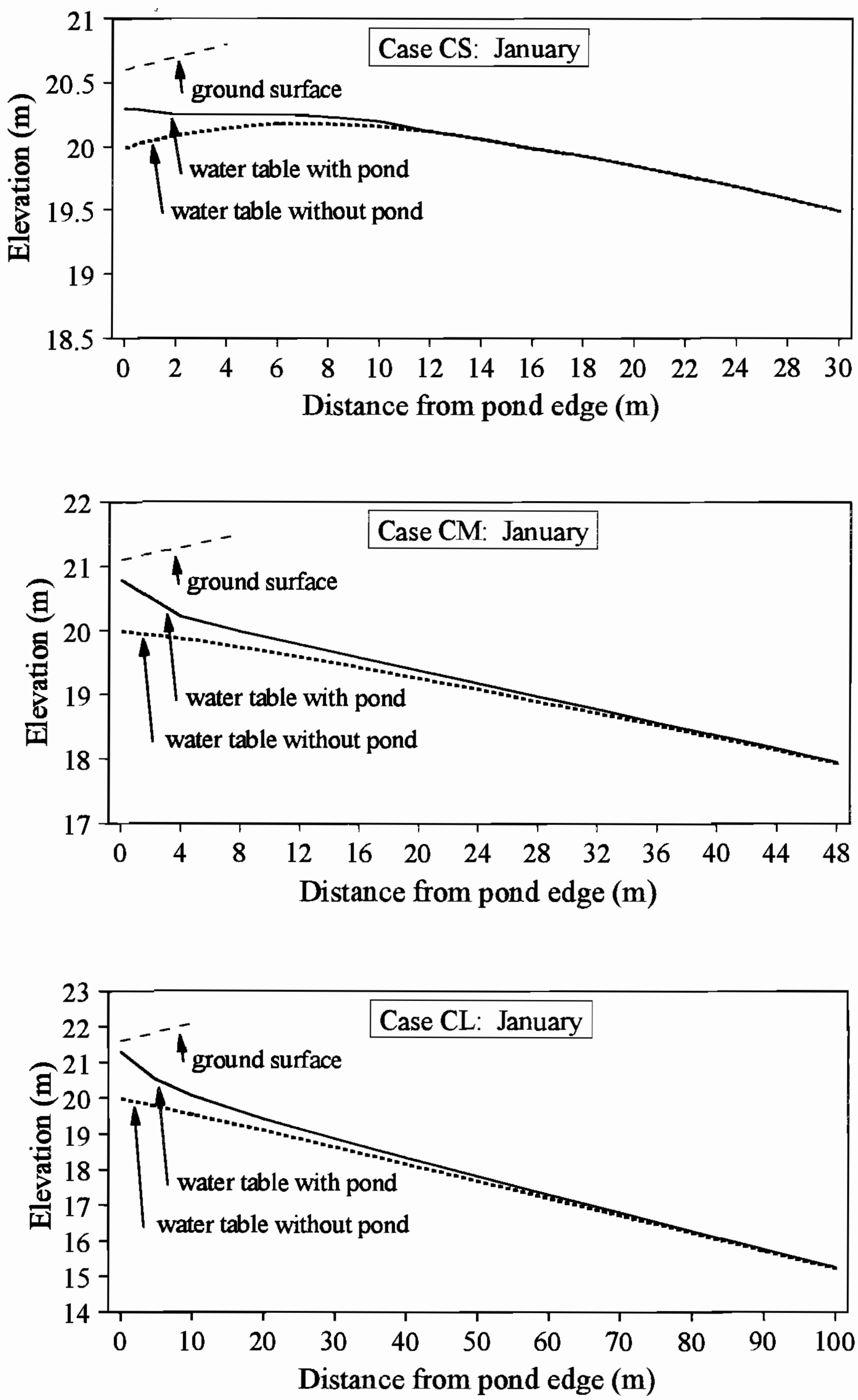


Figure 8. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Cases CS, CM and CL during January.

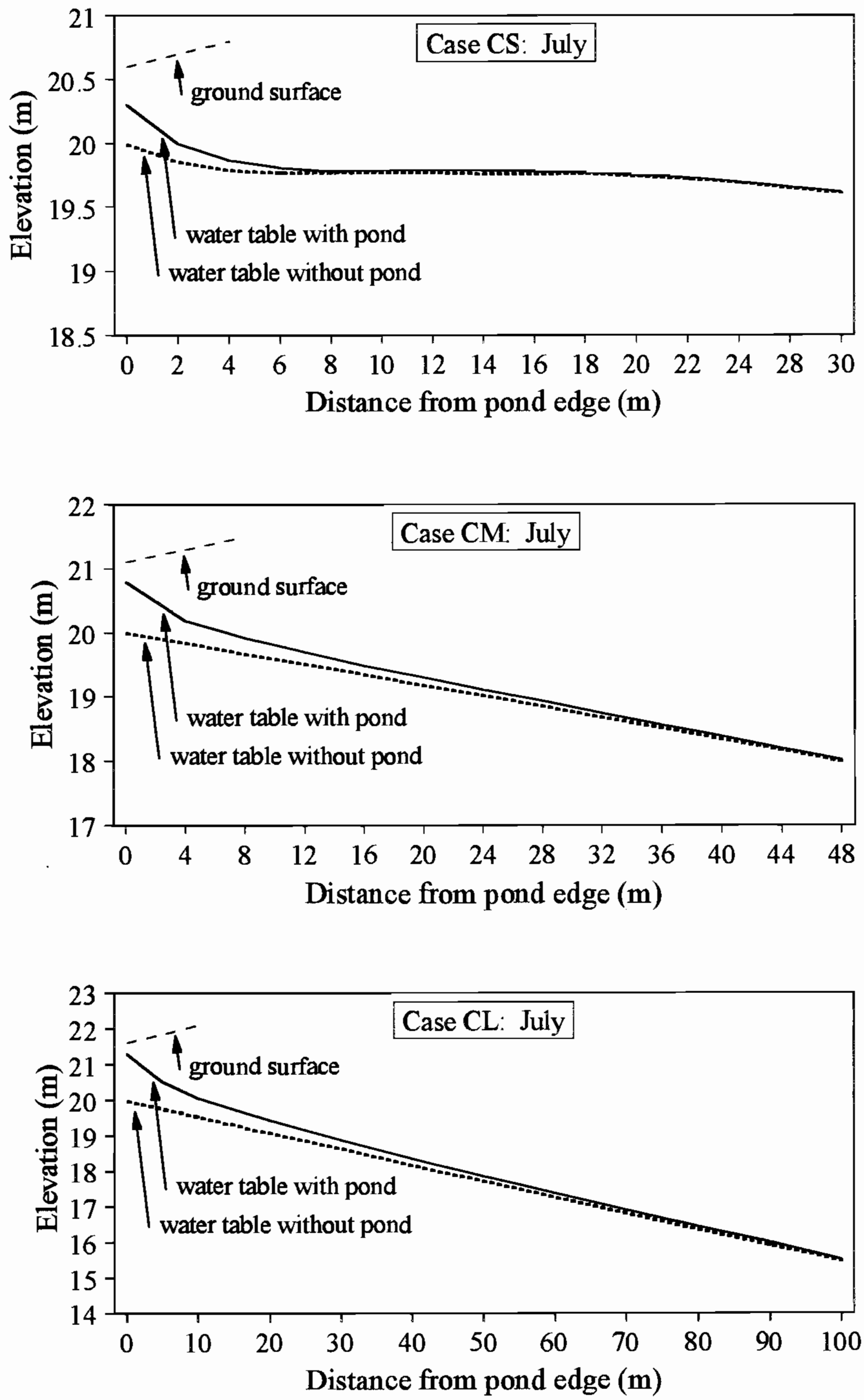


Figure 9. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Cases CS, CM and CL during July.

Table 9. Maximum vertical and lateral dimensions of the pond-adjacent saturated wedge for Cases WS, WM and WL.

Month	Case WS		Case WM		Case WL	
	Max. Vertical m	Max. Lateral m	Max. Vertical m	Max. Lateral m	Max. Vertical m	Max. Lateral m
Sep	0.3	8	1.0	25	1.7	70
Oct	"	8	"	35	"	90
Nov	"	10	"	35	"	90
Dec	"	6	"	20	"	55
Jan	"	6	"	15	"	45
Feb	"	6	"	15	"	45
Mar	"	4	"	20	"	55
Apr	"	4	"	20	"	60
May	"	8	"	25	"	70
Jun	"	8	"	35	"	80
Jul	"	10	"	35	"	90
Aug	"	8	"	20	"	80

Table 10. Maximum vertical and lateral dimensions of the pond- adjacent saturated wedge for Cases CS, CM and CL.

Month	Case CS		Case CM		Case CL	
	Max. Vertical m	Max. Lateral m	Max. Vertical m	Max. Lateral m	Max. Vertical m	Max. Lateral m
Sep	0.3	12	0.8	26	1.3	45
Oct	"	12	"	32	"	55
Nov	"	10	"	32	"	65
Dec	"	10	"	32	"	70
Jan	"	10	"	34	"	75
Feb	"	10	"	36	"	75
Mar	"	10	"	38	"	75
Apr	"	16	"	40	"	75
May	"	12	"	40	"	75
Jun	"	8	"	40	"	80
Jul	"	8	"	40	"	80
Aug	"	8	"	40	"	85

and was the same throughout each month of the simulation. The lateral dimension of the pond-adjacent saturated zone extended to 10 m by November, decreased to 4 m by March, spread to 10 m by July and decreased to 8 m in August. The pond-adjacent expansion of the saturated zone was greater in Case WM, in which the dam height was higher and the soil was more coarsely textured (K=0.10 m/day) than that in Case WS. The maximum increase in the elevation of the groundwater table for each month was 1.0 m. The elevated water surface extended out into the floodplain for a lateral distance of 35 m by October, decreased to 15 m by January, spread to 35 m by June then decreased to 20 m in August.

The increase in the saturated zone due to the beaver pond was greatest for the Case WL simulation, which had the highest dam height and most permeable soil (K=1.0 m/day). The dam-adjacent increase in the groundwater table elevation was 1.7 m for all months. The lateral extent of the pond-adjacent saturated zone spread to 90 m by October, decreased to 45 m by January, extended to 90 m by July and then receded to 80 m in August.

The dimensions of the pond-adjacent saturated wedge associated with each Central Site simulation are included in the following section. In Case CS the increased spread of the subsurface saturated zone due to the pond was the smallest; the groundwater table adjacent to the dam was 0.3 m higher for all months than it was in the condition without the pond. The elevated groundwater levels spread for a lateral distance of 12 m during September, decreased to 10 m by November, increased to 16 m by April then decreased to 8 m by June.

Results of the model simulations for Case CM show the pond-adjacent saturated zone was greater than in Case CS. The increase in the dam-adjacent groundwater table elevation was 0.8 m throughout the year. The expanded saturated zone spread to 32 m by October, continued to spread to 34 m by January and extended to 40 m from April through August.

The dimension of the pond-adjacent saturated zone for the central site simulations was the greatest in Case CL. The maximum increase in the elevation of the groundwater table for each month was 1.3 m, equivalent to the dam height. The elevated water surface spread laterally into the floodplain for a distance 55 m during October, increased to 75 m by January and continued to spread until it reached 85 m by August.

The vertical and lateral dimensions of the pond-adjacent saturated wedge at the Oak Creek site are listed in Table 11. These values were determined from the monthly groundwater table profiles included in Figures D25 to D29 in Appendix D; profiles for July 1991, January 1992 and July 1992 are given in Figure 10. Phreatic configurations in natural riparian aquifers are the result of great temporal and spatial hydrologic complexity; the diverse hydrologic interactions and aquifer properties inherent in natural systems produce varying groundwater tables. The monthly pond-adjacent groundwater tables shown are more simplified representations obtained by averaging weekly data collected during July 4, 1991 to July 30, 1992. The water table profiles representing the groundwater table configurations without the presence

Table 11. Maximum vertical and lateral dimensions of the pond adjacent saturated wedge for the Oak Creek site.

Month	Max. Vertical m	Max. Lateral m
Jul 1991	0.75	10
Aug	0.80	10
Sep	0.80	12
Oct	0.80	12
Nov	0.85	12
Dec	0.85	10
Jan 1992	0.85	10
Feb	0.85	10
Mar	0.85	10
Apr	0.80	10
May	0.80	12
Jun	0.80	12
Jul	0.75	12

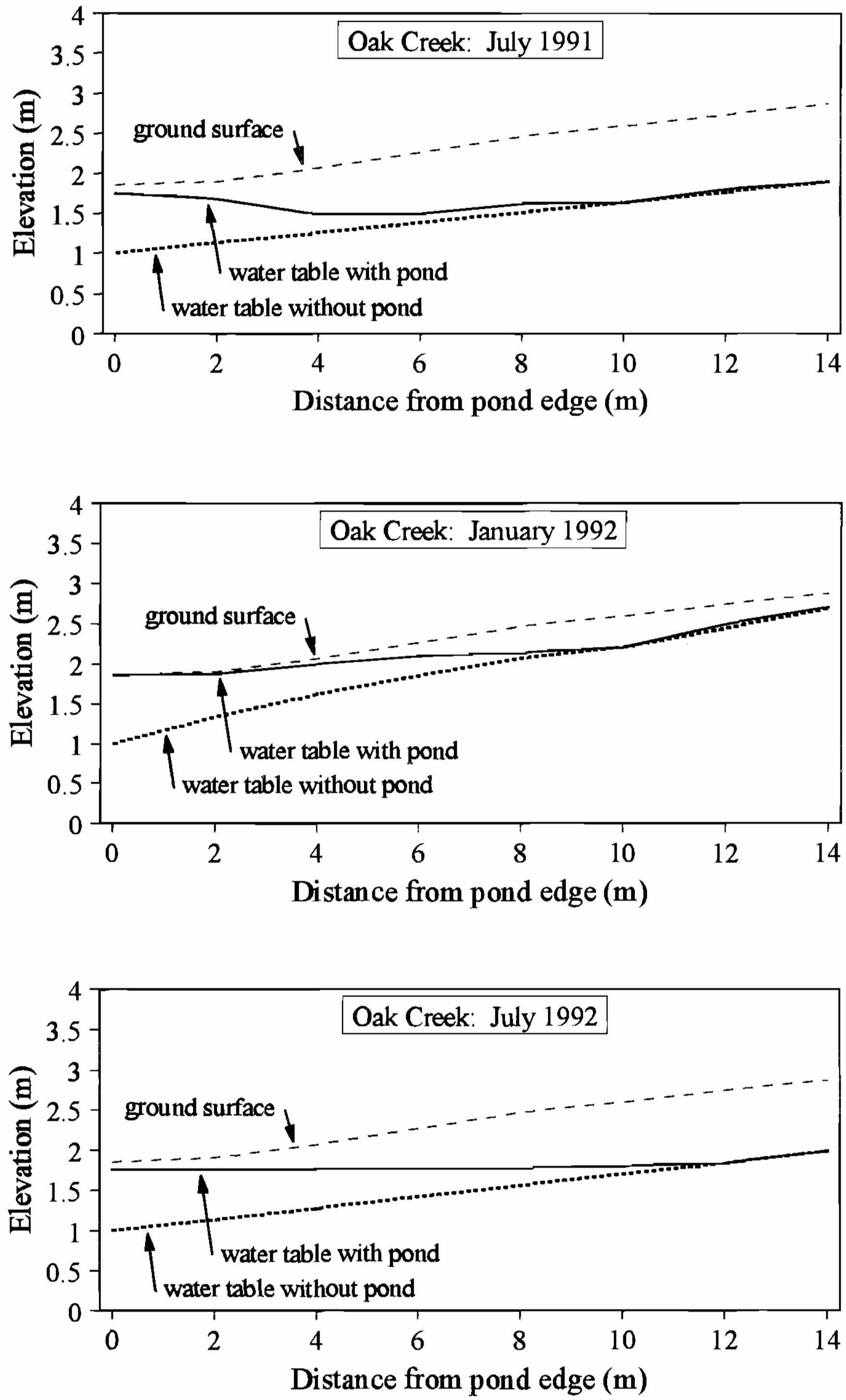


Figure 10. Riparian groundwater table elevations at the Oak Creek Site during July 1991, January 1992 and July 1992.

of the pond were extrapolated from the above-pond and downstream phreatic surfaces and are approximations.

The maximum vertical increase in the riparian groundwater level due to the pond occurred adjacent to the dam and was approximately 0.8 m throughout the year. The elevated water surface extended laterally into the riparian aquifer to approximately 10 m during July and August, increased to 12 m from September through November, decreased to 10 m from December through April, then increased to 12 m from May through July.

Comparison of the results shows that increased dimensions of the pond-adjacent saturated wedge were associated with increased dam heights and substrate hydraulic conductivities. This finding is consistent with Darcy's Law, since the hydrologic flux between the pond and the connected riparian aquifer was directly proportional to the increased head between the pond and stream level and associated hydraulic gradients, and to the hydraulic conductivity. The simulations for the Western Site which had higher dam heights than those of the Central Site had proportionally increased pond-adjacent groundwater table elevations. The dimensions of the pond-adjacent saturated wedge at the Oak Creek site were between those produced for the Western Site Cases WS and WM. These results were consistent since the dam height and the hydraulic conductivity of the soils at the Oak Creek site were intermediate to values used for the dam heights and hydraulic conductivities for Cases WS and WM. The lateral extents of the pond-adjacent wedge at the Oak Creek site were relatively small due to the clayey soils with low hydraulic conductivities.

Saturated Soil and Stored Groundwater Volumes

Objective Number Three: Quantify the increased saturated soil and stored groundwater volumes in pond-adjacent aquifers.

The pond-adjacent saturated soil and groundwater storage volumes were estimated for each riparian aquifer system using the groundwater tables produced during the aquifer simulations and the results from the Oak Creek study. The volume of the pond-adjacent saturated soil wedge was bounded above by the water table when the beaver pond was present and bounded below by the water table when the beaver pond was not present in each pond-riparian aquifer system.

The saturated soil volumes were calculated from the simulation results by determining the difference between the 'with pond' and 'without pond' groundwater table elevations at each node and multiplying this value by the cell area associated with each node, then summing the resulting values. These saturated soil volumes were calculated on a monthly basis for each simulated riparian aquifer system and are listed in Tables 12 and 13. The pond-adjacent stored groundwater volumes were found by multiplying the volume of the saturated soil lense by the storativity value used during model simulations for each riparian aquifer. Monthly values of this water volume for each simulated aquifer are also found in Tables 12 and 13.

Table 12. Pond-adjacent saturated soil and stored groundwater volumes for Cases WS, WM and WL.

Month	Case WS		Case WM		Case WL	
	Sat. Soil Vol. m^3	St. Gw. Vol. m^3	Sat. Soil Vol. m^3	St. Gw. Vol. m^3	Sat. Soil Vol. m^3	St. Gw. Vol. m^3
Sep	12	0.6	250	33	2000	400
Oct	16	0.8	370	47	2800	560
Nov	19	1.0	440	58	3400	680
Dec	10	0.5	150	20	2000	400
Jan	10	0.5	92	12	1200	240
Feb	10	0.5	92	12	1200	240
Mar	10	0.5	130	17	1500	300
Apr	10	0.5	140	17	1500	310
May	12	0.6	250	33	2000	410
Jun	13	0.7	370	48	2900	580
Jul	17	0.9	300	39	3500	700
Aug	14	0.7	260	33	3100	620

Table 13. Pond-adjacent saturated soil and stored groundwater volumes for Cases CS, CM and CL.

Month	Case CS		Case CM		Case CL	
	Sat. Soil Vol. m^3	St. Gw. Vol. m^3	Sat. Soil Vol. m^3	St. Gw. Vol. m^3	Sat. Soil Vol. m^3	St. Gw. Vol. m^3
Sep	12	0.6	140	18	930	190
Oct	14	0.7	170	22	1200	230
Nov	18	0.9	190	25	1300	260
Dec	22	1.1	210	27	1400	270
Jan	24	1.2	210	28	1400	280
Feb	26	1.3	220	28	1500	290
Mar	28	1.4	220	29	1500	300
Apr	30	1.5	220	29	1500	300
May	28	1.4	220	29	1600	310
Jun	23	1.2	220	29	1600	310
Jul	21	1.1	220	29	1600	320
Aug	20	1.0	220	29	1600	320

The given values represent estimated saturated soil and groundwater storage volumes for only one side of the pond. The total pond-adjacent saturated soil and groundwater storage volumes would be double the given amounts, assuming equal volumes are present on the opposite sides of each pond.

For each site, the change in the saturated soil volume and in the amount of stored groundwater due to the presence of the beaver pond varied throughout the year. Simulation results from the Western Site show that for all cases the pond induced saturated soil lense and stored groundwater volumes increased as fall progressed, decreased during the winter, increased again in the spring and early summer, then receded again in late summer. Case WS had saturated soil lense volumes of 19, 9.8, 18 and 15 m^3 for November, January, July and August, respectively, and associated ground water storage volumes of 1.0, 0.5, 0.9 and 0.7 m^3. The results from Case WM showed a similar trend; the saturated soil lense volumes were 440, 90, 370 and 260 m^3 during November, January, June and August, respectively. The pond-adjacent ground water storage volumes for these same months were 58, 12, 48 and 33 m^3. In Case WL, the pond-adjacent saturated soil lense increased to 3400 m^3 by November, decreased to 1200 m^3 by January, increased to 3500 m^3 by July and decreased again to 3100 m^3 in August. The associated ground water volumes were 680, 240, 700 and 620 m^3.

The results from the riparian aquifer simulations for the Central Site indicated that the spread in the saturated soil lense and the amount of stored groundwater due to the presence of the beaver pond generally increased or remained the same as the simulations progressed. An exception to this trend occurred during the late spring and summer months for Case CS, when volumes decreased relative to those present during mid-spring. In Case CS, the saturated soil lense reached 30 m^3 in April, then decreased to 20 m^3 by August. The increased groundwater storage volume progressed to a maximum of 1.5 m^3 in April and receded to 1.0 m^3 by August. The results from Case CM show that the largest volume of the pond induced saturated soil lense increased to 220 m^3, and the associated ground water storage volume was 29 m^3 by the month of February. The remaining months from March to August showed a similar pattern of response, resulting in relatively little change in both volumes. The saturated soil lense volume for Case CL increased to 1600 m^3 by the end of the simulation in August; the increased groundwater storage volume was 320 m^3 at this time.

A similar technique was used to calculate the saturated soil lense and groundwater storage volumes at the Oak Creek site, except that the average monthly groundwater levels were used to represent the 'with pond' configurations and the groundwater tables extrapolated from above and below the pond to the pond-adjacent aquifer location were used to estimate the 'without pond' configurations. Estimates of the pond-adjacent saturated soil and stored groundwater volumes at the Oak Creek site for each month are listed in Table 14.

The saturated soil and stored groundwater volumes at the Oak Creek site showed similar trends to those produced during the Western Site simulations; they increased during fall, decreased during winter, increased again in spring and

Table 14. Pond-adjacent saturated soil and stored groundwater volumes for the Oak Creek site.

Month	Sat. Soil Vol. m^3	St. Gw. Vol. m^3
Jul 1991	71	4.9
Aug	73	5.1
Sep	77	5.4
Oct	110	7.3
Nov	110	7.7
Dec	99	7.0
Jan 1992	100	7.1
Feb	98	6.9
Mar	100	7.0
Apr	96	6.7
May	110	7.6
Jun	120	8.1
Jul	100	7.2

decreased in summer. The pond-adjacent saturated soil lense volumes for the months of July and November 1991, and February, June and July 1992 were 71, 110, 98, 120 and 100 m^3, respectively. The associated groundwater storage volumes for the same months were 4.9, 7.7, 6.9, 8.1 and 7.2 m^3. These values fell between those produced during the simulations for the Western Site Cases WS and WM.

The pond-adjacent saturated soil lense and stored groundwater volumes associated with each riparian system were commensurate with the increase in the groundwater table elevation due to the pond and the associated area of interface between the pond and adjacent channel banks, and with the storativity or specific yield of the aquifer substrate. These volumes were greatest in the simulation Cases WL and CL which had the highest dam heights, hydraulic conductivities and related pond-adjacent groundwater table elevations, larger interface areas and soils with high storativities. The volumes were least in Cases WS and CS, which had the lowest dam heights, hydraulic conductivities and related pond-adjacent groundwater tables, smaller interface areas, and the lowest storativities. The volume increases at the Oak Creek site were relatively small due to the clayey soils with low hydraulic conductivity and storativity values. In each case, the volume increases were greatest near the dam where the pond-adjacent saturated wedge was thickest.

Groundwater Table Responses In Effluent and Influent Stream Systems

Objective Number Four: Describe the effects of beaver ponds on riparian zone groundwater table configurations and flow dynamics in effluent and influent stream systems.

The effect of beaver ponds on riparian zone groundwater configurations and flow dynamics depended upon local groundwater hydraulic characteristics. The groundwater table gradients between the channel and connected aquifer affected the directions and relative rates of flow within each pond-stream-riparian groundwater system.

One means by which a beaver pond could contribute to locally elevated groundwater levels was by inducing the lateral flow of water from the pond into the adjacent channel banks and floodplain. This groundwater 'spreading' occurred when the pond level was greater than the downstream and adjacent riparian groundwater levels. The groundwater table profiles in Figure 11A illustrates this type of flow. The hydraulic head of the pond was greater than the hydraulic head of the stream level without the presence of the beaver pond; the resulting hydraulic differential created an increase in the pond adjacent groundwater table gradient. When viewed in context of Darcy's Law, the increased hydraulic gradient caused a proportional increase in flow into the riparian aquifer and an associated increase in the groundwater elevation adjacent to the pond:

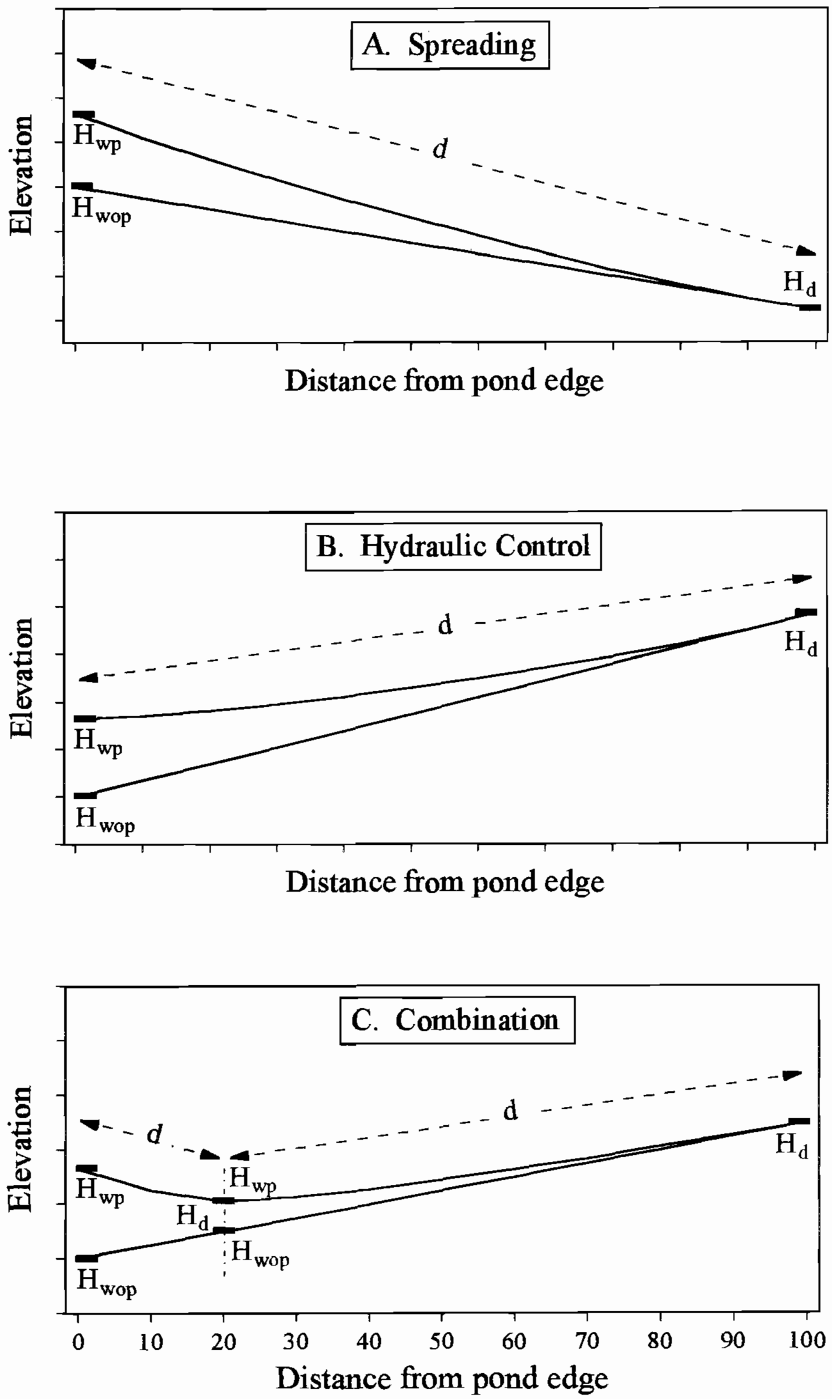


Figure 11. Hydraulic mechanisms that create elevated groundwater tables adjacent to beaver ponds include A) spreading, B) hydraulic control and C) a combination of spreading and hydraulic control.

$$\overleftrightarrow{Q}_{wp} = -AK\frac{H_d - H_{wp}}{d} \quad > \quad \overleftrightarrow{Q}_{wop} = -AK\frac{H_d - H_{wop}}{d}$$

where $\overleftrightarrow{Q}_{wp}$ = groundwater discharge rate from the channel towards the riparian zone when the pond was present

$\overleftrightarrow{Q}_{wop}$ = groundwater discharge rate from the channel towards the riparian zone when the pond was not present

A = cross-sectional area perpendicular to the direction of flow

K = saturated hydraulic conductivity

H_{wp} = elevated head due to effect of pond

H_{wop} = head without presence of pond

H_d = head at distance d

d = linear distance along direction of flow

A beaver pond could also cause elevated riparian groundwater levels by acting as a hydraulic control; this could occur when a hydraulic gradient from higher to lower potential existed from the saturated stream banks toward the pond, as shown in Figure 11B. The hydraulic head of the pond was greater in comparison to the stream level without the pond. Consequently, groundwater flowing towards the pond was maintained at a relatively higher level and the pond-adjacent water table was elevated. The hydraulic gradient as well as the flow rate from the upslope aquifer into the channel were reduced. This is described using Darcy's equation as:

$$\overleftrightarrow{Q}_{wp} = -AK\frac{H_{wp} - H_d}{d} \quad < \quad \overleftrightarrow{Q}_{wop} = -AK\frac{H_{wop} - H_d}{d}$$

where $\overleftrightarrow{Q}_{wp}$ = groundwater discharge rate from the riparian zone toward the channel when the pond was present

$\overleftrightarrow{Q}_{wop}$ = groundwater discharge rate from the riparian zone towards the channel when the pond was not present

and other variables are as previously defined.

The elevated water table adjacent to a beaver pond could also be due to a combination of both described hydraulic mechanisms, as shown in Figure 11C. Water could flow from the pond into the riparian aquifer when the pond level was higher than the adjacent riparian groundwater level. In addition, the subsequently elevated groundwater table within the riparian zone acted as a hydraulic control for inflowing groundwater from the upslope aquifer, maintaining higher groundwater tables and reducing subsurface flow from the upslope aquifer in the pond-adjacent area. The same hydraulic principles as previously described apply; the relatively elevated pond-adjacent groundwater table occured in response to a hydraulic differential between the ponded and unponded conditions. Groundwater flowed in a downhill, downvalley direction below the pond.

The descriptions of the pond-adjacent hydraulic relationships can be used to help interpret the effect of a beaver pond on riparian groundwater flow patterns. The groundwater profiles given in Figures 6 to 9 and D1 to D24 provide reference

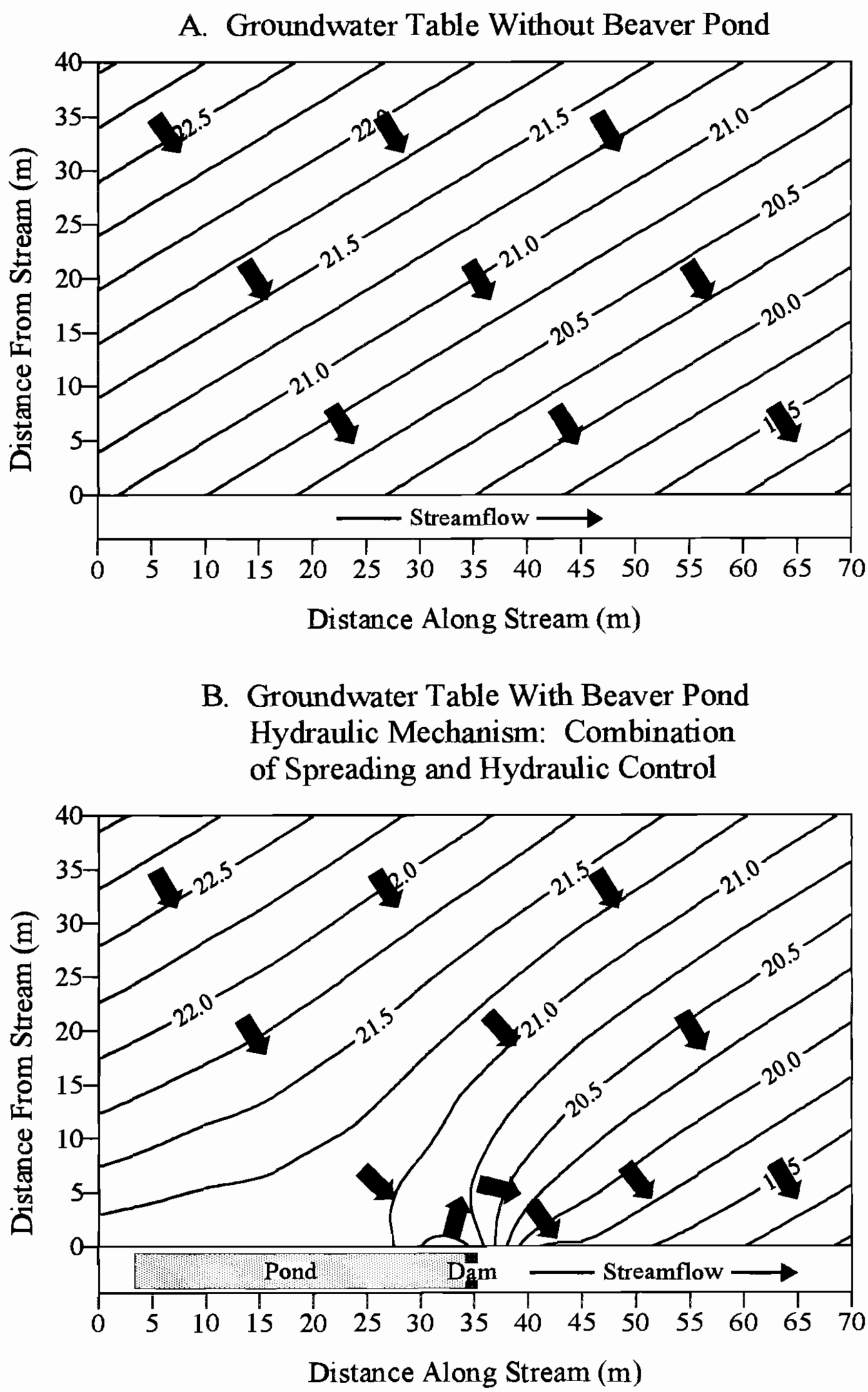
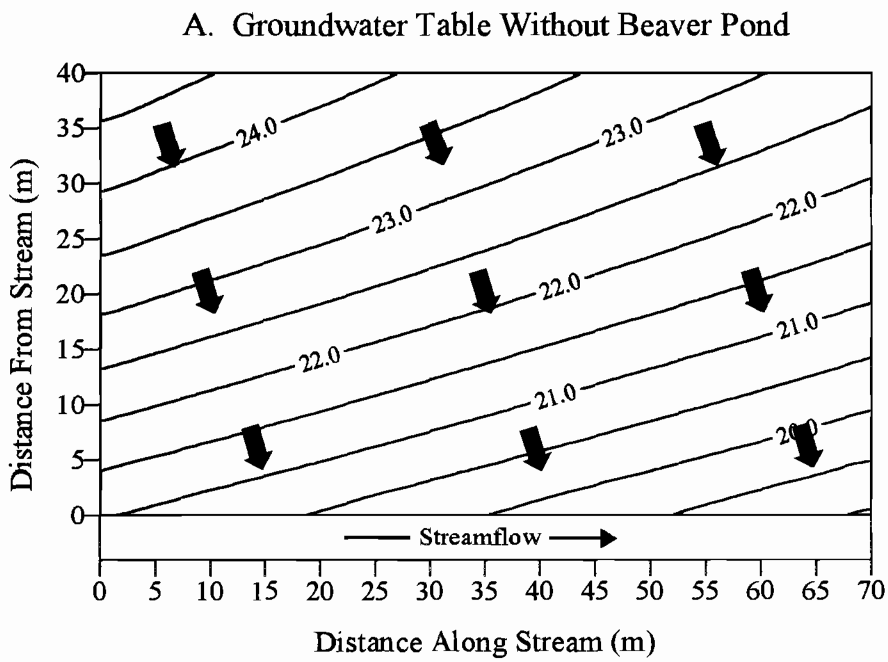


Figure 12. Riparian groundwater contours A) without the presence of a beaver pond compared to those B) with a pond and due to a combination of spreading and hydraulic control effects.

to the relative flow magnitudes and directions associated with each simulated pond adjacent aquifer. Groundwater flowed in the direction of and at a rate proportional to the hydraulic gradients and the hydraulic conductivity within each aquifer.

The results of the Western Site simulations that did not include a beaver pond indicated that the groundwater flowed in a downhill and downvalley direction towards the channel throughout the year. Figure 12A provides an example of this effluent flow pattern, groundwater flow occurred perpendicular to the water elevation contours.

In contrast, the results from the complementary simulations that did include a beaver pond showed that the direction and/or magnitude of groundwater flow changed. The pond adjacent groundwater table configurations for Cases WL, WM and WS during the fall, spring and summer months were due to a combination of the groundwater spreading and the hydraulic control effects of the pond. Figure 12B illustrates this type of flow pattern. Groundwater flow from the hillslope toward the pond was decreased as shown by the wider contour intervals in the pond adjacent area. The subsoil drainage from the upslope area into the riparian aquifer continued but at a decreased rate due to a decrease in the groundwater table gradient. In addition, in the near dam area water flowed away from the pond in toward the floodplain and through the riparian aquifer then partially circulated back into the channel downstream of the pond, forming a flow cycling zone, or a localized cyclic pathway of surface-subsurface water exchange through the riparian zone. The flow cycling zone can also be characterized as the zone within the



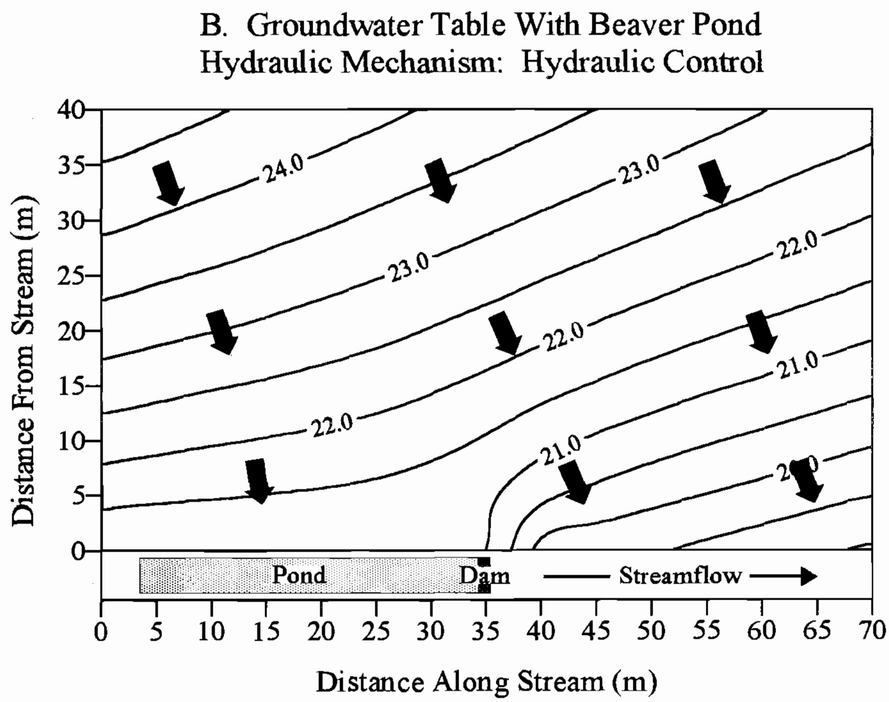
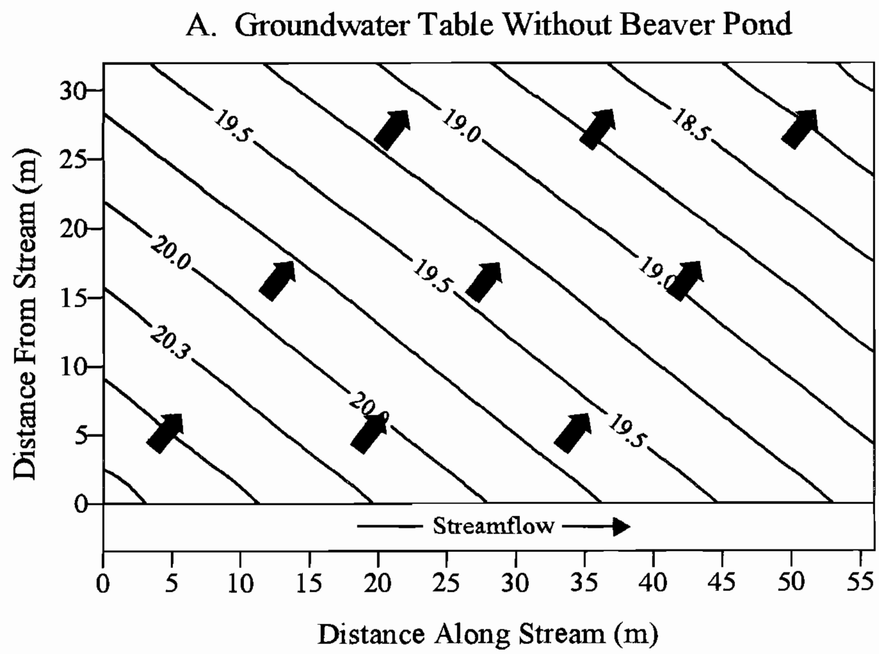


Figure 13. Riparian groundwater contours A) without the presence of a beaver pond compared to those B) with a pond and due to hydraulic control effects.

riparian aquifer where the groundwater table gradient changed sign as the groundwater flowing from the upslope aquifer converged with the groundwater spreading from the pond.

Subsurface water flowed towards the channel in both the unponded and ponded groundwater configurations during the winter months when the riparian groundwater tables were higher, as shown in Figures 13A and 13B. The pond adjacent hydraulic gradient became oriented towards the pond, congruous with the hydraulic control groundwater flow pattern. The subsurface flow rate to the channel when the pond was present was decreased compared to the flow rate to the channel when the pond was not present.

The results from the Central Site simulations also show that the beaver pond had an effect on the groundwater table gradients and flow in the adjacent riparian zone. Aquifer simulations for cases CL and CM that did not include a beaver pond produced water tables that sloped away from the channel and in a down valley direction throughout the year, this influent flow pattern is represented in Figure 14A. The predominant direction of flow remained the same after the addition of the beaver pond. Groundwater flowed away from the channel along a hydraulic gradient from higher to lower potential, spreading from the pond into the riparian zone. However, the presence of the pond increased the magnitude of the hydraulic gradient and therefore increased the magnitude of groundwater flow into the riparian aquifer lateral to and in a downvalley direction below the pond, as shown in Figure 14B. Also, a small amount of circulation occurred between the riparian aquifer and



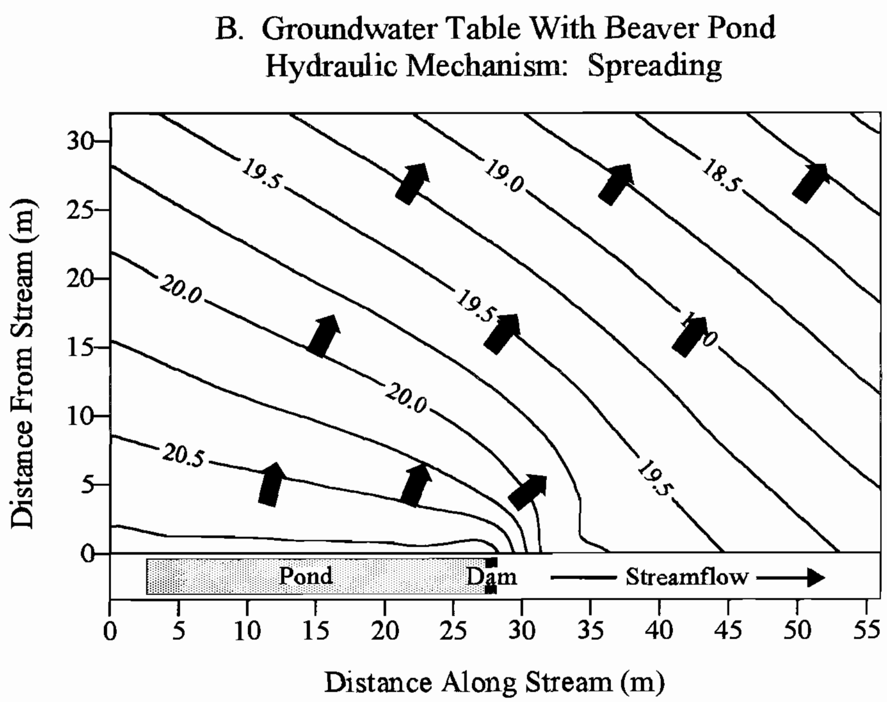


Figure 14. Riparian groundwater contours A) without the presence of a beaver pond compared to those B) with a pond and due to spreading effects.

the stream as groundwater flowed in response to a local gradient from the relatively elevated saturated lense just below the dam to the channel.

The hydraulic gradients and associated groundwater flow patterns that were produced during the simulations for Case CS differed from those for Cases CL and CM. During the fall months both the “with” and “without pond” groundwater table configurations for Case CS sloped away from the channel. During the winter months the groundwater table within the riparian zone near to the channel and/or pond rose, producing a groundwater ridge in both groundwater table profiles. The simulation results that did not include a pond show that the groundwater table sloped from the ridge towards the channel. The simulations that did include a beaver pond produced a reversal in the groundwater gradient and flow direction; a flow cycling zone developed between the pond and the groundwater ridge. This response was due to a combination of the groundwater spreading and the hydraulic control effects of the pond, similar to earlier descriptions. During the late spring and summer months the water tables fell and the groundwater ridges diminished; the pond-adjacent hydraulic gradient once again sloped away from the channel into the riparian aquifer.

The groundwater flow patterns found at the Oak Creek site were similar to those described for the Western Site simulations that included a beaver pond. However, the groundwater table responses at Oak Creek were more complex than those produced during the simulations due to the heterogeneity of aquifer material

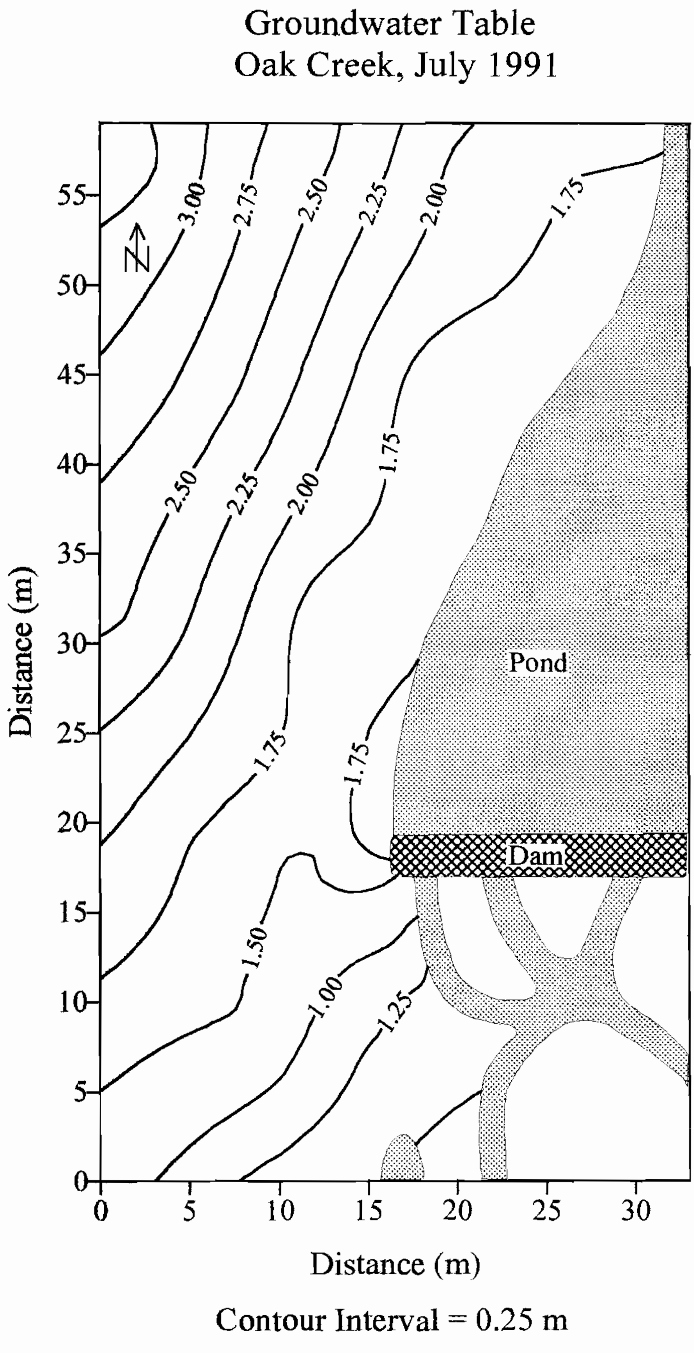


Figure 15. Groundwater contours at the Oak Creek site during July 1991.

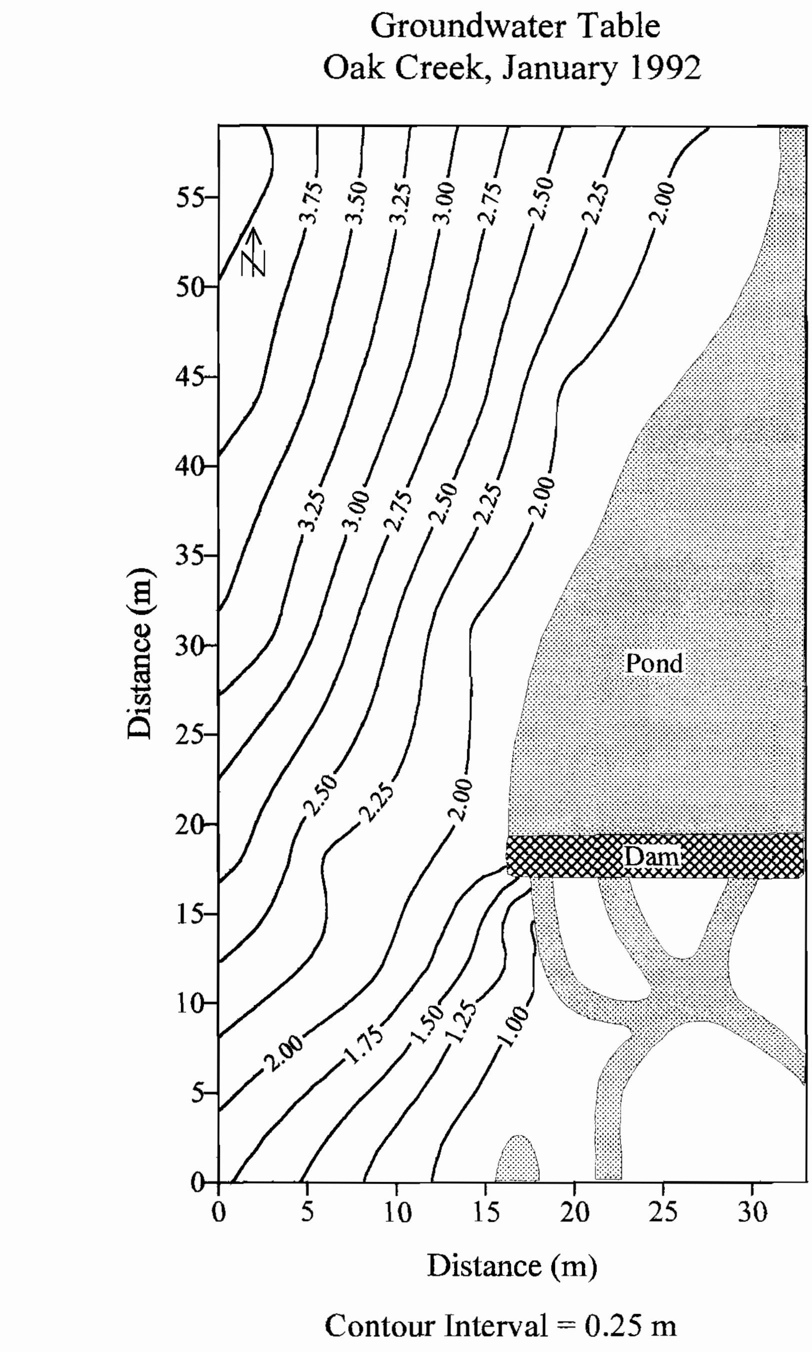
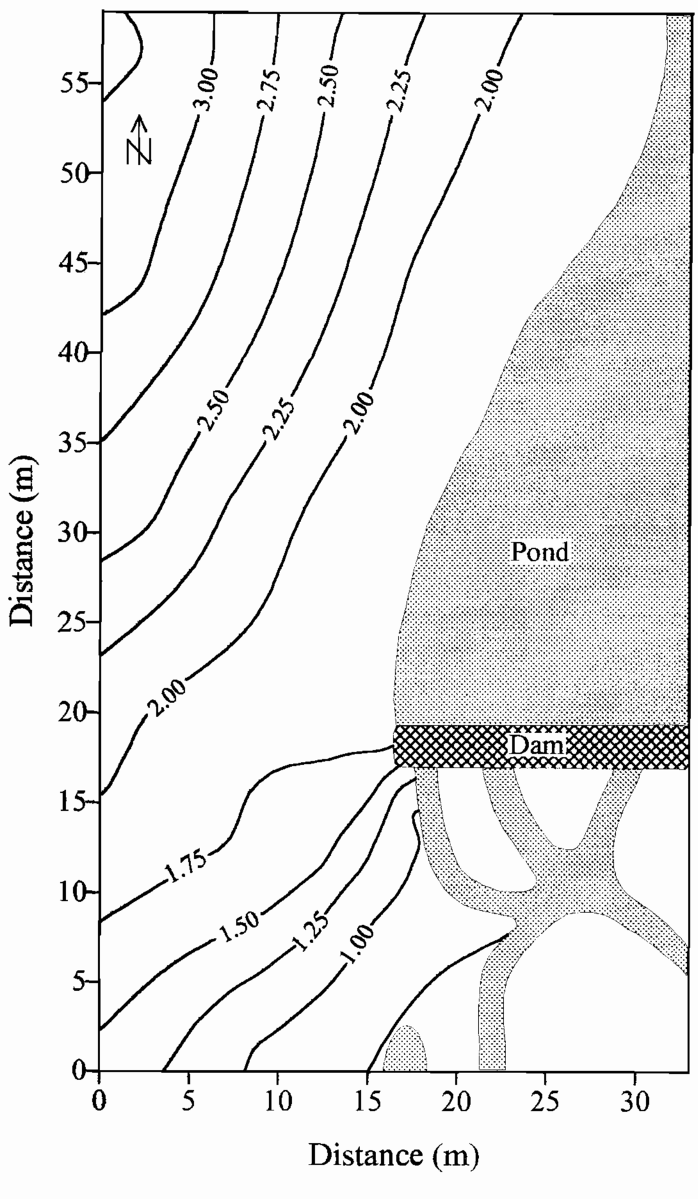


Figure 16. Groundwater contours at the Oak Creek site during January 1992.

Groundwater Table
Oak Creek, July 1992



Contour Interval = 0.25 m

Figure 17. Groundwater contours at the Oak Creek site during July 1992.

and hydrologic pathways. The groundwater table gradients and patterns given in Figures 15 to 17 and D25 to D29 represent averaged groundwater flow.

During the late summer and fall of 1991, flow spread from the pond into the riparian aquifer due to the increased elevation of the pond water compared to the adjacent and downstream aquifer water levels. The elevated groundwater table within the riparian zone lateral to the pond slowed the rate of release of water from the upslope aquifer and created a flow cycling zone. The orientation of the groundwater table gradient adjacent to the pond shifted and groundwater flowed towards the channel during the winter months. The elevated groundwater table was then due to the hydraulic control effect of the pond. This groundwater flow pattern continued into the spring and early summer, however the water table gradient from the upslope to the channel gradually decreased as the stored water volume within the upslope and riparian aquifer was reduced. By the end of the well monitoring period in July, the water table gradient from the upslope aquifer towards the pond was still from higher to lower potential.

The groundwater table gradient and flow pattern described for July 1992 differed from that of the previous July; during the first summer the groundwater table was lower and groundwater partially spread from the pond into the adjacent aquifer, rather than flowing solely from the aquifer to the pond. This difference may have occurred since 1991 was an exceptionally dry year, only 21 cm of precipitation fell between January and July of 1991 compared to 58 cm of normal precipitation for the same time span. Lower precipitation and recharge resulted in depleted subsurface source flow from the upslope aquifer and subsequently lower riparian groundwater tables. Though January through July of 1992 was still drier than normal, the riparian groundwater table was supplied with comparatively greater precipitation and subsurface flow from the upslope aquifer than in 1991; thus the July 1992 profile may be more representative of typical summer groundwater configurations at the Oak Creek site.

Each of the riparian groundwater tables from the Western and Central Site simulations as well as the Oak Creek site indicated that the hydrologic flux between the channel and the riparian aquifer was affected by the beaver pond. The groundwater flow patterns and relative contributions of flow from the pond and/or the upslope subsurface to each riparian aquifer were spatially and temporally dynamic. The pond induced hydraulic gradients affected the direction of riparian groundwater flow, the expansion and contraction of the pond adjacent saturated wedge and the location of the groundwater cycling zone, when present.

Seasonal Groundwater Table Dynamics

Objective Number Five: Describe the variation of the pond-adjacent groundwater levels through time on a seasonal basis.

Seasonal variations in the groundwater table configurations were primarily the result of climate dependent changes in the inflows and outflows associated with each pond-riparian aquifer system. Throughout the year, the presence of the beaver pond increased the groundwater table elevation and prolonged the saturation hydroperiod within each riparian aquifer. The seasonal fluctuations in each pond adjacent phreatic surface were variable according to aquifer characteristics, pond level relative to stream stage, and precipitation and evapotranspiration rates relative to the volume of available pore space and groundwater storage volumes through time. However, general trends in seasonal groundwater table dynamics were identifiable for the Western, Central and Oak Creek sites.

The following is a discussion of the seasonal groundwater trends produced during each of the Western Site simulations. In late summer, the groundwater tables were low because of water loss through evapotranspiration and groundwater seepage to the stream, with little or no recharge from precipitation. With the addition of the beaver pond the resulting pond-adjacent groundwater table began to rise; water flowed into the riparian aquifer from the pond and the groundwater table was held at a greater elevation in comparison to that without the presence of the beaver pond.

As fall progressed, evapotranspiration rates decreased due to plant maturation, reductions in solar radiation and colder temperatures. Concurrent increases in precipitation inputs began to recharge the soil and contributed to rising groundwater tables. The groundwater table adjacent to the beaver pond was relatively higher than that within the riparian aquifer without the pond due to seepage flow from the pond into the stream adjacent zone and to the hydraulic control effect of the pond. The zone of saturation next to the beaver pond expanded through the fall months.

During the winter months, evapotranspiration losses were minimal and precipitation rates were high. As the ground became saturated through precipitation recharge and downslope subsurface seepage, the relative influence of the pond on the water level within the riparian aquifer was reduced. The groundwater tables for both the ponded and unponded configurations rose towards the ground surface and began to converge. The size of the pond-adjacent saturated lense due to the difference between the two groundwater surfaces diminished; however, the water table adjacent to the pond was still held at a relatively higher level throughout the season.

During spring, precipitation rates were reduced and soil water was transpired at increasing rates as the growing season began. When water loss through evapotranspiration and subsurface flow into the channel exceeded recharge through infiltration and groundwater seepage, the groundwater table elevations in each riparian system decreased. However, the size of the subsurface water contribution area or discharge zone in the riparian aquifer with the pond remained greater than that in the aquifer without the pond, prolonging the subsoil saturation from the upslope area through the riparian zone and to the pond and stream channel.

As spring progressed into summer, water use through evapotranspiration in both the ponded and unponded riparian aquifer systems reached a maximum and the associated groundwater table elevations decreased. Soil water content limited evapotranspiration as available subsurface water was reduced. Water use through evapotranspiration was highest where water tables were closer to the ground surface in the near pond zone. During the early summer months the pond-adjacent recharge from net seepage occurred at a faster rate than the stored water in the aquifer profile was removed by evapotranspiration, so the pond induced saturated wedge continued to expand. The pond-adjacent saturated wedge continued to be sustained throughout the summer months. During the latter part of summer the elevated ground water table adjacent to the beaver pond began to recede. The rate of water loss through evapotranspiration and groundwater seepage was relatively greater than the rate of water flowing into the pond-adjacent saturated zone.

The seasonal groundwater table dynamics produced during the Central Site simulations were generally not as variable as those of the Western Site. The groundwater table configurations in both Case CL and CM followed similar serial trends and showed less response to seasonal influences. After the construction of the dam in August, subsurface water flowed from the beaver pond into the riparian aquifer and caused the adjacent water table to rise. The pond induced saturated zone continued to gradually increase as fall progressed. During the winter months both of the ponded and unponded water tables rose slightly due to a net increase in recharge as precipitation exceeded evapotranspiration. Expansion of the pond-adjacent saturated zone continued during the spring months, though the lense shifted slightly downward; both groundwater tables fell slightly as precipitation decreased and evapotranspiration increased. Evapotranspiration was highest near the pond and stream where water levels were closer to the ground surface and the plant rooting zone intersected the available soil moisture. The dimensions of the saturated soil lense adjacent to the pond in Case CM reached equilibrium from April through August; the flux of water into the riparian aquifer from subsurface recharge and from precipitation was equal to the outflow from subsurface discharge and evapotranspiration. The pond adjacent saturated wedge in Case CL continued to gradually expand through the remainder of the simulation period in the late spring and summer months due to recharge from the pond, though the increase was minimal.

The phreatic surfaces produced in the Case CS simulations showed greater seasonal fluctuations than those in Cases CL and CM. The addition or removal of a given volume of water through net areal recharge caused a more pronounced groundwater table response in the finer textured substrate with lower storativity. In the fall, the pond-adjacent groundwater table rose relative to the water level in the aquifer without the pond, as subsurface flow from the pond entered the riparian zone. During the winter months both the ponded and unponded groundwater tables rose and formed a groundwater ridge in the riparian aquifer near the channel as precipitation percolated downward. The water tables began to converge as the ridges developed; the increased saturated zone due to the pond became smaller. Also, a swale-like flow cycling zone (described earlier) was created between the pond and the groundwater ridge. In spring the subsurface water tables began to fall and the groundwater ridges diminished as precipitation decreased and evapotranspiration increased. The pond-adjacent saturated zone expanded further as the subsurface flow from the pond recharged the riparian aquifer and maintained the water table at a higher level. As evapotranspiration increased in the summer, both water tables adjacent to the pond and/or channel continued to drop. The evapotranspiration rate was the greatest in the near pond zone in the lower floodplain where the elevated water levels were near to the ground surface and water use was not limited by available soil moisture. As the season progressed, water was extracted from the pond-adjacent riparian aquifer at a faster rate than the water was transmitted from the channel so the pond-adjacent saturated zone diminished. However, the pond-adjacent water table was still elevated compared to the water table without the presence of the pond.

The seasonal trends of the pond-adjacent groundwater table and saturated wedge at the Oak Creek site were generally similar to those described for the Western Site simulations. In the beginning of the study during July, August and September of 1991 the elevation of the pond-adjacent groundwater table was at its lowest. The summer season was exceptionally dry; relatively high water use through evapotranspiration in comparison to precipitation recharge and subsurface inflow reduced the dimensions of the pond-adjacent saturated wedge. With the onset of the rainy season in October the riparian groundwater table began to rise and the pond-adjacent saturated wedge expanded. As recharge from rain continued into winter the pond-adjacent groundwater table continued to rise; the groundwater table configuration resembled that of the ground surface as the riparian aquifer neared saturation. However, the elevation of the estimated groundwater table without the presence of the pond also rose. As the ground became saturated the water tables began to converge; the dimensions of the pond-adjacent saturated wedge decreased in December then remained approximately the same through April. During May, recharge through precipitation decreased and evapotranspiration increased as the growing season progressed. The riparian groundwater table elevations decreased; water loss from the riparian aquifer exceeded recharge through infiltration and subsurface seepage. However, the elevation of the pond-adjacent groundwater table dropped relatively less than the estimated water table without the presence of the pond; thus the dimensions of the pond-adjacent saturated wedge increased slightly during May and June. During July at the end of the monitoring period the pond-adjacent saturated wedge diminished as the rate of water loss through evapotranspiration and groundwater seepage exceeded the rate of recharge flowing into the pond-adjacent saturated zone. As previously described, the riparian groundwater table elevations were higher during July 1992 than they were during July 1991. Reduced precipitation and recharge during 1991 resulted in relatively lower groundwater volumes.

The seasonal response of the pond-adjacent groundwater table varied with each aquifer system and depended upon net recharge rates relative to groundwater storage. The seasonal fluctuations in the water tables of the Western and Oak Creek sites were affected by the groundwater flux between the pond and the riparian aquifer, as well as by relatively high recharge from precipitation and by discharge through evapotranspiration related to available soil moisture levels. The pond-adjacent saturated soil wedges produced during the Central Site simulations showed comparatively less seasonal fluctuation since the water table responses were primarily associated with the recharge occurring across each channel-riparian aquifer interface. The effects of net areal recharge through precipitation contributions and export through evapotranspiration were not as influential as the pond induced groundwater flux, thus seasonal groundwater table responses were reduced.

Sensitivity Analysis

Objective Number Six: Conduct a sensitivity analysis to determine how variation of the riparian aquifer values for hydraulic conductivity, storativity, pond level relative to stream stage, lateral slope of the groundwater table and recharge rates affect pond adjacent groundwater table elevations.

The results of the sensitivity analysis indicated that the simulated pond adjacent ground water table elevations and associated saturated zone volumes showed varying degrees of sensitivity to the range of values used as input parameters. Cross-sections of the pond adjacent saturated wedge lateral to the dam for each of the sensitivity analysis variations are shown in Figures 18 through 22. Changing the lateral gradient of the initial water table (SL) had the least effect on the model results. The pond adjacent saturated zones were nearly the same size in response to changing the SL value, though their lateral orientation and elevations relative to the datum did vary. The storativity (S) value appeared to have a small degree of influence with respect to the model sensitivity. Varying the value of the

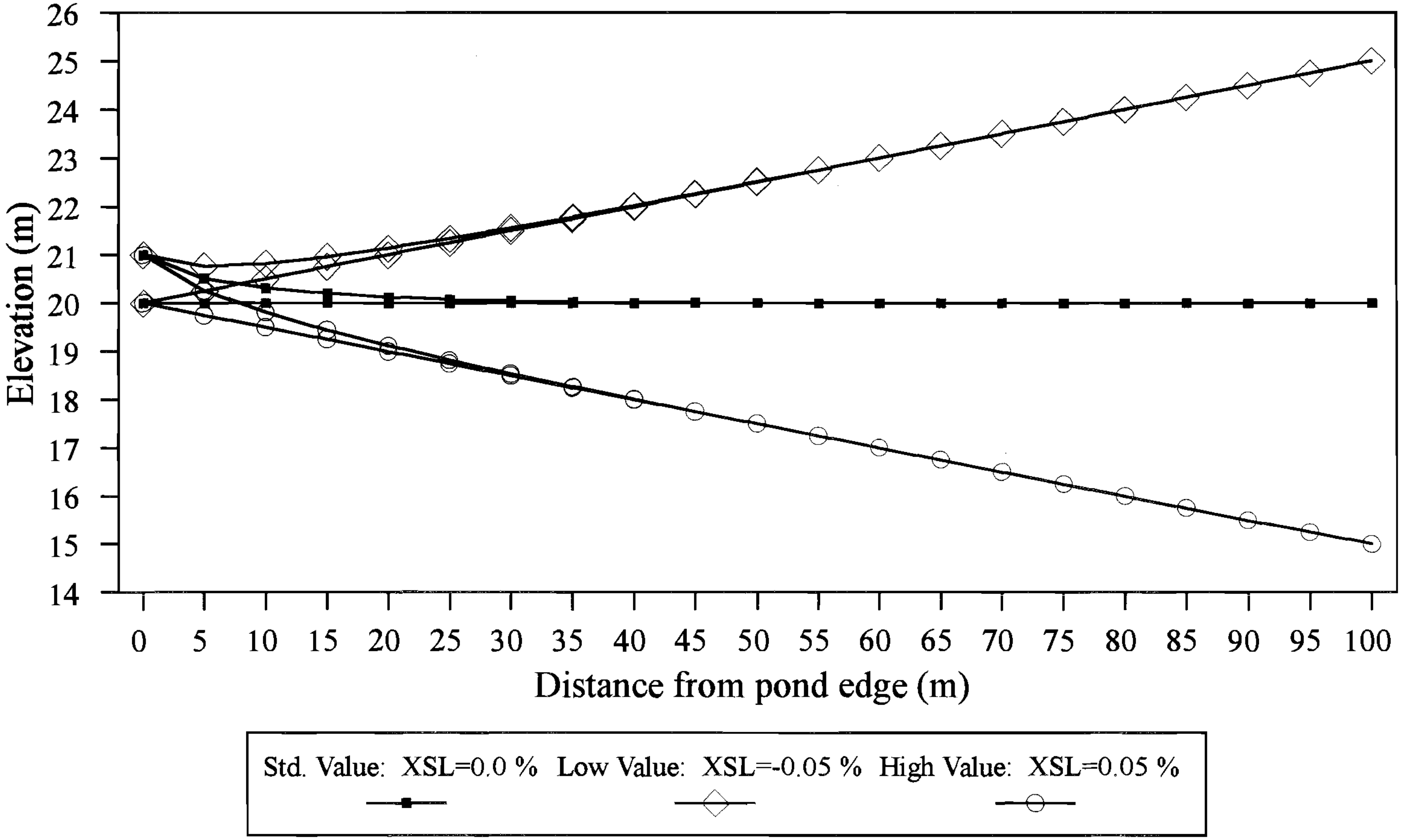


Figure 18. Results of sensitivity analysis; variation of the lateral gradient of the initial water table (%).

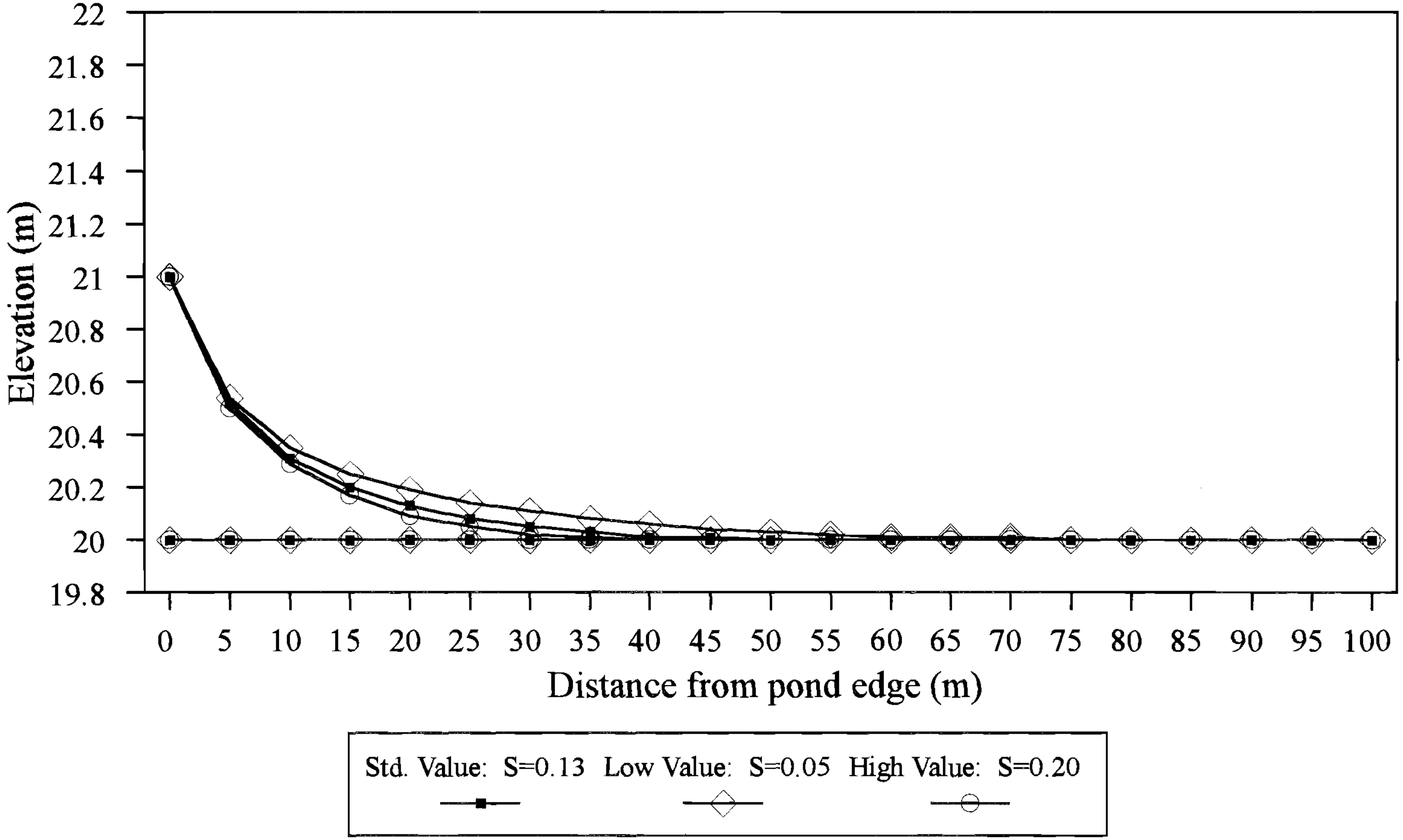


Figure 19. Results of sensitivity analysis; variation of the storativity value.

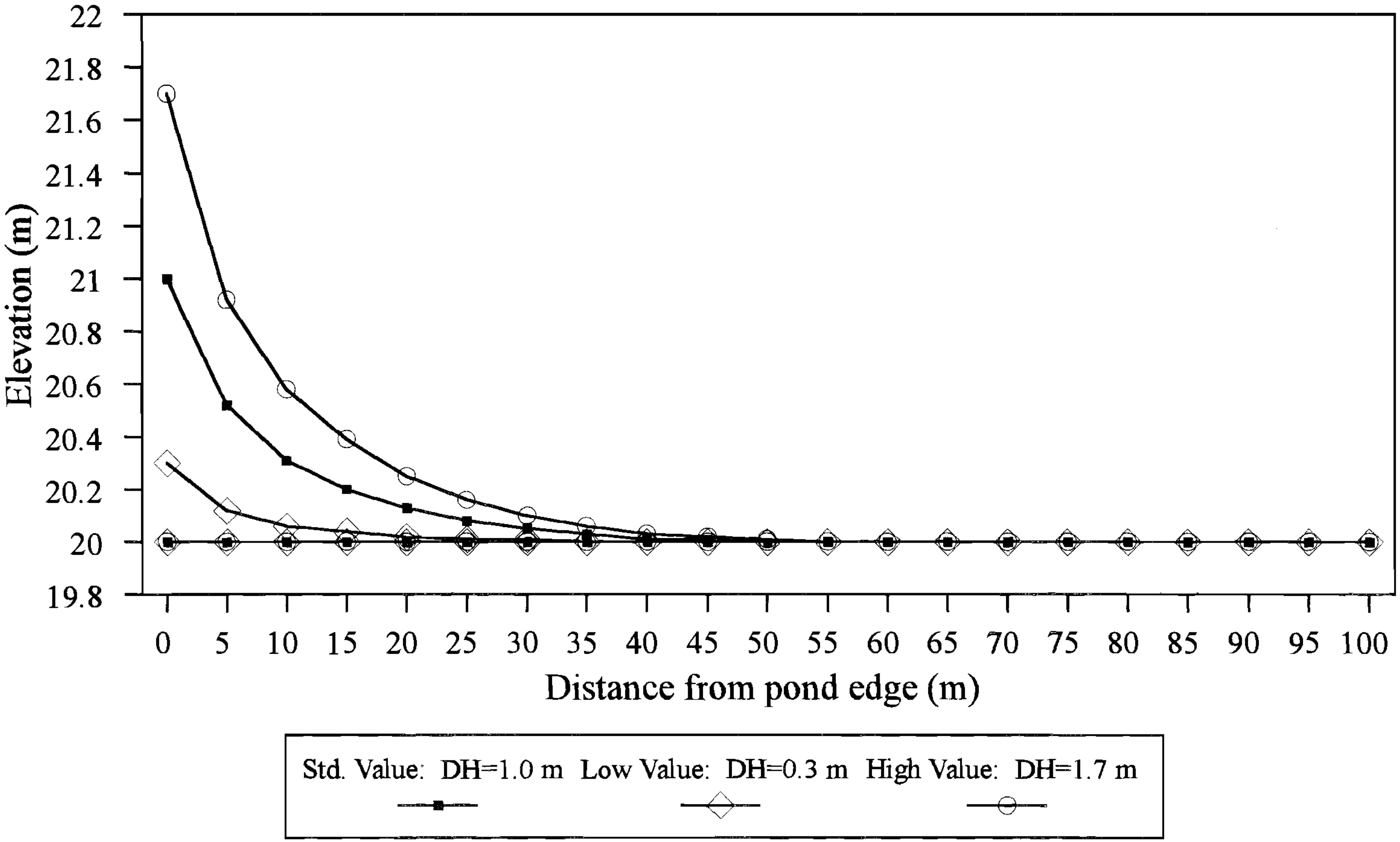


Figure 20. Results of sensitivity analysis; variation of the head difference between the pond and stream stages (m).

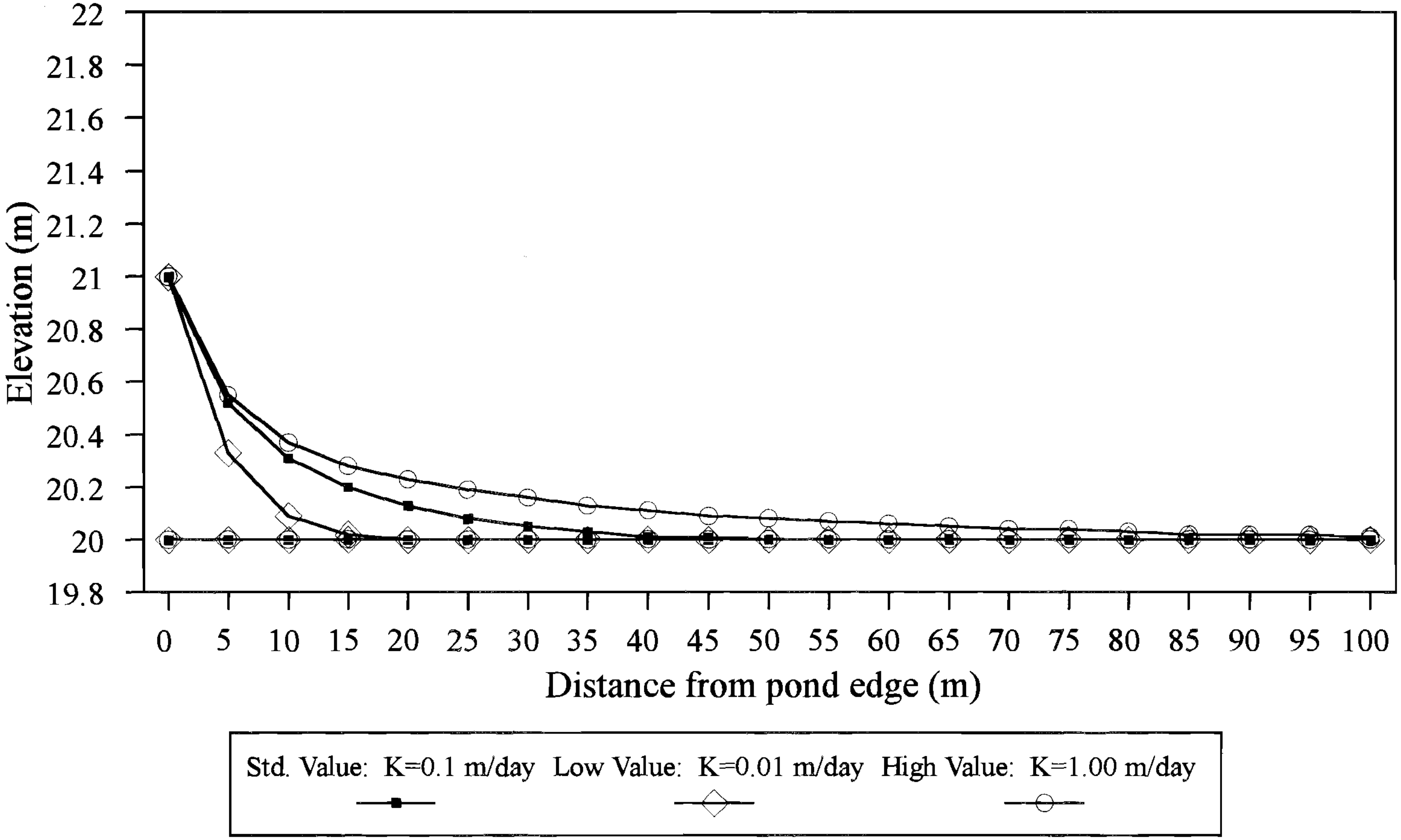


Figure 21. Results of sensitivity analysis; variation of the saturated hydraulic conductivity value (m/day).

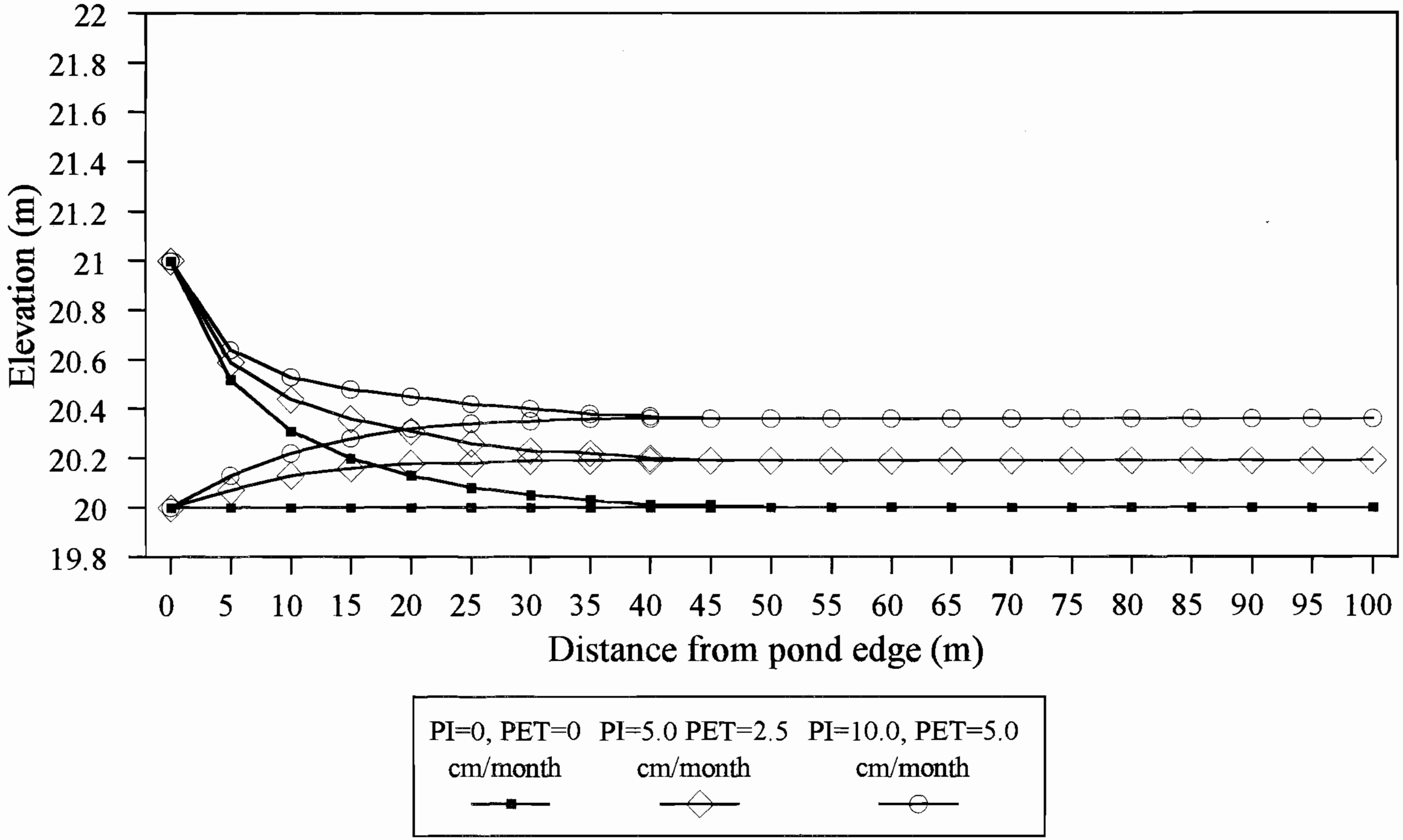


Figure 22. Results of sensitivity analysis; variation of the recharge parameters PI and PET (cm/month).

head difference between the pond and stream stages (ΔDH) had an important effect on the model results; the groundwater elevations and saturated zone dimensions adjacent to the beaver pond responded proportionally to increasing or decreasing ΔDH values. The variation of the hydraulic conductivity (K) value also produced substantial changes in the size of the pond adjacent saturated wedge. Net recharge (R) variation produced proportional changes in the riparian groundwater table elevations.

Pond Adjacent Groundwater Levels and Riparian Ecology

Riparian hydrology affects many riparian zone ecological properties and processes; thus an increased spread of the subsurface saturated zone, elevated water tables and greater surface-subsurface hydrologic flux due to the presence of beaver ponds can influence riparian zone features. The types of influences are determined by the spatial patterns and temporal dynamics created by the many interacting hydrologic, geomorphic, chemical and biological factors present in each riparian system. Examples of how elevated groundwater levels adjacent to beaver ponds can potentially affect several riparian zone characteristics follow.

Hydrologic patterns and proximity to the groundwater table have a pronounced effect on riparian vegetation and influence the abundance and diversity of species, rooting depths and densities, herb, shrub and tree stratification levels, and the release of coarse and fine plant detritus which in turn influence riparian ecosystem structure and function (Vannote et al., 1980; Gregory et al., 1991;

Swanson et al., 1992). The saturation gradient varies in time and space across the floodplain. Consequently, riparian plant communities show a range of compositional and structural diversity. However the degree of saturation and soil moisture availability generally diminish laterally away from the channel; vegetation associations reflect this gradient (Mitsch and Gosselink, 1986).

Beaver ponds expand the dimensions of the saturated zone, extend the subsurface saturation hydroperiod and increase soil moisture availability. As vegetative succession progresses under the influence of rising water tables the riparian plant community composition shifts; hydrophytic plant species become established further from the channel and plant richness can increase. The effect of the groundwater regime near beaver ponds on vegetative productivity and composition can be particularly dramatic within moisture depleted riparian zones in semi-arid areas (Brayton, 1984). The pond adjacent increase in soil moisture can produce more favorable growing environments compared to formerly drier conditions, promoting increased vegetation. Species can shift from mesic varieties including sagebrush (Artemesia and Sarcobatus) to hydrophytic species such as sedges (Carex), rushes (Juncus) and willows (Salix) (Johnson, 1984). The effects of elevated groundwater on riparian vegetation may not be as evident in humid regions as in drier areas but can nevertheless be significant within the riparian ecosystem. For example, large woody debris recruitment may increase as pond-adjacent saturation zones influence tree rooting zones. Also, subirrigation from ponds may help vegetation with higher moisture requirements withstand drought periods.

The increased riparian vegetation growth in beaver inhabited stream systems can be important in sediment filtering and depositional processes and in maintaining bank stability (Heede, 1985). The greater abundance of vegetation increases channel and floodplain roughness and results in lower streamflow velocities and erosional energy. The soil mantle can increase as channel and overbank flows slow and the sediment transported by the stream is trapped by vegetation and deposited. This accumulation of sediment can be important in increasing the volume of the aquifer substrate. Also, the increased riparian plant root systems help to bind the soil and provide resistance to stream erosional energy, creating more stable channel systems.

Furthermore, habitat value for both aquatic organisms and wildlife can be affected by alterations in riparian vegetation characteristics associated with beaver ponds. The type of plant cover affects the light availability and the food quality and timing of litter inputs, which influence the physical habitat conditions in addition to the autochthonous or allochthonous energy base of the aquatic community (Agee, 1988; Gregory et al.,1991). Pond related changes in riparian vegetation can influence wildlife habitat as well due to the diversity of plant composition and structure, the number of strata and edges, and the presence of forage species. By affecting the type and density of vegetation in the adjacent riparian zone, ponds can influence habitat cover and the extent of corridors available for wildlife dispersal and migration (Carlson, 1991). Changes may also occur in the biotic species composition, abundance of hyporheic organisms and the biotrophic food web due to pond induced changes in water and nutrient flux within the riparian subsurface-surface water continuum.

Nutrient transformations and biogeochemical pathways for various chemical species can be increased by subsurface moisture and water table dynamics near beaver ponds. The expanded saturated zone and longer, more complex hydrologic pathways may increase surface-subsurface solute interactions and retention times, and promote greater nutrient exchange within the stream-riparian system (Elwood et al., 1983). Water saturation causes soils to be in a highly reduced oxidation state and often causes a shift in pH. Consequently, certain mineral species including phosphorous, magnesium, sulphur and iron can become more mobile. The expanded wetted areas have adjacent oxidation and reduction zones wherein oxidized nitrogen species can be rapidly lost through denitrification by bacteria that reduce nitrate to nitrous and nitrogen gases (Green and Kauffman, 1989). This reduction in nitrate within the riparian zone is an important pollutant removal process and can prevent high levels of nitrate from entering the stream (Lowrance et al., 1983; Rhodes et al., 1985).

Riparian soils are also influenced by groundwater table dynamics and may reflect shifts in the subsurface hydrologic regime and presence of high water tables due to beaver ponds. The prevalence of hydric soils can increase near ponds; these soils are associated with anaerobic conditions during the growing season (Mitsch and Gosselink, 1986). Mottling and/or gleying manifest changes in chemical speciation and microbial activity and are common indications of alternating redox processes or a prolonged reducing environment within hydric soils. Boersma (1970) found excellent correlation between the depth to faint mottling and the groundwater level during the early part of the growing season. The soils in the dam-adjacent transect at the Oak Creek site exhibited frequent reddish mottles within the zone of water table fluctuation, these diminished with depth as anaerobic conditions predominated. The organic content of moist pond adjacent riparian soils can be higher due to increased vegetation growth and subsequent decomposition. However, a permanently anaerobic environment may restrict chemical and biological weathering processes in the soil which can also inhibit soil genesis and promote the development of peat (Platts et al, 1987).

The increase in the volume of water held in the riparian stream banks associated with beaver ponds can affect the magnitude and permanence of channel flow and aquifer recharge. The subsurface flow entering a channel from hillslope and riparian floodplains provides the dominant water source for stream baseflow in effluent streams (Freeze and Cherry, 1979). Drainage from the riparian aquifer occurs as long as there is available soil pore water, there is a hydraulic gradient between the level of the water stored in the streambanks and the stream stage, and sufficient water exchange conditions exist. The potential expansion of the groundwater wedge and the aquifer storage volume due to the presence of beaver ponds may prolong subsurface saturation and increase water available for baseflow. This subsurface water can also be significant in providing for plant moisture requirements and for flow maintenance during drier months of the year. The flow cycling zones that develop adjacent to ponds in effluent reaches can increase surface water-groundwater exchange and hydrologic connectivity within the stream-riparian continuum. For influent stream reaches, water which flows to the riparian zone from the pond may be used through evapotranspiration, recharge the underlying aquifer or return to the stream lower in the drainage basin. The flux of subsurface water between the pond and the adjacent aquifer can be particularly important in areas where the riparian zone has been dewatered due to streambed lowering.

Channel Incision, Riparian Restoration and Beaver Ponds

Recognizing the role of beaver activities and their associated influence on groundwater table dynamics and related riparian zone processes is integral to understanding the channel system evolution and rehabilitation of many streams. Stream systems are dynamic and adjust to the complex sets of interrelated climatic, hydrologic, lithologic, topographic and biological factors and processes that exist within a given setting (Power et al., 1988; Schumm, 1977; Swanson et al., 1988). Environmental alterations of significant magnitude can produce severe impacts on lotic systems. For example, changes in land use and channel modification have resulted in land conservation and riparian management problems throughout the west (Elmore and Beschta, 1987). The loss of beaver dams associated with widespread beaver trapping is likely to have caused many streams to become incised and confined to more discrete channels rather than to flow through broader, complex channel systems and expanded floodplains (Parker et al., 1985). Vegetation removal, soil compaction and riparian zone degradation associated with livestock grazing and agricultural and timber production practices have caused substantially decreased infiltration rates and increased runoff and erosion on many watersheds (Campion, 1988). In addition, many streams have been channelized in order to increase channel conveyance capacity or to drain surrounding land. These imposed hydrologic and sedimentologic changes have increased the erosion potential of many stream systems, causing channel incision and furthering riparian deterioration (Campion, 1988).

Incised stream systems are characterized by lowered streambeds, unstable banks and widened channels. As a streambed is lowered and the associated riparian zone is dewatered, the functional integrity of the riparian ecosystem becomes endangered. Many of the hydrologically interdependent ecological links between the stream and the riparian zone are severed and the flux of materials, energy and organisms are significantly altered. Degraded riparian zones exhibit the loss of many characteristics and functions associated with healthier stream systems. Elmore and Beschta (1987) site several examples: lowered saturated zone, reduced subsurface storage of water, little or no summer streamflow, diminished floodplain area, reduced vegetation and associated loss of bank stability, loss of thermal buffering, low diversity of wildlife habitat, low forage production and quality, and poor habitat for fish and other aquatic organisms.

Beaver activities can enhance the ability of degraded stream systems to recover and/or resist further perturbations and disturbances by reestablishing the hydrologic link between the stream and riparian zone, increasing channel stability and improving riparian conditions (Apple, 1985; Naiman et al., 1988). As previously described, the elevated groundwater tables and increased hydrologic diversity associated with beaver ponds can increase connectivity between the stream and adjacent riparian zone, improve moisture availability, enhance vegetation growth and related channel aggradation, increase nutrient transformation and availability and thus promote restoration.

Ecological Effects Summary

The subsurface hydrologic regime near beaver ponds can affect numerous ecological processes and features associated with the land-water interface. The pond adjacent saturated wedge creates an expanded dynamic zone of influence within a riparian ecosystem. Pond locations shift as dams are built along various stream reaches, this adds further complexity to riparian corridors. Linked within the context of the hydrologic patterns are other specific ecological processes with unique spatial and temporal characteristics. The composite array of processes and characteristics results in greater intrariparian diversity and increased resilience to disturbance.

The influence of pond associated changes can be incorporated within a landscape perspective and viewed over broad spatial and temporal scales. Whether beaver ponds exist as localized features or as widely distributed, contiguous impoundments along entire valleys and throughout drainage systems, they can have significant effects on stream and riparian conditions. Furthermore, the ecological influence associated with expanded pond adjacent saturated zones can be immediate and can also persist through time, helping to create a variety of ecological patterns and successional histories of landscape form and function.

SUMMARY

Beaver are an important component within lotic ecosystems and influence many riparian zone characteristics and processes including the groundwater flux within the surface-subsurface continuum. In this research both a numerical hydrologic model and a case study were used to provide information about the potential effects of beaver ponds on groundwater table configurations, storage volumes and flow patterns in adjacent riparian aquifers. A two-dimensional, horizontal, finite-difference numerical model was developed and utilized to simulated groundwater elevations through time. Two hypothetical pond-riparian aquifer systems were utilized as model sites: a stable, effluent stream reach located in the humid Coast Range in western Oregon and an incised, influent stream reach located in the semi-arid region east of the Cascade Range in central Oregon. Within the context of regional site parameters a range of input values were used to determine the effects of alternative hydrologic and hydraulic site conditions on groundwater tables. These input data included water level energy gradients, substrate hydraulic conductivity and storativity values and sources and magnitudes of recharge and discharge. In addition, a case study was conducted in which groundwater levels next to a beaver pond located on Oak Creek in western Oregon were monitored from July 1991 through July 1992.

Beaver ponds were found to contribute to greater spatial and temporal hydrologic diversity within beaver inhabited stream systems compared to those

without the influence of a pond. The groundwater flow between each pond and adjacent riparian aquifer showed a change in magnitude and/or direction due to the presence or absence of the pond.

Data from both parts of the study indicated that beaver ponds caused elevated groundwater tables and increased the dimensions of the subsurface saturated soil zone in adjacent riparian aquifers. The relative increase in each case could be viewed as a semi-elliptical wedge shaped lense that was thickest nearest the dam and decreased radially away from the pond. The simulation results included small, intermediate and large dimensions of the pond-adjacent saturated wedge per month throughout a one year period for each of the two synthesized riparian aquifer systems; dimensions of the saturated wedge at the Oak Creek site were also estimated. The maximum vertical and lateral extents and the saturated soil groundwater volumes were calculated for each pond-adjacent wedge. The quantitative bounds of the saturated wedge, including all sites and all cases, ranged between 0.3 m high and 4 m wide to 1.7 m high and 90 m wide. Monthly values of these dimensions for each site are listed in Tables 9, 10 and 11. Similarly, the volume of the pond-adjacent saturated soil wedge ranged between 12 and 3500 m^3; the associated volumes of stored groundwater ranged from 0.6 to 700 m^3. Monthly values of these volumes are given in Tables 12, 13 and 14.

Sensitivity analysis indicated that the substrate hydraulic conductivity and the head difference between the pond surface and the below dam stream stage had the greatest effect on the pond-adjacent groundwater levels within each system. The expansion of the saturated zone was directly proportional to the aquifer transmissivity and to the dam height.

The hydraulic gradients between the pond and connected aquifer affected the groundwater table configurations and flow patterns within each system. Types of pond-adjacent flow patterns are shown in Figures 11 through 17. When the pond level was greater than the adjacent riparian groundwater levels water spread laterally from the pond into the adjacent channel banks and floodplain. The increased hydraulic gradient due to the pond caused a proportional increase in flow into the riparian aquifer. Alternatively, when a hydraulic gradient from higher to lower potential existed from the saturated stream banks towards the pond, the pond acted as a hydraulic control. The groundwater that flowed toward the pond was maintained at a higher level; the hydraulic gradient as well as the flow from the upslope aquifer to the channel were reduced. A combination of both spreading and hydraulic control mechanisms existed when water flowed from the pond into the adjacent aquifer and caused elevated riparian groundwater levels, which subsequently created a hydraulic control for inflowing water from the upslope aquifer. The subsoil drainage from the upslope area into the riparian aquifer occured at a lower rate due to a decrease in the groundwater table gradient. In addition, water flowed from the pond in toward the floodplain and through the riparian aquifer then partially circulated back into the channel downstream of the pond, forming a flow cycling zone or a localized cyclic pathway of surface-subsurface water exchange through the riparian zone. The pond-adjacent groundwater flow patterns in the effluent stream reaches of the western Oregon sites were due to either the hydraulic control or combined spreading and hydraulic control mechanisms, whereas the groundwater flow patterns produced for the influent central Oregon stream reach generally resulted from spreading effects.

Seasonal variations in net recharge also influenced the dimensions of the pond-adjacent saturated wedge and the groundwater table response within each aquifer system. The seasonal fluctuations in the water tables of the Western and Oak Creek sites were affected by the groundwater flow between the pond and the riparian aquifer, as well as by high recharge from precipitation and increased evaporation losses related to available soil moisture levels. The pond-adjacent saturated zone expanded during the fall due to subsurface flow spreading from the pond. Groundwater tables were further elevated as precipitation increased and evapotranspiration decreased. During the wet winter months the effect of the pond on the riparian subsurface water levels was reduced as the riparian aquifer became increasingly saturated from precipitation recharge and subsurface flow from the hillslope; the size of the pond-adjacent saturated wedge was smaller during this time. During spring the riparian groundwater elevations decreased as the growing season began and evapotranspiration increased. However, the elevation of the pond-adjacent groundwater table dropped relatively less compared to the water table without the presence of the pond, thus the dimensions of the pond-adjacent wedge increased. In late summer the pond-adjacent saturated wedge diminished and the groundwater elevations dropped as the rate of water loss through evapotranspiration and groundwater seepage exceeded the rate of recharge flowing into the pond-adjacent saturated zone.

The pond-adjacent saturated soil wedges produced during the Central Site simulations showed comparitively smaller seasonal fluctuations since the water table responses were primarily associated with the recharge occurring across each channel-riparian aquifer interface. The effects of inflow from precipitation and outflow from evapotranspiration were not as influential as the pond induced groundwater flux, so the seasonal groundwater table fluctuations were reduced. In general, the pond- adjacent saturated zone continued to expand after dam construction in August then approached equilibrium during the latter part of the simulation period in either the late spring or summer months. Mild seasonal fluctuations did occur; during winter the groundwater tables rose as precipitation exceeded evapotranspiration, the reverse happened during the drier summer months. The groundwater table response to seasonal changes in net recharge was greater in finer textured substrates that had lower storativity values.

The subsurface hydrologic regime can influence a wide array of ecological processes and features associated with the land-water interface. In this study only preliminary aspects of the physical distribution of groundwater near beaver ponds were investigated. However, the results can be synthesized within the context of five unifying attributes of groundwater ecology (Stanford and Ward, 1992) to provide a more illuminating ecological view.

First, groundwater flows through a continuum of geohydrologic units in which water volume and residence time are primary physical features. The subsurface saturated zones adjacent to beaver ponds form part of the interconnected mosaic or stygoscape of an aquifer system. Spatio-temporal variations in occurance and magnitude depend upon conjunctive hydrologic and hydraulic site conditions. Each of the western and central Oregon sites exhibited varying pond-adjacent saturated zones and groundwater flow patterns, and created a unique zone of influence within each aquifer continuum.

Second, biogeochemical transformations usually occur as water and materials flux through the continuum. Pond associated changes in geohydrologic gradients may induce changes in hyporheic interstitial chemistry patterns. The expanded saturated zones and longer, more complex hydrologic pathways may increase surface-subsurface solute interactions and retention times, decrease spiraling lengths and promote greater biophysical exchange within stream-riparian systems.

Third, food webs composed of microbes and metazoans occur within groundwater. The organisms can mediate biochemical transformations as waters flux through various geohydrologic units. Changes may occur in species abundance, composition and distribution according to pond induced changes in groundwater flux. For example, stream to subsurface water exchange may increase bioproduction by raising interstitial supplies of oxygen and dissolved organic carbon.

Fourth, variations in groundwater flow through aquifer systems add richness to local and regional biodiversity patterns. Pond induced changes in groundwater and associated biogeochemical components increase landscape complexity. A wide array of characteristics and processes within the groundwater-surface water ecotone of a stream corridor may be affected. Variations may occur in groundwater elevations and flow patterns, soil moisture levels, interstitial chemistry, functional interactions within biotrophic webs, and abundance and distribution of riparian vegetation and other organisms.

Fifth, groundwaters are being progressively polluted causing degredation of water related values from organismal to ecosystem levels of organization. The term pollution in this context refers to the physical and biological as well as chemical degradation of surface-groundwater systems (Committee Report on Clean Water Act, 1988). The loss of physical and biological connectivity between surface and groundwaters is included; groundwater abstraction and pollution deteriorate the functional integrity of the hydrologically interdependent ecological links within riparian systems. Beaver activities increase intrariparian diversity and ecosystem resilience and can improve degraded riparian conditions. The elevated water tables and greater surface water-groundwater exchange create hydrologic connectivity within the stream-riparian continuum.

Stanford and Simons (1992) indicate that "Proper management and protection of groundwater resources requires: 1) an ecosystem approach in which physical and biological connectivity between surface and groundwaters is recognized and quantified and 2) enactment and enforcement of federal and state statutes that ensure the long term sustainability of this natural connectivity, thereby protecting groundwater quantity and quality."

By including the effects of beaver ponds on adjacent groundwater elevations and flow patterns, riparian ecologists may broaden their understanding of the hydrologic processes and associated transformations that shape the stream environment. This information may also be useful for land managers and the general public toward a goal of reconnecting ecosystem attributes through land use practices, including those that support the presence of beaver.

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APPENDICES

Appendix A:

Program Listing for Groundwater Model

```
{A computer program was written in ThinkPascal version 3.1 to implement the numerical groundwater model}
{and consists of a series of subprograms for calculating the aquifer bottom, ground surface and initial ground}
{water table elevations, recharge values and groundwater levels after some initial time.  The program}
{sequence was begun by calculating values for the aquifer bottom, ground surface and initial water table}
{at each node throughout the model area using subprograms GW_AB, _GS and _H , respectively.  Calculations}
{for recharge and groundwater head values were then performed in conjunction through a series of model runs}
{using subprograms GW_R and _BP to represent groundwater response through time . A modular design was}
{chosen to allow for greater flexibility of model use; variations in selected input data could be made to}
{evaluate model response without reconfiguring the entire program sequence.  Data values for variables}
{common between subprograms were equivalent.}

{--------------------------------------------------------------------------------------------}
{--------------------------------------------------------------------------------------------}

program GW_BP;

{This program is designed as a series of subprograms that are used in conjunction to calculate groundwater}
{elevations throughout a riparian aquifer adjacent to a beaver pond.}
{Input Files:  aquifer bottom (AB), ground surface (GS), recharge (R), water table (H) from the previous}
{time step}
{Output Files:  water table (H)}

{-----------------------------------Set    Variables------------------------------------------}

  type
    twodstorage = array[0..40, 0..40] of real;
    ptwodstorage = ^twodstorage;

  var
    AB, GS, R, H, HS: ptwodstorage;
    DISTX, DISTY, DX, DT, K, S, TTERM, HTERM: real;
    XINC, YINC, TINC, I, J, Z, N, M, TIMELOOPS: integer;
    ABFOLD, GSFOLD, RFOLD, HFOLD, HFNEW: text;
    WINDOWRECT: rect;

{-----------------------------------Begin    Program-----------------------------------------}

begin   {program}

{------------------------------Create    Pointer    For    Arrays-----------------------------}

  new(AB);
  new(GS);
  new(H);
  new(R);
  new(HS);

{--------------------------------Set    Up    Text    Window----------------------------------}

  hideall;
  setrect(windowrect, 2, 35, 512, 342);
  settextrect(windowrect);
  showtext;

{------------------------------Define    Input    Parameters---------------------------------}

  writeln('Enter the following values:   ');
```

```
writeln('Distance increment or length between nodes is  ?  (m)');
readln(DX);
writeln('Total distance along the boundary perpendicular to the stream (in the X direction) in multiples');
writeln('of', DX, 'm. is ?');
readln(DISTX);
writeln('Total distance along the boundary parallel to the stream (in the Y direction) in multiples ');
writeln('of ', DX, 'm. is ?  ');
readln(DISTY);
writeln('Size of time increment is  ?  (days)');
readln(DT);
writeln('Number of time increments is  ?  ');
readln(TINC);
writeln('Hydraulic conductivity value is  ?  (m/day)');
readln(K);
writeln('Storativity value is  ?  (unitless)');
readln(S);

{------------------------------Define   Node   Variables-------------------------------------------}

 {Calculate the number of nodes in the X direction, perpendicular to the channel.}
 XINC := trunc(DISTX / DX) + 1;
  {Calculate the number of nodes in the Y direction, parallel to the channel.}
 YINC := trunc(DISTY / DX) + 1;

 If (XINC > 39) then
   begin {check boundary, DX distances}
     writeln('The number of nodes in the X direction, perpendicular to the channel, is ', XINC, '.');
     writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
     writeln('distance between nodes or the distance in the X direction.');
   end; {check boundary, DX distances}

 If (YINC > 39) then
   begin {check boundary, DX distances}
     writeln('The number of nodes in the Y direction, parallel to the channel, is ', YINC, '.');
     writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
     writeln('distance between nodes or the distance in the Y direction.');
   end; {check boundary, DX distances}

 I := XINC;
 J := YINC;
 Z := TINC;

{------------------------------------Open   GW   Storage   Files--------------------------------------}

{Values defining the aquifer bottom and ground surface are from the input files AB and GS. Recharge values}
{are from input file R. Values for the pond and strem levels as well as the riparian groundwater table}
{elevations from the previous time step ar defined with input file H.}

 reset(ABFOLD, OldFileName);
 for N := 0 to J + 1 do
   begin  {ABF}
     for M := 0 to I + 1 do
       begin   {read file}
         readln(ABFOLD, AB^[M, N]);
       end;   {readfile}
   end;  {ABF}
 close(ABFOLD);
```

```
reset(GSFOLD, OldFileName);
for N := 0 to J + 1 do
  begin {GSF}
    for M := 0 to I + 1 do
      begin {read file}
        readln(GSFOLD, GS^[M, N]);
      end; {read file}
  end; {GSF}
close(GSFOLD);

reset(HFOLD, OldFileName);
for N := 0 to J + 1 do
  begin {HF}
    for M := 0 to I + 1 do
      begin {read file}
        readln(HFOLD, H^[M, N]);
      end; {read file}
  end; {HF}
close(HFOLD);

reset(RFOLD, OldFileName);
for N := 0 to J + 1 do
  begin {RF}
    for M := 0 to I + 1 do
      begin {read file}
        readln(RFOLD, R^[M, N]);
      end; {read file}
  end; {RF}
close(RFOLD);

{---------------------------------Initialize Head Storage Array---------------------------------}

for N := 0 to J + 1 do
  begin {HS}
    for M := 0 to I + 1 do
      begin {calculation}
        HS^[M, N] := 0
      end; {calculation}
  end; {HS}

{------------------------Groundwater Level Calculations For A Series Of Time Loops-----------------}

for TIMELOOPS := 1 to Z do
  begin {timeloops}

{-------------------------------------GW Head Calculations-------------------------------------}

    for N := 1 to J do
      begin {H loop}
        for M := 1 to I do
          begin {calculation}
            TTERM := (4 * K * (H^[M, N] - AB^[M, N]) * DT) / (S * DX * DX);
            HTERM := H^[M + 1, N] + H^[M - 1, N] + H^[M, N + 1] + H^[M, N - 1];
            HS^[M, N] := ((1 - TTERM) * H^[M, N] + (TTERM * (HTERM / 4)) + (R^[M, N] * DT / S));
          end; {calculation}
      end; {H loop}
```

```
{---------------------Transfer New Head Values Into Old Head Values (Array HS into Array H)---------}

   for N := 1 to J do
     begin  {transfer array}
       for M := 1 to I do
         begin  {enter values}
           H^[M, N] := HS^[M, N];
         end;  {enter values}
     end;  {transfer array}

{----------------------------------GW Table at Ground Surface ?  ------------------------------}

   for N := 0 to J + 1 do
     begin  {check H vs. GS}
       for M := 0 to I + 1 do
         begin  {if,then}
           if H^[M, N] > GS^[M, N] then
             begin  {replace}
               H^[M, N] := GS^[M, N];
             end;  {replace}
         end;  {if,then}
     end;  {check H vs. GS}

{-----------------------------------GW Table at Aquifer Bottom ?  -----------------------------}

   for N := 0 to J + 1 do
     begin  {check H vs. AB}
       for M := 0 to I + 1 do
         begin  {if,then}
           if H^[M, N] < AB^[M, N] then
             begin  {replace}
               H^[M, N] := AB^[M, N];
             end;  {replace}
         end;  {if,then}
     end;  {check H vs. AB}

{----------------------------------------Reset Boundary Conditions-------------------------------}

{---------------Uphill and Downhill Semi-infinite Boundary Conditions , Perpendicular to the Channel-------}

   for M := 1 to I + 1 do
     begin  {calculations}
       H^[M, 0] := H^[M, 1] + (H^[M, 1] - H^[M, 2]);
       H^[M, J + 1] := H^[M, J] + (H^[M, J] - H^[M, J - 1]);
     end;  {calculations}

{----------------------------Upslope Semi-infinite Boundary Conditions, Parallel to Channel)-----------}

   for N := 0 to J + 1 do
     begin  {calculation}
       H^[I + 1, N] := H^[I, N] + (H^[I, N] - H^[I - 1, N]);
     end;  {calculation}

{-----------------Stream and Pond Constant Head Boundary Conditions Along Channel Interface-----------}
```

```
{The H values for the stream and pond along the channel interface remain unaltered during the calculations, so}
{no resetting of this boundary condition is necessary.}

{----------------------------------------End    Timeloops--------------------------------------------}

   end;  {Timeloops}

{----------------------------Write  New  H  Values  To  A  GW  Storage  File-----------------------------}

  rewrite(HFNEW, NewFileName('Output File Name, H :   '));
  for N := 0 to J + 1 do
    begin  {HF}
      for M := 0 to I + 1 do
        begin  {write file}
          writeln(HFNEW, H^[M, N] : 12 : 4);
        end;  {write file}
    end;  {HF}
  close(HFNEW);

{----------------------------------Write  Results  To  The  Text  Window------------------------------}

  for N := O to J + 1 do
    begin  {conv. nodes to distance}
      for M := 0 to I + 1 do
        begin  {calculation}
          DVALX := M * DX;
          DVALY := N * DX;
        end;  {calculation}
    end;  {conv. nodes to distance}

  writeln('___DIST X___DIST Y_____GW LEVEL_(m)__________________________________________');
  writeln;

  for N := 0 to J + 1 do
    begin  {text}
      for M := 0 to I + 1 do
        begin  {write}
          writeln(DVALX : 6 : 2, DVALY : 6 : 2, H^[M, N] : 12 : 2);
        end;  {write}
    end;  {text}

{----------------------------------Dispose  Pointer  For  Arrays-------------------------------------}

  dispose(AB);
  dispose(GS);
  dispose(H);
  dispose(R);
  dispose(HS);

{------------------------------------------End    Program------------------------------------------}

end.  {program}
```

```
program GW_AB:

{This program calculates the elevation of the aquifer bottom at each node throughout the modeled area. with }
{uniform gradients in the x and y directions.}
{Use in conjunction with the groundwater_beaver_pond program.}
{Input Files: none}
{Output Files: aquifer bottom (AB)}

{------------------------------------Set Variables------------------------------------------------}

  type

   twodstorage = array[0..40. 0..40] of real:

  var

   ABX. ABY. AB: twodstorage;
   DX. DISTX, DISTY. ABYZZ, ABXSLOPE. ABYSLOPE: real:
   XINC. YINC. I. J. M. N: integer;
   WINDOWRECT: rect;
   ABFNEW: text:

{------------------------------------Begin Program-----------------------------------------------}

begin {program}

{--------------------------------Set Up Text Window-----------------------------------------------}

  hideall:
  setrect(windowrect. 2. 35. 512. 342):
  settextrect(windowrect):
  showtext:

{-------------------------------Define Input Parameters-----------------------------------------}

  writeln('Enter the following values: ');
  writeln('Distance increment or length between nodes is ? (m)');
  readln(DX):
  writeln('Total distance along the boundary perpendicular to the stream (in the X direction) in multiples');
  writeln('of'. DX. 'm. is ?');
  readln(DISTX):
  writeln('Total distance along the boundary parallel to the stream (in the Y direction) in multiples'):
  writeln('of '. DX. 'm. is ? '):
  readln(DISTY):
  writeln('Elevation of the aquifer bottom at the downstream channel adjacent boundary (at i,j = 0,0)');
  writeln('is ? (m)'):
  readln(ABYZZ):
  writeln('Slope of the aquifer bottom in the X direction is ? (express as a decimal value'):
  readln(ABXSLOPE):
  writeln('Slope of the aquifer bottom in the Y direction is ? (express as a decimal value)');
  readln(ABYSLOPE):

{------------------------------Define Node Variables----------------------------------------------}

  {Calculate the number of nodes in the X direction. perpendicular to the channel.}
  XINC := trunc(DISTX / DX) + 1:
  {Calculate the number of nodes in the Y direction, parallel to the channel.}
```

```
YINC := trunc(DISTY / DX) + 1;

If (XINC > 39) then
  begin {check boundary, DX distances}
    writeln('The number of nodes in the X direction, perpendicular to the channel, is ', XINC, '.');
    writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
    writeln('distance between nodes or the distance in the X direction.');
  end; {check boundary, DX distances}

If (YINC > 39) then
  begin {check boundary, DX distances}
    writeln('The number of nodes in the Y direction, parallel to the channel, is ', YINC, '.');
    writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
    writeln('distance between nodes or the distance in the Y direction.');
  end; {check boundary, DX distances}

I := XINC;
J := YINC;

{----------------------------Calculate  Aquifer  Bottom  Elevations-----------------------------------}

for N := 0 to J + 1 do
  begin {ABX}
    for M := 0 to I + 1 do
      begin {calculation}
        ABX[M, N] := (ABXSLOPE * M * DX) + 0;
      end; {calculation}
  end; {ABX}

for N := 0 to J + 1 do
  begin {ABY}
    for M := 0 to I + 1 do
      begin {calculation}
        ABY[M, N] := (ABYSLOPE * N * DX) + ABYZZ;
      end; {calculation}
  end; {ABY}

for N := 0 to J + 1 do
  begin {AB}
    for M := 0 to I + 1 do
      begin {calculation}
        AB[M, N] := ABX[M, N] + ABY[M, N];
      end; {calculation}
  end; {AB}

{----------------------------Write  AB  Results  to  Storage  File----------------------------------}

open(ABFNEW, NewFileName('Output File Name, AB : '));

for N := 0 to J + 1 do
  begin {ABF}
    for M := 0 to I + 1 do
      begin {write}
        writeln(ABFNEW, AB[M, N] : 12 : 4);
      end; {write}
  end; {ABF}
```

```
  close(ABFNEW);
{---------------------------------------End      Program--------------------------------------------}
end.  {program}
```

```
program GW_GS;

{This program calculates the elevation of the ground surface at each node throughout the modeled area, with}
{uniform gradients parallel to the stream and perpendicular to the stream, or a uniform gradient parallel to}
{the stream and a break in slope perpendicular to the stream that defines a lower and an upper terrace.}
{Use in conjunction with the groundwater_beaver_pond program.}
{Input Files:  none}
{Output Files:  ground surface (GS)}

{------------------------------------Set    Variables---------------------------------------------}

  type
    twodstorage = array[0..40, 0..40] of real;

  var
    GSX, GSY, GS: twodstorage;
    DX, DISTX, DISTY, GSXSLOPE, GSYSLOPE, GSZZ: real;
    LXDIST, UXDIST, LGSXSLOPE, UGSXSLOPE, GSZSLBR: real;
    SLBR, XINC, YINC, SB, I, J, K, M, N: integer;
    WINDOWRECT: rect;
    GSFNEW: text;

{------------------------------------Begin    Program--------------------------------------------}

begin  {program}

{---------------------------------Set   Up   Text   Window--------------------------------------}

  hideall;
  setrect(windowrect, 2, 35, 512, 342);
  settextrect(windowrect);
  showtext;

{-------------------------------Define   Input   Parameters-------------------------------------}

  writeln('Enter the following values:   ');
  writeln('Distance increment or length between nodes is  ?  (m)');
  readln(DX);
  writeln('Total distance along the boundary perpendicular to the stream  (in the X direction) in multiples');
  writeln('of', DX, 'm. is ?');
  readln(DISTX);
  writeln('Total distance along the boundary parallel to the stream (in the Y direction) in multiples');
  writeln('of ', DX, 'm. is ?  ');
  readln(DISTY);

  writeln('Is there a break in the slope of the ground surface, forming a lower and upper terrace? ');
  writeln('(YES = 1 or NO = 0)');
  readln(SLBR);

  If SLBR = 0 then
    begin {no slope break}
      writeln('Slope of the ground surface in the X direction is ?  (express as a decimal value)');
      readln(GSXSLOPE);
      writeln('Slope of the ground surface in the Y direction is ?  (express as a decimal value)');
      readln(GSYSLOPE);
      writeln('Elevation of the ground surface at the downhill boundary adjacent to the stream');
      writeln('(at i,j = 0,0) is  ?  (m)');
```

```
    readln(GSZZ);
  end; {no slope break}

 if SLBR = 1 then
   begin {slope break}
     writeln('Distance between the stream and the slope break (in the X direction, perpendicular to');
     writeln('the stream) is ?  (m)');
     readln(LXDIST);
     writeln('Slope of the lower terrace in the X direction is ?  (express as a decimal value)');
     readln(LGSXSLOPE);
     writeln('Slope of the upper terrace in the X direction is ?  (express as a decimal value)');
     readln(UGSXSLOPE);
     writeln('Slope of the ground surface in the Y direction is ?  (express as a decimal value)');
     readln(GSYSLOPE);
     writeln('Elevation of the ground surface at the downhill boundary adjacent to the stream ');
     writeln('(at i,j = 0,0) is  ?  (m)');
     readln(GSZZ);
     writeln('Elevation of the ground surface at the downhill boundary at edge of the upper terrace is ? (m)');
     readln(GSZSLBR);
   end; {slope break}

{--------------------------------Define   Node   Variables------------------------------------------}

 {Calculate the number of nodes in the X direction, perpendicular to the channel.}
 XINC := trunc(DISTX / DX) + 1;
 {Calculate the number of nodes in the Y direction, parallel to the channel.}
 YINC := trunc(DISTY / DX) + 1;
 {Calculate the number of nodes from the stream to the slope break.}
 SB := trunc(LXDIST / DX);

 if (XINC > 39) then
   begin {check boundary, DX distances}
     writeln('The number of nodes in the X direction, perpendicular to the channel, is ', XINC, '.');
     writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
     writeln('distance between nodes or the distance in the X direction.');
   end; {check boundary, DX distances}

 if (YINC > 39) then
   begin {check boundary, DX distances}
     writeln('The number of nodes in the Y direction, parallel to the channel, is ', YINC, '.');
     writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
     writeln('distance between nodes or the distance in the Y direction.');
   end; {check boundary, DX distances}

 I := XINC;
 J := YINC;
 K := SB;

{------------------------------Calculate   Ground   Surface   Elevations---------------------------------}

 if SLBR = 0 then
   begin {x dir., no slope break}

     for N := 0 to J + 1 do
       begin {GSX}
         for M := 0 to I + 1 do
           begin  {calculation}
```

```
          GSX[M, N] := (GSXSLOPE * M * DX) + 0;
        end;  {calculation}
      end; {GSX}

    end; {x dir., no slope break}

  if SLBR = 1 then
    begin {x dir.,  slope break}

      for N := 0 to J + 1 do
        begin {GSX}
          for M := 0 to K do
            begin  {calculation}
              GSX[M, N] := (LGSXSLOPE * M * DX) + 0;
            end;  {calculation}
        end; {GSX}

      for N := 0 to J + 1 do
        begin {GSX}
          for M := K + 1 to I + 1 do
            begin  {calculation}
              GSX[M, N] := (UGSXSLOPE * M * DX) + GSZSLBR;
            end;  {calculation}
        end; {GSX}

    end; {x dir.,  slope break}

  for N := 0 to J + 1 do
    begin  {GSY}
      for M := 0 to I + 1 do
        begin  {calculation}
          GSY[M, N] := (GSYSLOPE * N * DX) + GSZZ;
        end;  {calculation}
    end;  {GSY}

  for N := 0 to J + 1 do
    begin  {GS}
      for M := 0 to I + 1 do
        begin  {calculation}
          GS[M, N] := GSX[M, N] + GSY[M, N];
        end;  {calculation}
    end;  {GS}

{------------------------------Write   GS   Results   to   Storage   File-------------------------------------}

  open(GSFNEW, NewFileName('OutputFileName,GS: '));

  for N := 0 to J + 1 do
    begin  {GS}
      for M := 0 to I + 1 do
        begin  {write}
          writeln(GSFNEW, GS[M, N] : 12 : 4);
        end;  {write GS}
    end;  {GS}

  close(GSFNEW);
```

```
{-------------------------------------End    Program--------------------------------------------}

end.  {program}
```

```
program GW_H;

{This program calculates the elevation of the initial water table for each node throughout the modeled area}
{with uniform gradients in the x and y directions, with the exception of a break in slope to define the pond}
{along the channel boundary or the y-axis.}
{Use in conjunction with the groundwater_beaver_pond program.}
{Input Files:  none}
{Output Files:  initial water table (H)}

{----------------------------------------Set   Variables------------------------------------------}

  type

   twodstorage = array[0..40, 0..40] of real;

  var
   HX, HY, H: twodstorage;
   DX, DISTX, DISTY, HYZZ, HXSLOPE, HYSLOPE, DSL, DH, PL, PH: real;
   XINC, YINC, DAMLOC, PONDEND, PN, I, J, M, N: integer;
   WINDOWRECT: rect;
   HFNEW: text;

{----------------------------------------Begin   Program-----------------------------------------}

begin  {program}

{---------------------------------------Set   Up   Text   Window------------------------------------}

  hideall;
  setrect(windowrect, 2, 35, 512, 342);
  settextrect(windowrect);
  showtext;

{--------------------------------------Define   Input   Parameters----------------------------------}

  writeln('Enter the following values:  ');
  writeln('Distance increment or length between nodes is  ?  (m)');
  readln(DX);
  writeln('Total distance along the boundary perpendicular to the stream (in the X direction) in multiples');
  writeln('of', DX, 'm. is ?');
  readln(DISTX);
  writeln('Total distance along the boundary parallel to the stream (in the Y direction) in multiples ');
  writeln('of ', DX, 'm. is ?  ');
  readln(DISTY);
  writeln('Distance from the downstream boundary to the dam in multiples of ', DX, 'm. is?');
  readln(DSL);
  writeln('Height of the dam is  ?  (m)');
  readln(DH);
  writeln('Elevation of the initial water table at the downstream channel adjacent boundary');
  writeln('(at i,j = 0,0) is  ?  (m)');
  readln(HYZZ);
  writeln('Slope of the initial water table in the X direction  is  ?  (express as a decimal value)');
  readln(HXSLOPE);
  writeln('Slope of the initial water table in the Y direction is  ?  (express as a decimal value)');
  readln(HYSLOPE);

{------------------------------Define   Node   Variables-------------------------------------------}
```

```
{Calculate the number of nodes in the X direction, perpendicular to the channel.}
XINC := trunc(DISTX / DX) + 1;
{Calculate the number of nodes in the Y direction, parallel to the channel.}
YINC := trunc(DISTY / DX) + 1;
writeln('The number of nodes in the Y direction, parallel to the channel, is ', YINC, '.');

if (XINC > 39) then
  begin {check boundary, DX distances}
    writeln('The number of nodes in the X direction, perpendicular to the channel, is ', XINC, '.');
    writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
    writeln('distance between nodes or the distance in the X direction.');
  end; {check boundary, DX distances}

if (YINC > 39) then
  begin {check boundary, DX distances}
    writeln('The number of nodes in the X direction, perpendicular to the channel, is ', XINC, '.');
    writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
    writeln('distance between nodes or the distance in the Y direction.');
  end; {check boundary, DX distances}

I := XINC;
J := YINC;

 {Calculate the number of nodes from the downstream boundary to the dam.}
DAMLOC := trunc(DSL / DX);
 {Calculate the pond length.}
PL := DH / HYSLOPE;
 {Calculate the number of nodes from the dam to the end of the pond.}
PN := trunc(PL / DX);
 {Calculate the number of nodes from the downstream boundary to the end of the pond.}
PONDEND := DAMLOC + PN;

If (PONDEND > YINC) then
  begin {check pond length}
    writeln('The pond length exceeds the upstream boundary; select new pond location or');
    writeln('distance  parameters.');
  end; {check pond length}

{--------------------------Calculate   Initial   Water   Table   Elevations---------------------------------}

for N := 0 to J + 1 do
  begin  {HX}
    for M := 0 to I + 1 do
      begin  {calculation}
        HX[M, N] := (HXSLOPE * M * DX) + 0;
      end;  {calculation}
  end; {HX}


for N := 0 to J + 1 do
  begin  {HY}
    for M := 0 to I + 1 do
      begin  {calculation}
        HY[M, N] := ((HYSLOPE * N * DX) + HYZZ);
      end;  {calculation}
  end;  {HY}
```

```
for N := 0 to J + 1 do
  begin {H}
    for M := 0 to I + 1 do
      begin {calculation}
        H[M, N] := HX[M, N] + HY[M, N];
      end; {calculation}
  end; {H}

{------------------------------- Pond Head Calculations-----------------------------------------}

  PH := H[0, DAMLOC] + DH;

  for N := DAMLOC to PONDEND do
    begin {calculation}
      H[0, N] := PH;
    end; {calculation}

{----------------------------Write H Results to Storage File-------------------------------------}

  open(HFNEW, NewFileName('OutputFileName, H : '));

  for N := 0 to J + 1 do
    begin {HF}
      for M := 0 to I + 1 do
        begin {write}
          writeln(HFNEW, H[M, N] : 12 : 4);
        end; {write}
    end; {HF}

  close(HFNEW);

{----------------------------------------End Program---------------------------------------------}

end. {program}
```

```
program GW_R;

{This program calculates net areal recharge to the groundwater table for each node throughout the modeled }
{area, based on precipitation, infiltration and evapotranspiration rates.}
{Use in conjunction with the groundwater_beaver_pond program.}
{Input Files: groundsurface (GS), water table (H) from the previous time step}
{Output Files: recharge (R)}

{-----------------------------------Set   Variables--------------------------------------------}

 type

  twodstorage = array[0..40, 0..40] of real;
  ptwodstorage = ^twodstorage;

 var
  GS, S_ET, GW_ET, AET, H, R: ptwodstorage;
  DISTX, DISTY, DX, PINF, P, INFFACTOR, PET, ED: real;
  XINC, YINC, M, N, I, J: integer;
  GSFOLD, HFOLD, RFNEW: text;
  WINDOWRECT: rect;

{-----------------------------------Begin   Program-------------------------------------------}

begin {program}

{--------------------------------Create   Pointer   for   Arrays------------------------------------}

 new(GS);
 new(S_ET);
 new(GW_ET);
 new(R);
 new(H);

{----------------------------------Set   Up   Text   Window------------------------------------------}

 hideall;
 setrect(windowrect, 2, 35, 512, 342);
 settextrect(windowrect);
 showtext;

{---------------------------------Define   Input   Parameters---------------------------------------}

 writeln('Enter the following values:  ');
 writeln('Distance increment or length between nodes is  ?  (m)');
 readln(DX);
 writeln('Total distance along the boundary perpendicular to the stream (in the X direction) in multiples');
 writeln('of', DX, 'm. is ?');
 readln(DISTX);
 writeln('Total distance along the boundary parallel to the stream (in the Y direction) in multiples');
 writeln('of ', DX, 'm. is ?  ');
 readln(DISTY);
 writeln('Precipitation (rainfall and/or snowmelt) rate is ?  (m/day)');
 readln(P);
 writeln('Ratio of soil infiltration capacity to incident precipitation rate is ?  (0.0..1.0)');
 readln(INFFACTOR);
  {Calculate rate of infiltrating precipitation.}
```

```
PINF := P * INFFACTOR;
writeln('Rate of potential evapotranspiration is ?  (m/day)');
readln(PET);
writeln('Extinction depth of evapotranspiration is ?  (m)');
readln(ED);

{------------------------------Define   Node   Variables------------------------------------------}

{Calculate the number of nodes in the X direction, perpendicular to the channel.}
XINC := trunc(DISTX / DX) + 1;
{Calculate the number of nodes in the Y direction, parallel to the channel.}
YINC := trunc(DISTY / DX) + 1;

if (XINC > 39) then
  begin {check boundary, DX distances}
    writeln('The number of nodes in the X direction, perpendicular to the channel, is ', XINC, '.');
    writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
    writeln('distance between nodes or the distance in the X direction.');
  end; {check boundary, DX distances}

if (YINC > 39) then
  begin {check boundary, DX distances}
    writeln('distance between nodes or the distance in the Y direction.');
    writeln('The number of nodes exceeds the array capacity, select new input parameters for the ');
    writeln('The number of nodes in the Y direction, parallel to the channel, is ', YINC, '.');
  end; {check boundary, DX distances}

I := XINC;
J := YINC;

{--------------------------------Get   GS   File   From   Storage   ------------------------------------}

reset(GSFOLD, OldFileName);
for N := 0 to J + 1 do
  begin  {GSF}
    for M := 0 to I + 1 do
      begin  {read file}
        readln(GSFOLD, GS^[M, N]);
      end;  {read file}
  end;  {GSF}
close(GSFOLD);

{--------------------------------Get   H   File   From   Storage   ------------------------------------}

reset(HFOLD, OldFileName);
for N := 0 to J + 1 do
  begin  {HF}
    for M := 0 to I + 1 do
      begin  {read file}
        readln(HFOLD, H^[M, N]);
      end;  {read file}
  end;  {HF}
close(HFOLD);

{-----------------------------------S_ET   Calculations------------------------------------------}

for N := 0 to J + 1 do
```

```
    begin {if PINF < PET}
      for M := 0 to I + 1 do
        begin  {if,then}
          If PINF < PET then
            begin  {calculation}
              S_ET^[M, N] := PINF;
            end;  {calculation}
        end;  {if,then}
    end; {if PINF < PET }

  for N := 0 to J + 1 do
    begin {if PINF >= PET}
      for M := 0 to I + 1 do
        begin  {if,then}
          If PINF >= PET then
            begin  {calculation}
              S_ET^[M, N] := PET;
            end;  {calculation}
        end;  {if,then}
    end; {if PINF >= PET}

{----------------------------------GW_ET    Calculations------------------------------------------}

  for N := 0 to J + 1 do
    begin {if H >= GS - ED}
      for M := 0 to I + 1 do
        begin  {if,then}
          If H^[M, N] >= GS^[M, N] - ED then
            begin  {calculation}
              GW_ET^[M, N] := PET * ((H^[M, N] - (GS^[M, N] - ED)) / ED);
            end;  {calculation}
        end;  {if,then}
    end; {if H>= GS - ED}

  for N := 0 to J + 1 do
    begin {if H < GS - ED}
      for M := 0 to I + 1 do
        begin  {if,then}
          If H^[M, N] < GS^[M, N] - ED then
            begin  {calculation}
              GW_ET^[M, N] := 0;
            end;  {calculation}
        end;  {if,then}
    end; {if H < GS - ED}

{-------------------------------------AET    Calculation------------------------------------------}

  for N := 0 to J + 1 do
    begin  {AET}
      for M := 0 to I + 1 do
        begin  {calculation}
          AET^[M, N] := S_ET^[M, N] + GW_ET^[M, N]
        end;  {calculation}
    end; {AET}

{---------------------------------AET   Greater   Than   PET   ?-------------------------------------}
```

```
  for N := 0 to J + 1 do
    begin  {if AET > PET}
      for M := 0 to I + 1 do
        begin  {if,then}
          if AET^[M, N] > PET then
            begin  {replace}
              AET^[M, N] := PET;
            end;  {replace}
        end;  {if,then}
    end;  {if AET > PET}

{----------------------------------Recharge  Calculation----------------------------------------}

  for N := 0 to J + 1 do
    begin  {R}
      for M := 0 to I + 1 do
        begin  {calculation}
          R^[M, N] := (PINF - AET^[M, N]);
        end;  {calculation}
    end;  {R}

{-------------------------------Write  R  Results  to  Storage  File-----------------------------------}

  open(RFNEW, NewFileName('OutputFileName, R: '));
  for N := 0 to J + 1 do
    begin  {R}
      for M := 0 to I + 1 do
        begin  {write}
          writeln(RFNEW, R^[M, N] : 12 : 4);
        end;  {write}
    end;  {R}
  close(RFNEW);

{------------------------------Dispose  Pointer  For  Arrays---------------------------------------}

  dispose(GS);
  dispose(S_ET);
  dispose(GW_ET);
  dispose(R);
  dispose(H);

{----------------------------------------End  Program---------------------------------------------}

end.  {program}
```

Appendix B:

Western and Central Field Site
Dam Height and Hydraulic Conductivity Values

Table B1: Dam height and hydraulic conductivity values for the western Oregon field sites.

Stream	Site No.	Dam Height m	Hydraulic Conductivity m/day					
			K1	K2	K3	K4	K5	Avg. K
Flynn Creek*	W1	0.31	2.3×10^{-3}	4.4×10^{-4}	2.7×10^{-2}	9.5×10^{-3}	5.7×10^{-3}	5.4×10^{-3}
"	W2	1.10	1.5×10^{-1}	5.0×10^{-2}	3.4×10^{-3}	3.6×10^{-2}	4.9×10^{-2}	5.7×10^{-2}
"	W3	1.44	4.5×10^{-1}	9.9×10^{-4}	4.9×10^{-3}	6.5×10^{-4}	1.4×10^{-1}	1.2×10^{-1}
Deer Creek*	W4	0.66	6.5×10^{-4}	1.0×10^{-3}	2.8×10^{-4}	4.1×10^{-2}	5.8×10^{-3}	9.7×10^{-3}
"	W5	0.85	3.4×10^{-2}	8.7×10^{-2}	5.0×10^{-2}	2.9×10^{-3}	5.5×10^{-3}	3.6×10^{-2}
"	W6	0.96	8.4×10^{-4}	7.9×10^{-4}	6.1×10^{-3}	1.4×10^{-1}	9.0×10^{-5}	2.9×10^{-2}
Canal Creek*	W7	1.05	8.0×10^{-3}	5.8×10^{-4}	1.2×10^{-2}	3.5×10^{-2}	1.8×10^{-4}	1.1×10^{-2}
Esmond Creek**	W8	0.47	7.7×10^{-1}	2.2×10^{0}	3.6×10^{-1}	8.6×10^{-1}	4.7×10^{-2}	8.5×10^{-1}
"	W9	1.25	2.3×10^{-2}	7.4×10^{-3}	3.9×10^{-3}	1.7×10^{-2}	4.3×10^{-3}	1.1×10^{-2}
"	W10	1.70	5.0×10^{-2}	1.9×10^{-1}	2.7×10^{-3}	1.8×10^{-3}	3.8×10^{-3}	5.1×10^{-2}

* Located in Lincoln County.

** " " Douglas County.

Table B2: Dam height and hydraulic conductivity values for the central Oregon field sites.

Stream	Site No.	Dam Height m	Hydraulic Conductivity m/day					
			K1	K2	K3	K4	K5	Avg. K
Bridge Creek*	C1	0.28	7.3×10^{-4}	3.6×10^{-2}	2.4×10^{-3}	8.9×10^{-4}	3.0×10^{-3}	8.8×10^{-3}
"	C2	0.36	3.1×10^{-1}	2.7×10^{-2}	3.3×10^{-3}	4.7×10^{-2}	9.5×10^{-3}	1.8×10^{-2}
"	C3	0.78	6.6×10^{-4}	1.9×10^{-2}	3.6×10^{-3}	3.0×10^{-2}	7.8×10^{-4}	1.1×10^{-2}
"	C4	0.89	4.3×10^{-2}	6.8×10^{-3}	1.5×10^{-2}	6.7×10^{-4}	3.7×10^{-1}	8.7×10^{-2}
Beaver Creek**	C5	0.66	2.7×10^{-3}	1.9×10^{-2}	2.3×10^{-3}	3.6×10^{-2}	2.7×10^{-3}	1.2×10^{-2}
"	C6	1.14	4.2×10^{-4}	1.8×10^{-3}	6.2×10^{-2}	4.7×10^{-4}	1.2×10^{-3}	5.3×10^{-2}
"	C7	1.31+	7.0×10^{-2}	2.05×10^{0}	2.37×10^{0}	0.58×10^{-1}	9.2×10^{-3}	1.01×10^{0}
Long Creek***	C8	0.53	8.7×10^{-3}	2.4×10^{-3}	6.7×10^{-3}	2.9×10^{-2}	1.6×10^{-3}	9.8×10^{-3}
"	C9	0.81	5.5×10^{-3}	8.9×10^{-2}	4.2×10^{-2}	3.7×10^{-4}	6.8×10^{-3}	2.9×10^{-2}
"	C10	0.92	2.2×10^{-1}	7.6×10^{-2}	1.6×10^{-2}	3.1×10^{-1}	9.1×10^{-3}	1.3×10^{-1}

* Located in Wheeler County.
** " " Crook County.
*** " " Grant County.
\+ From historical records, Crook County survey notes.

APPENDIX C:

Oak Creek Hydraulic Conductivity and Storativity Values

Table C1. Hydraulic conductivity and storativity values for the Oak Creek site.

Well No.	K m/day	S
A1	$6.4x10^{-3}$	0.057
A2	$5.8x10^{-3}$	0.052
A3	$5.0x10^{-3}$	0.048
A4	$9.7x10^{-3}$	0.066
A5	$2.0x10^{-2}$	0.074
B1	$4.6x10^{-3}$	0.046
B2	$7.1x10^{-3}$	0.060
B3	$3.0x10^{-2}$	0.079
B4	$1.1x10^{-2}$	0.070
C1	$7.0x10^{-3}$	0.062
C2	$5.2x10^{-3}$	0.056
C3	$1.9x10^{-2}$	0.070
D1	$4.1x10^{-3}$	0.037
D2	$5.3x10^{-3}$	0.043
D3	$6.4x10^{-3}$	0.055
D4	$4.7x10^{-3}$	0.042
D5	$8.7x10^{-3}$	0.063
D6	$1.5x10^{-2}$	0.072
D7	$2.5x10^{-2}$	0.076

Well No.	K m/day	S
E1	$5.8x10^{-3}$	0.050
E2	$6.3x10^{-3}$	0.053
E3	$9.8x10^{-3}$	0.062
E4	$2.5x10^{-2}$	0.066
E5	$1.1x10^{-2}$	0.072
F1	$6.3x10^{-3}$	0.058
F2	$8.0x10^{-3}$	0.059
F3	$9.5x10^{-3}$	0.065
F4	$1.2x10^{-2}$	0.068
G1	$5.0x10^{-3}$	0.044
G2	$7.1x10^{-3}$	0.050
G3	$8.4x10^{-3}$	0.059
G4	$7.9x10^{-3}$	0.060
G5	$1.4x10^{-2}$	0.070
H1	$4.3x10^{-3}$	0.045
H2	$6.7x10^{-3}$	0.054
H3	$1.0x10^{-2}$	0.068
H4	$3.5x10^{-2}$	0.080

APPENDIX D:

Monthly Groundwater Table Profiles for
the Western, Central and Oak Creek Sites

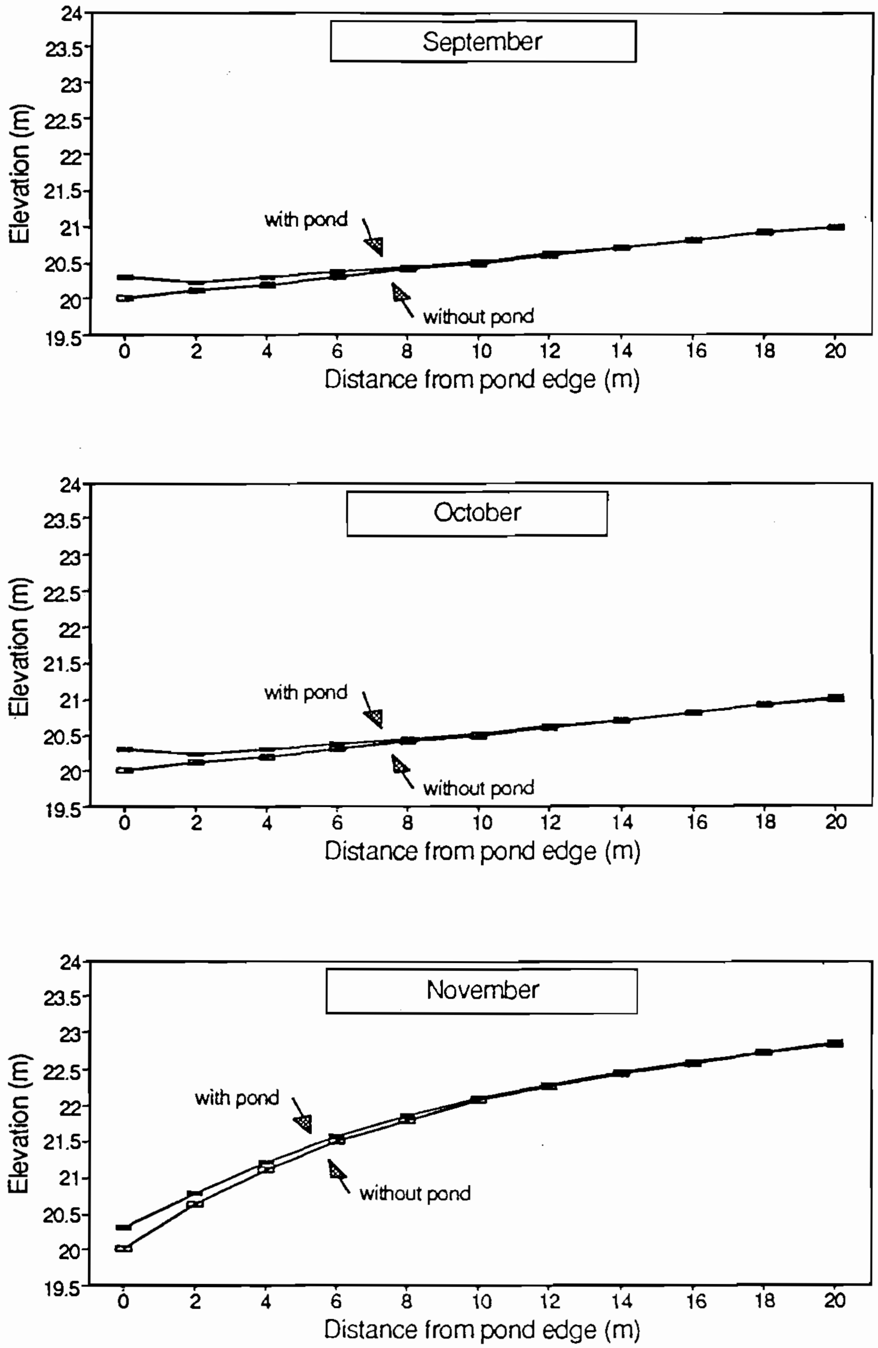


Figure D1. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WS during September, October and November.

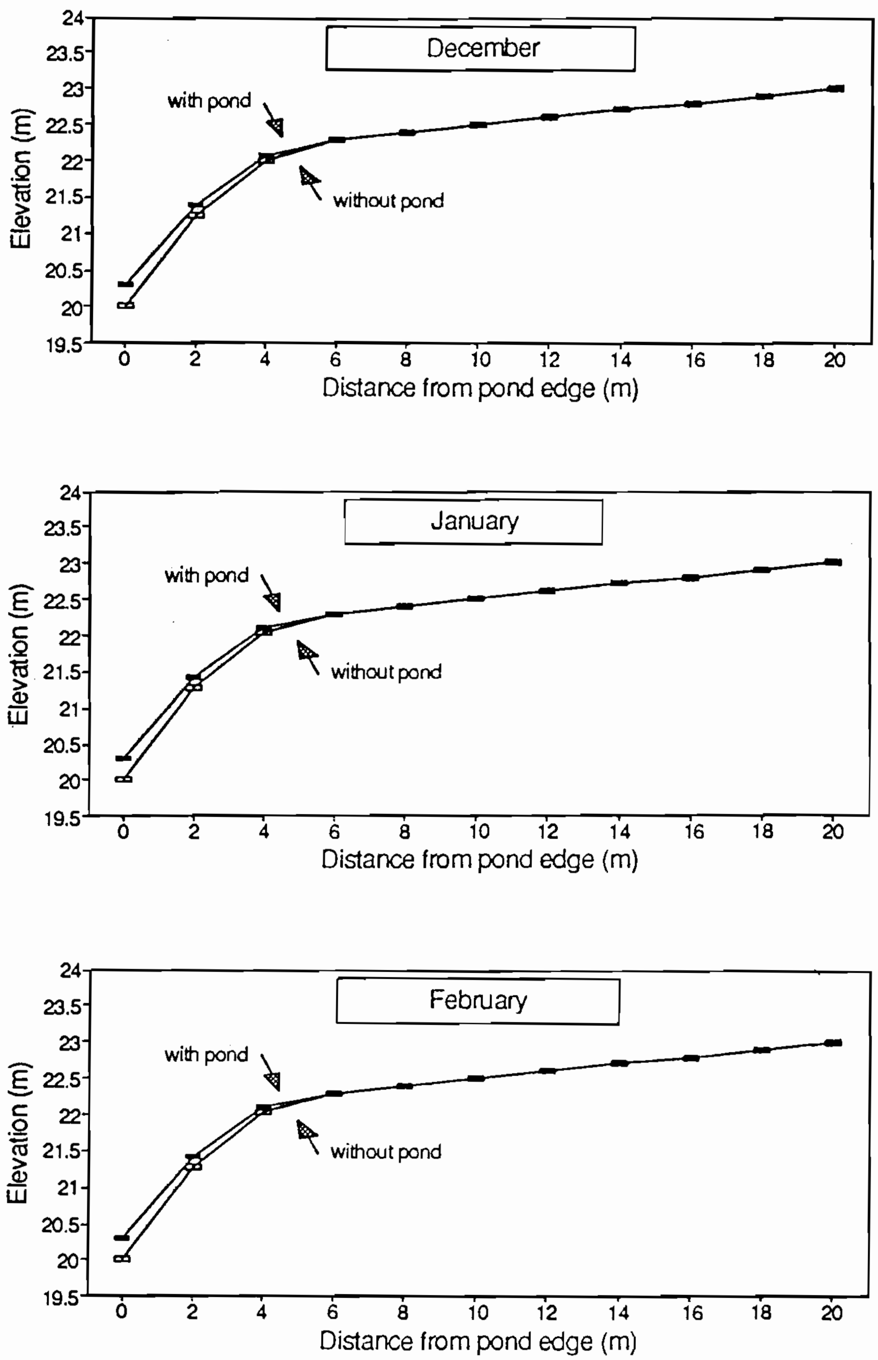


Figure D2. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WS during December, January and February.

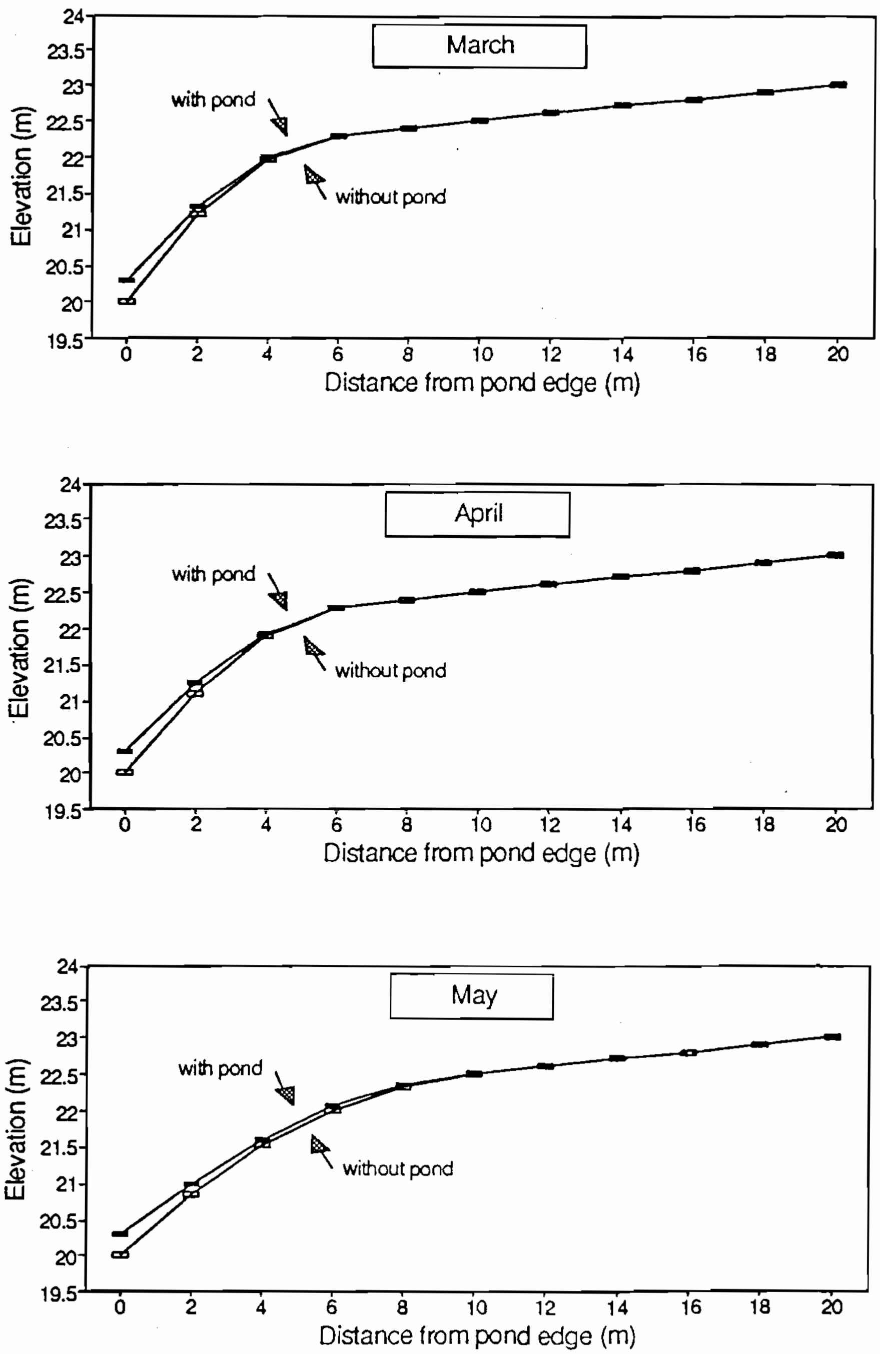


Figure D3. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WS during March, April and May.

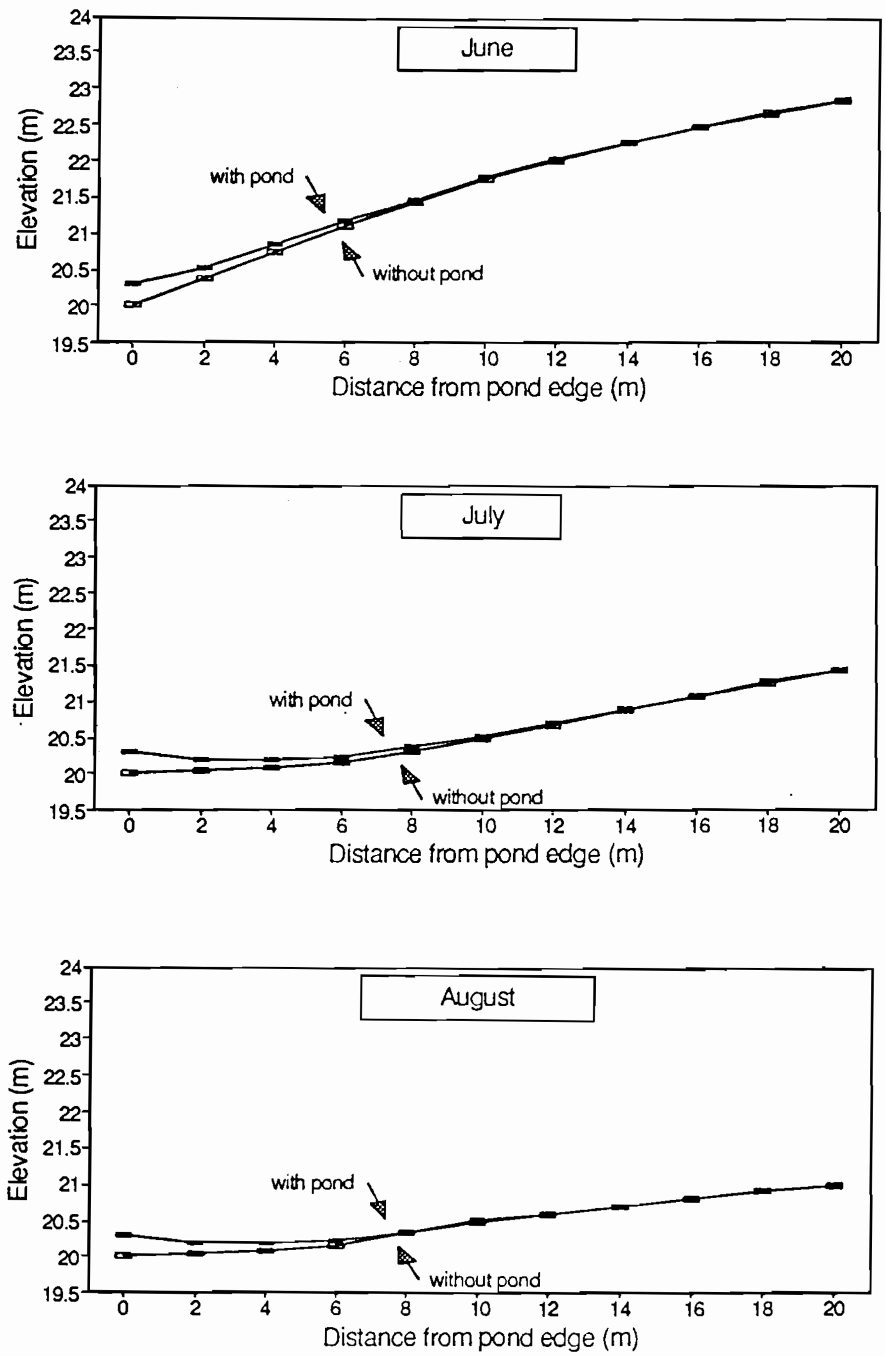


Figure D4. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WS during June, July and August.

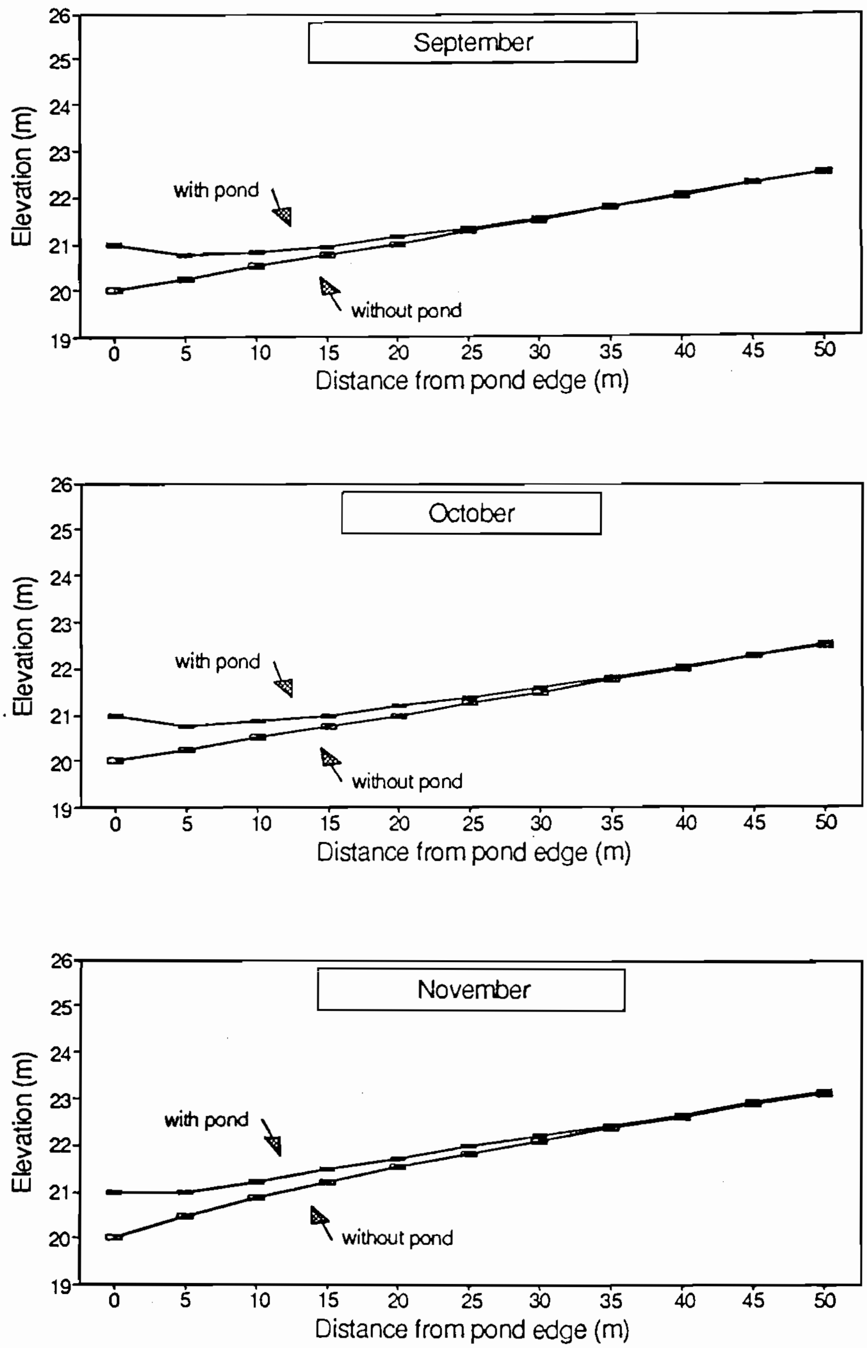


Figure D5. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WM during September, October and November.

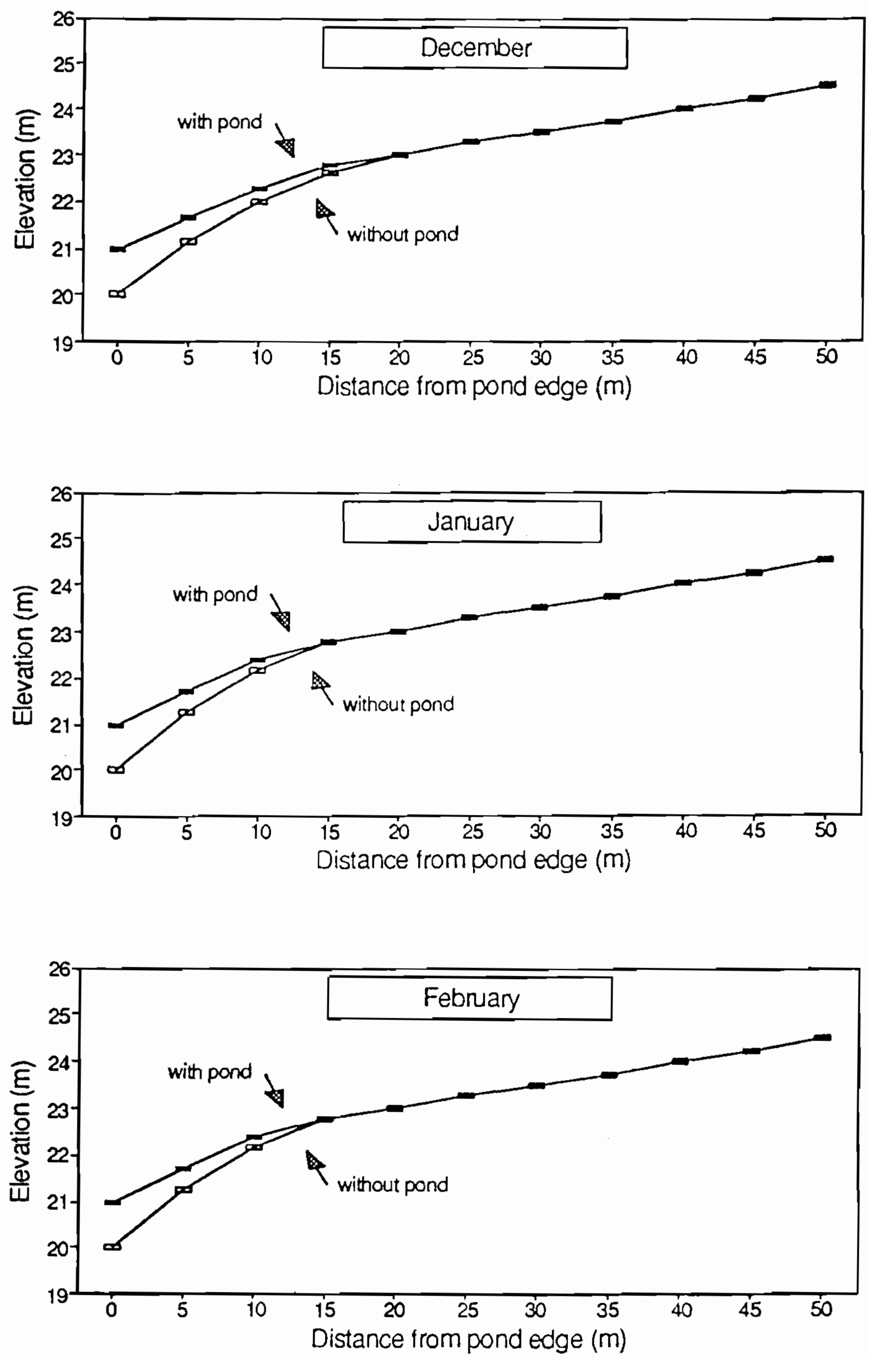


Figure D6. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WM during December, January and February.

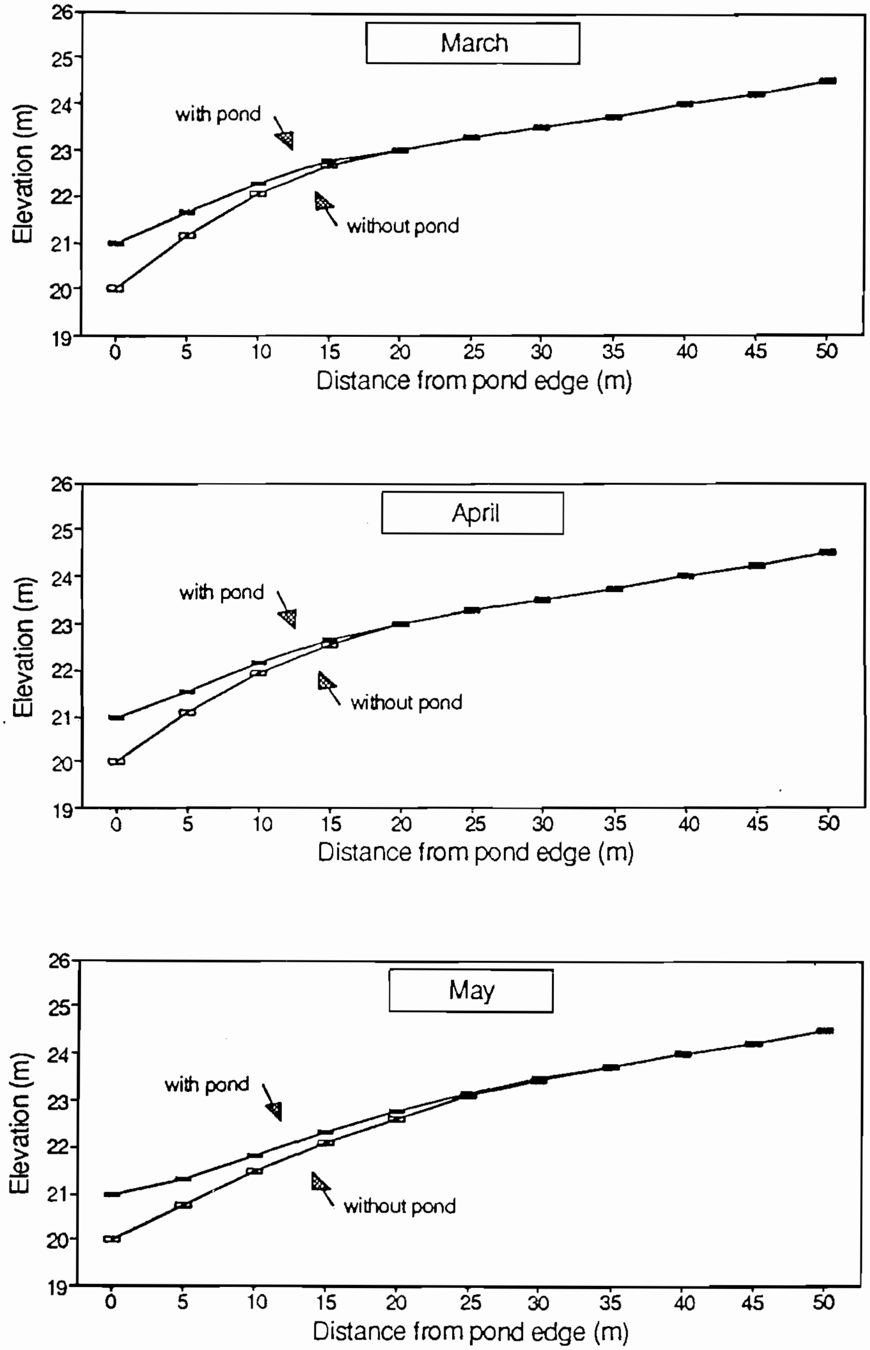


Figure D7. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WM during March, April and May.

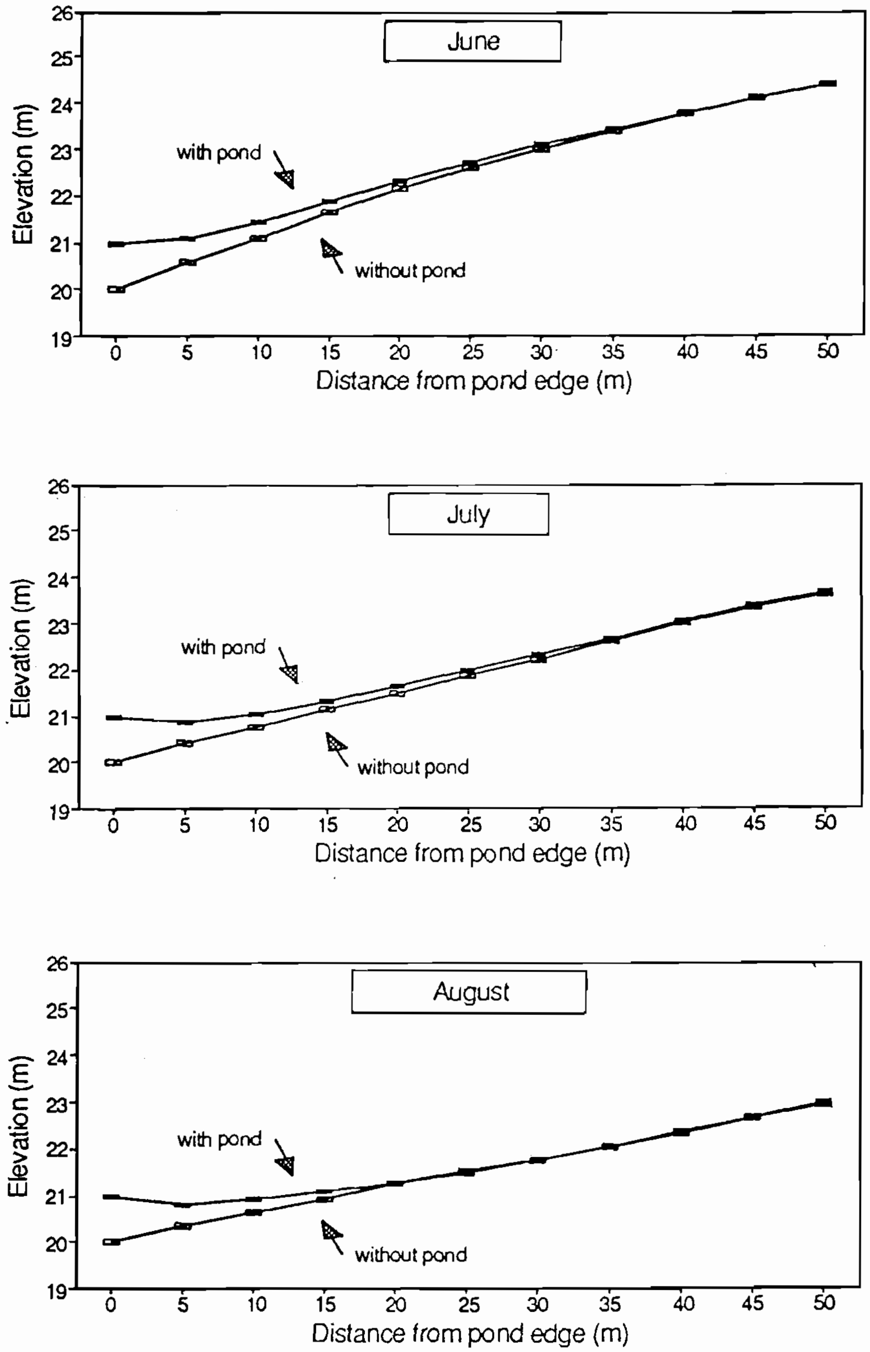


Figure D8. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WM during June, July and August.

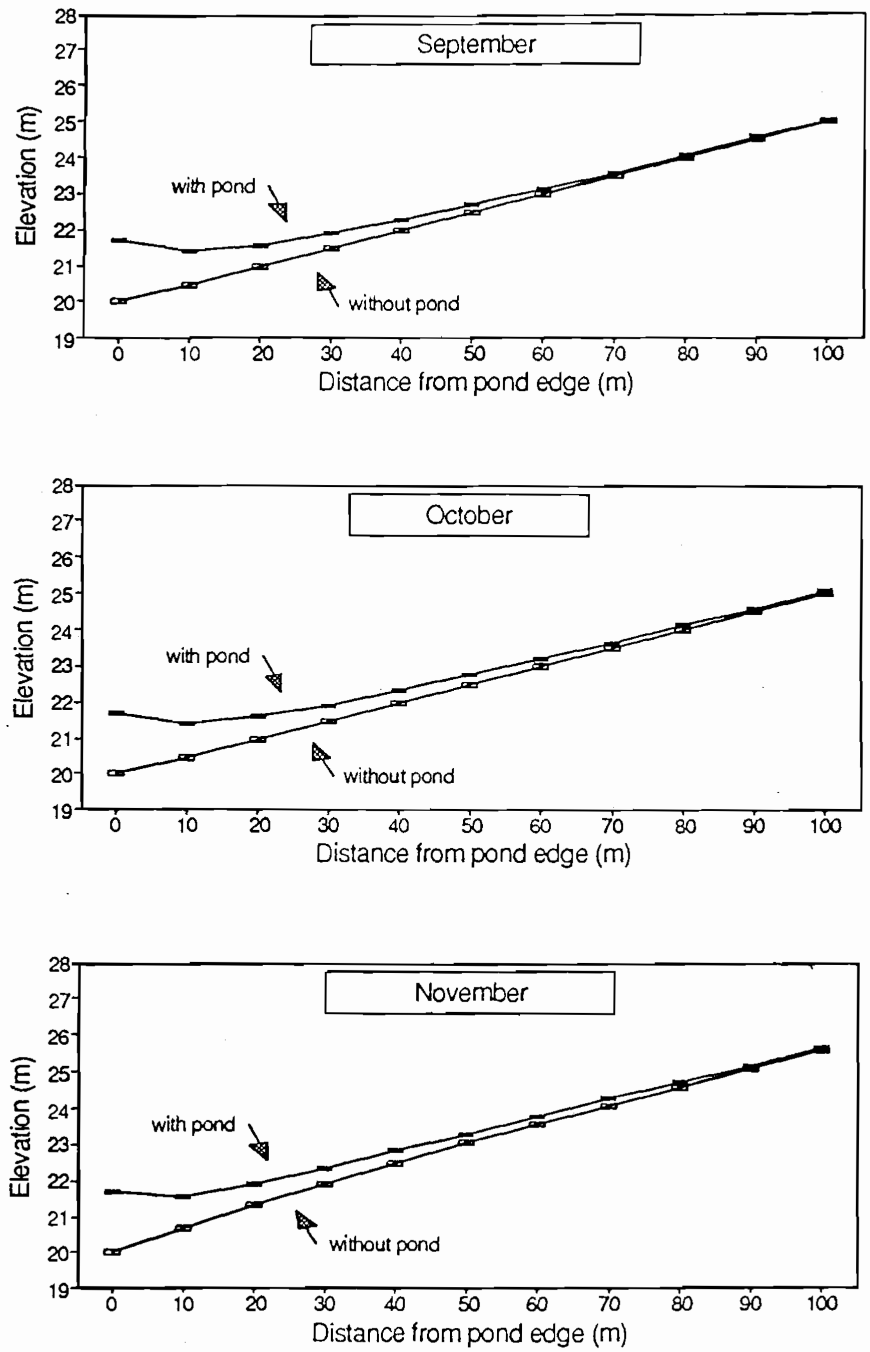


Figure D9. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WL during September, October and November.

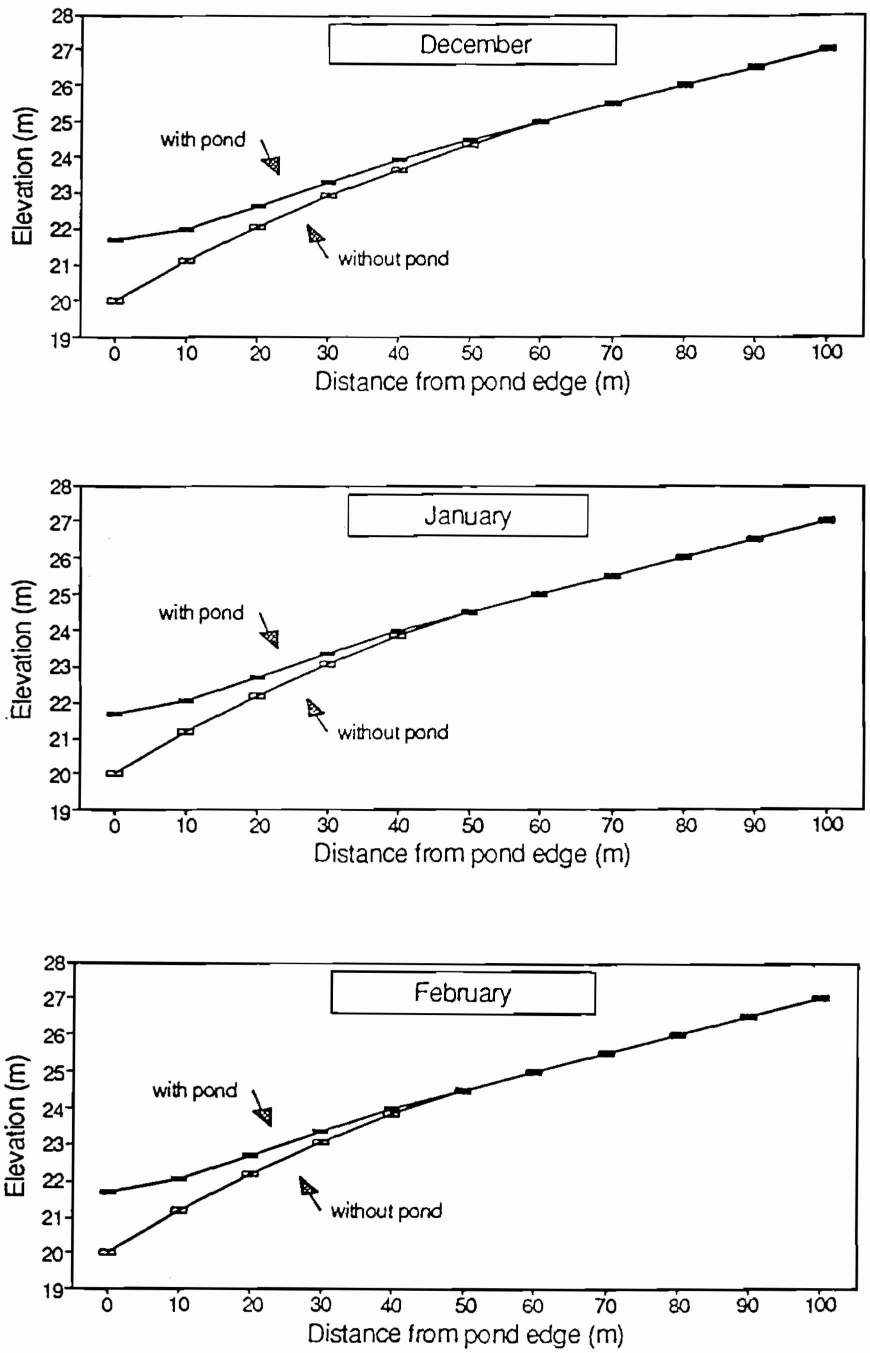


Figure D10. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WL during December, January and February.

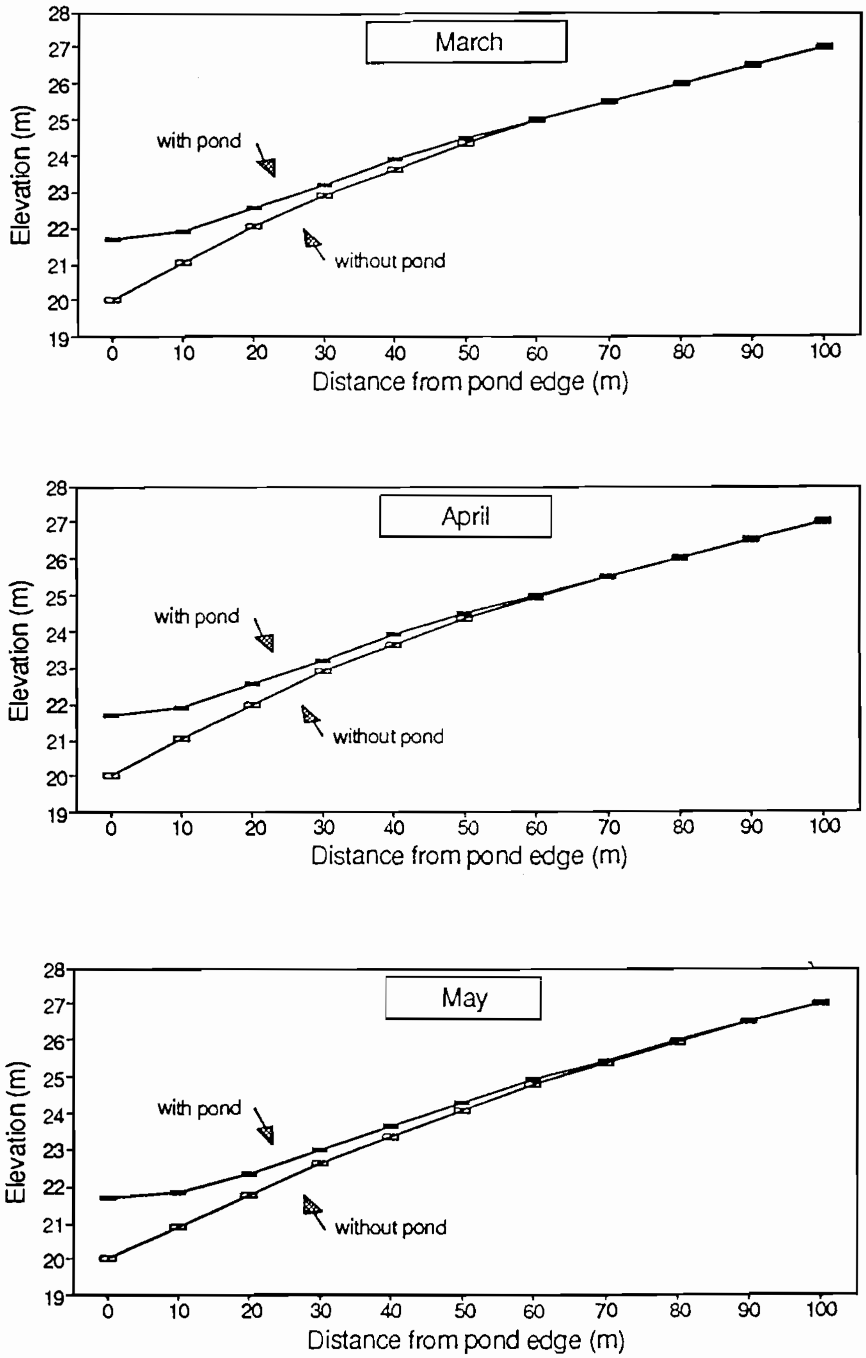


Figure D11. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WL during March, April and May.

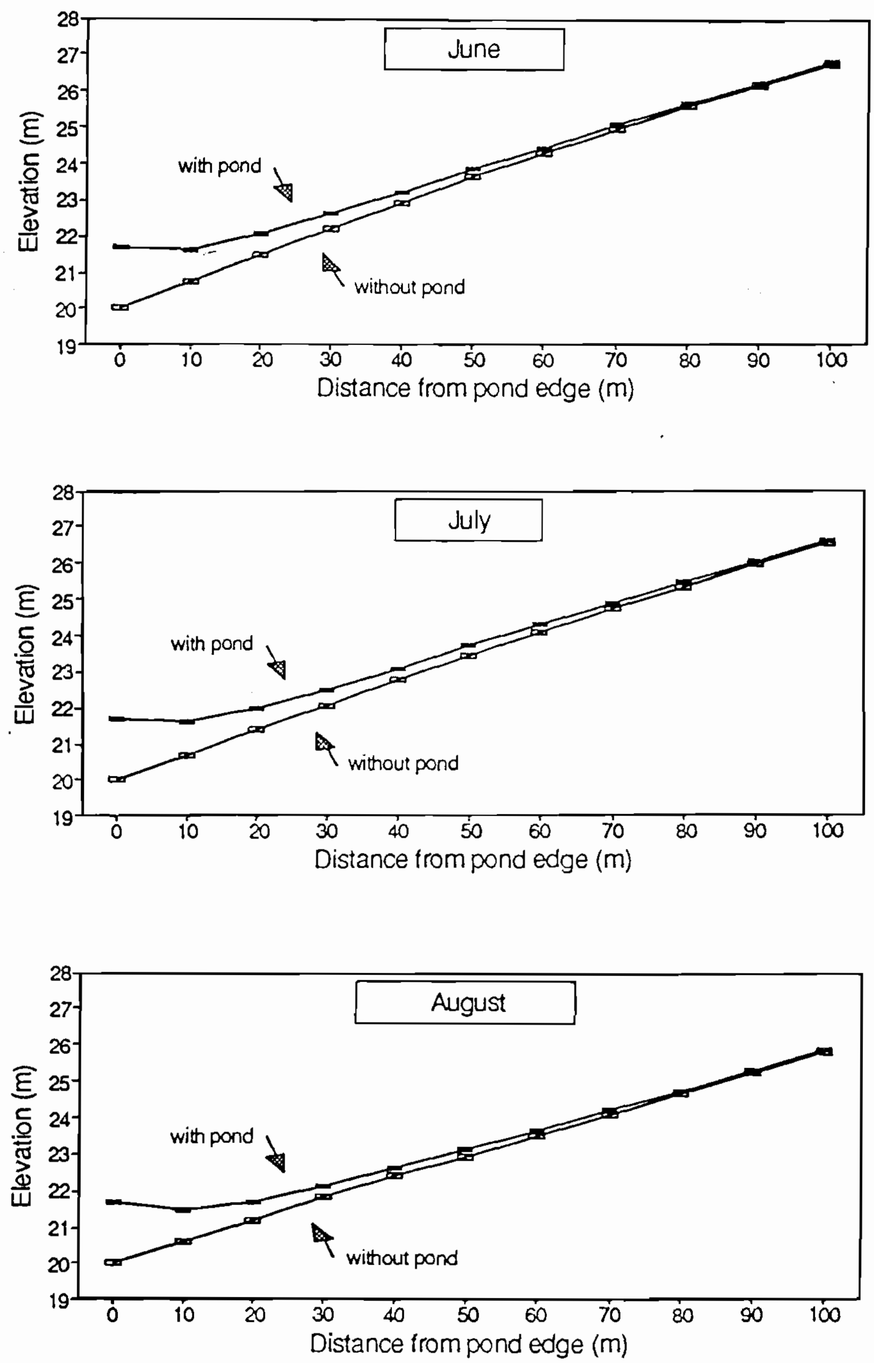


Figure D12. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case WL during June, July and August.

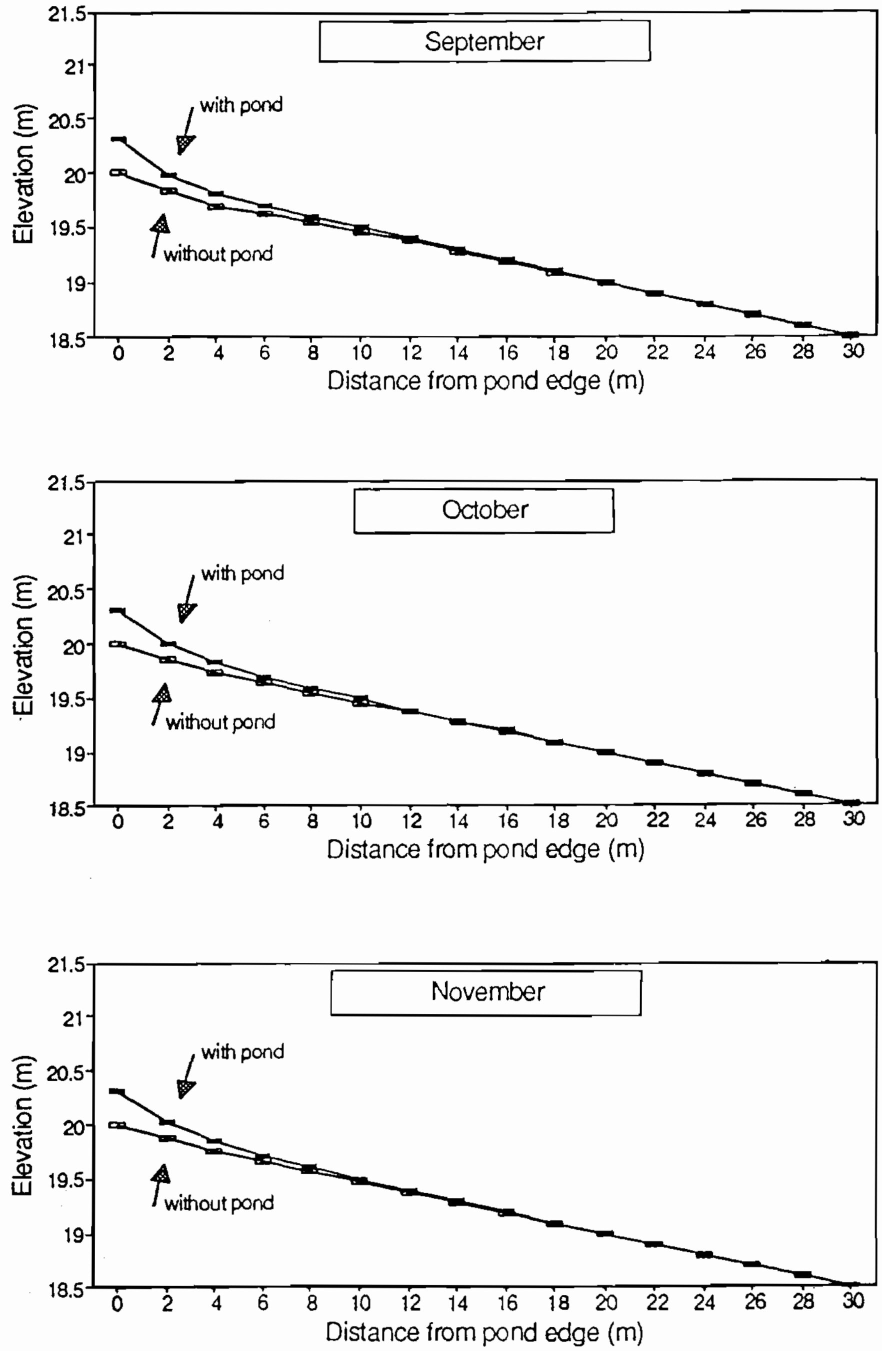


Figure D13. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CS during September, October and November.

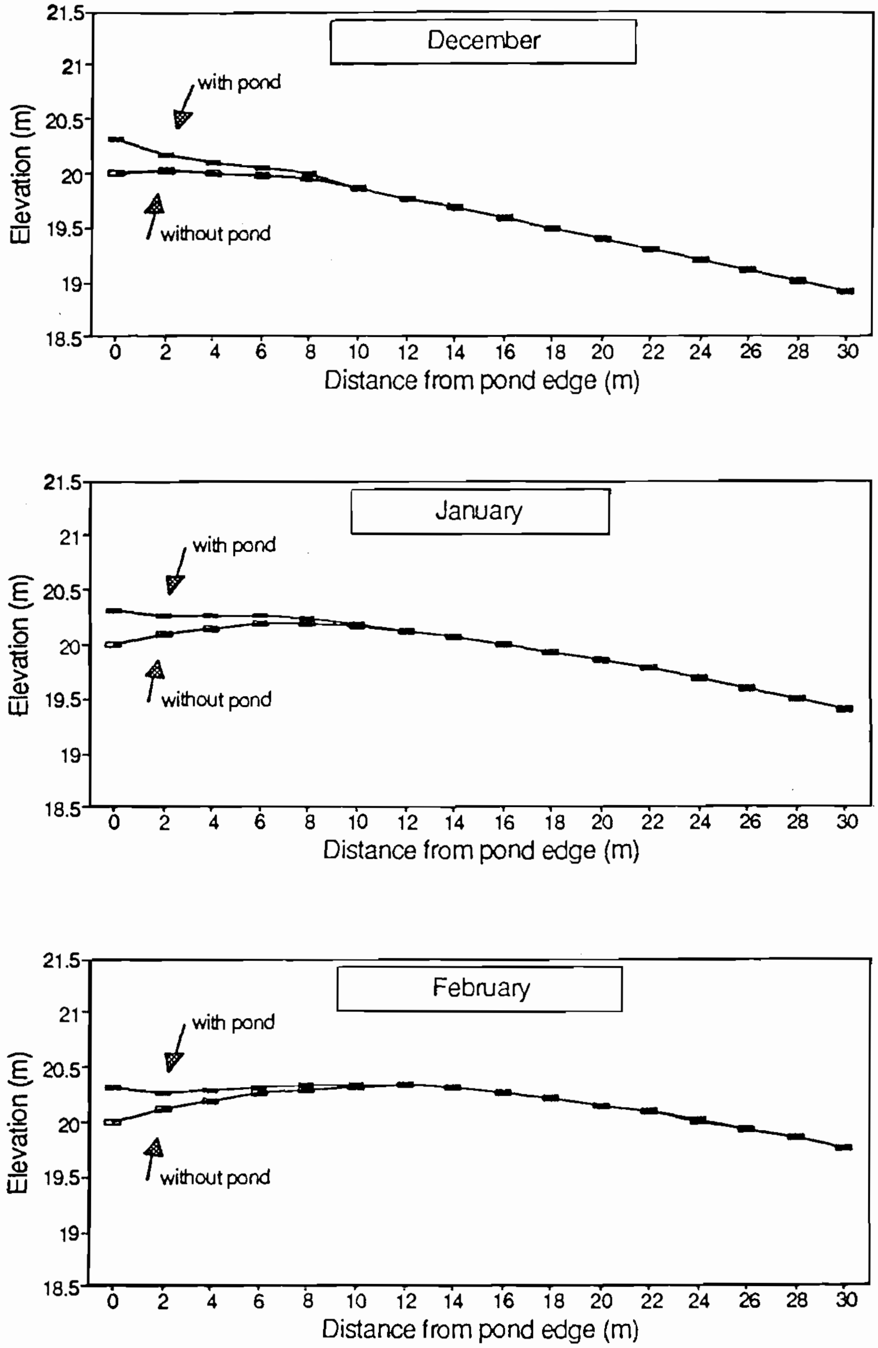


Figure D14. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CS during December, January and February.

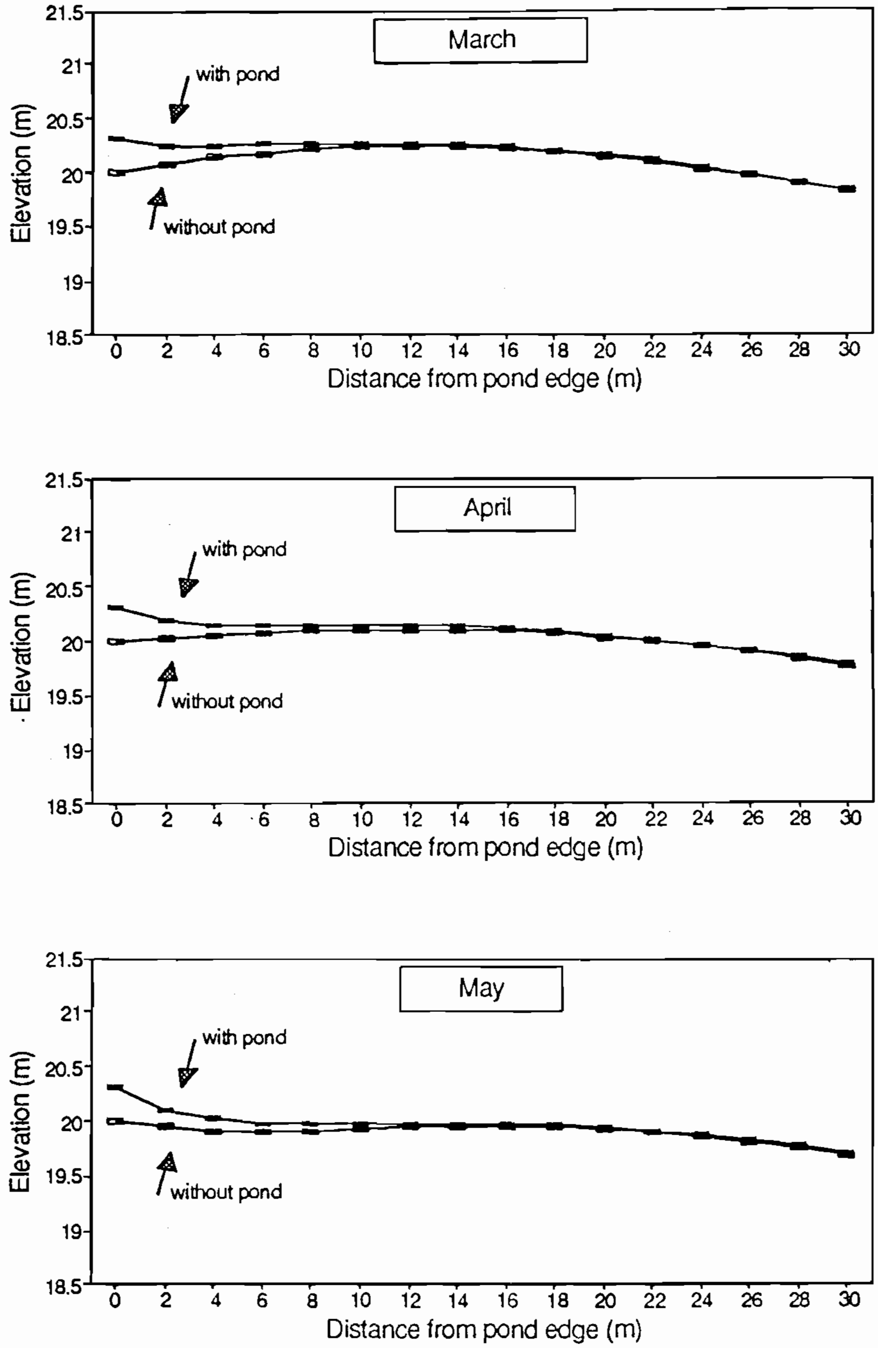


Figure D15. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CS during March, April and May.

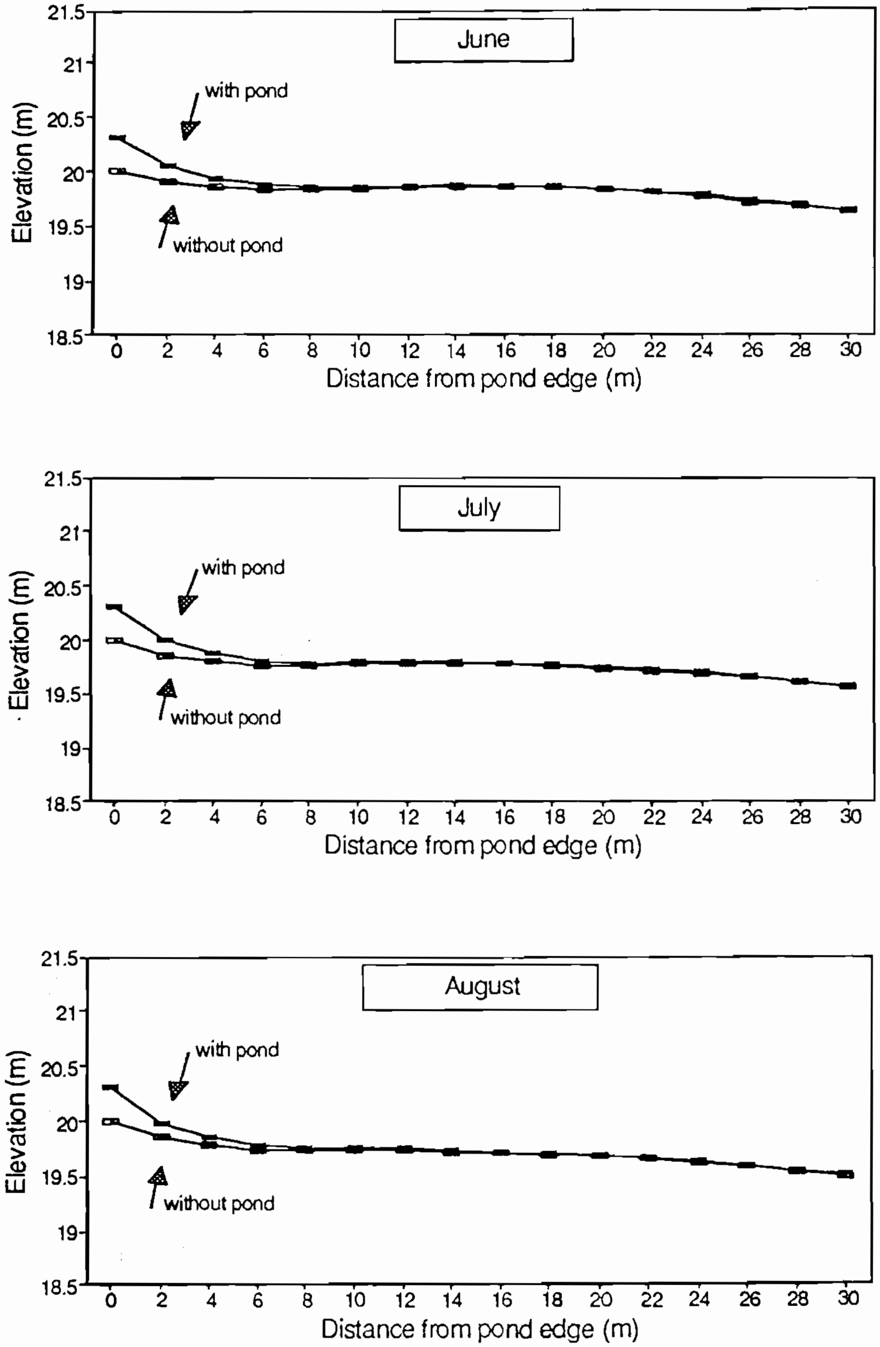


Figure D16. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CS during June, July and August.

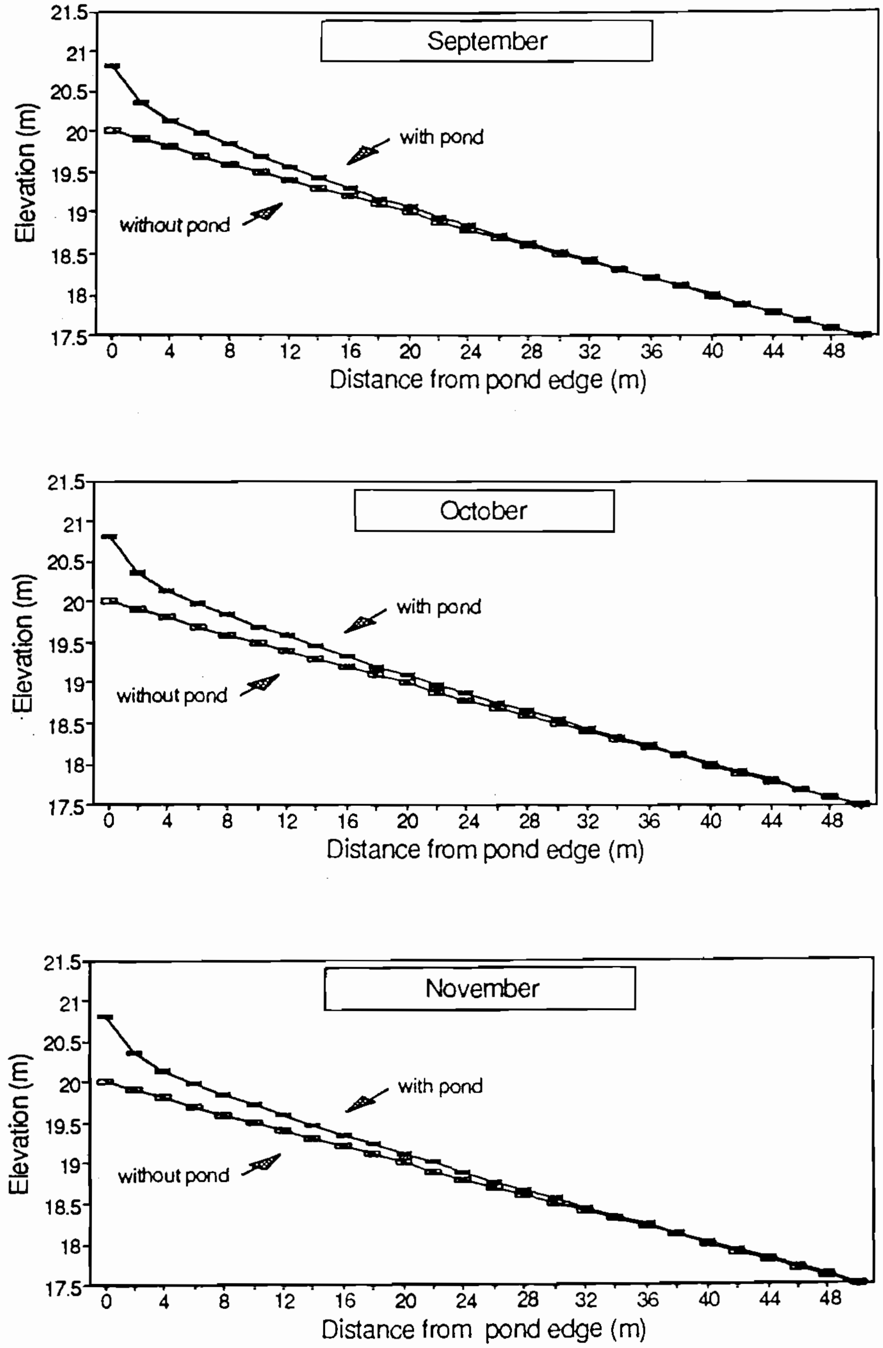


Figure D17. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CM during September, October and November.

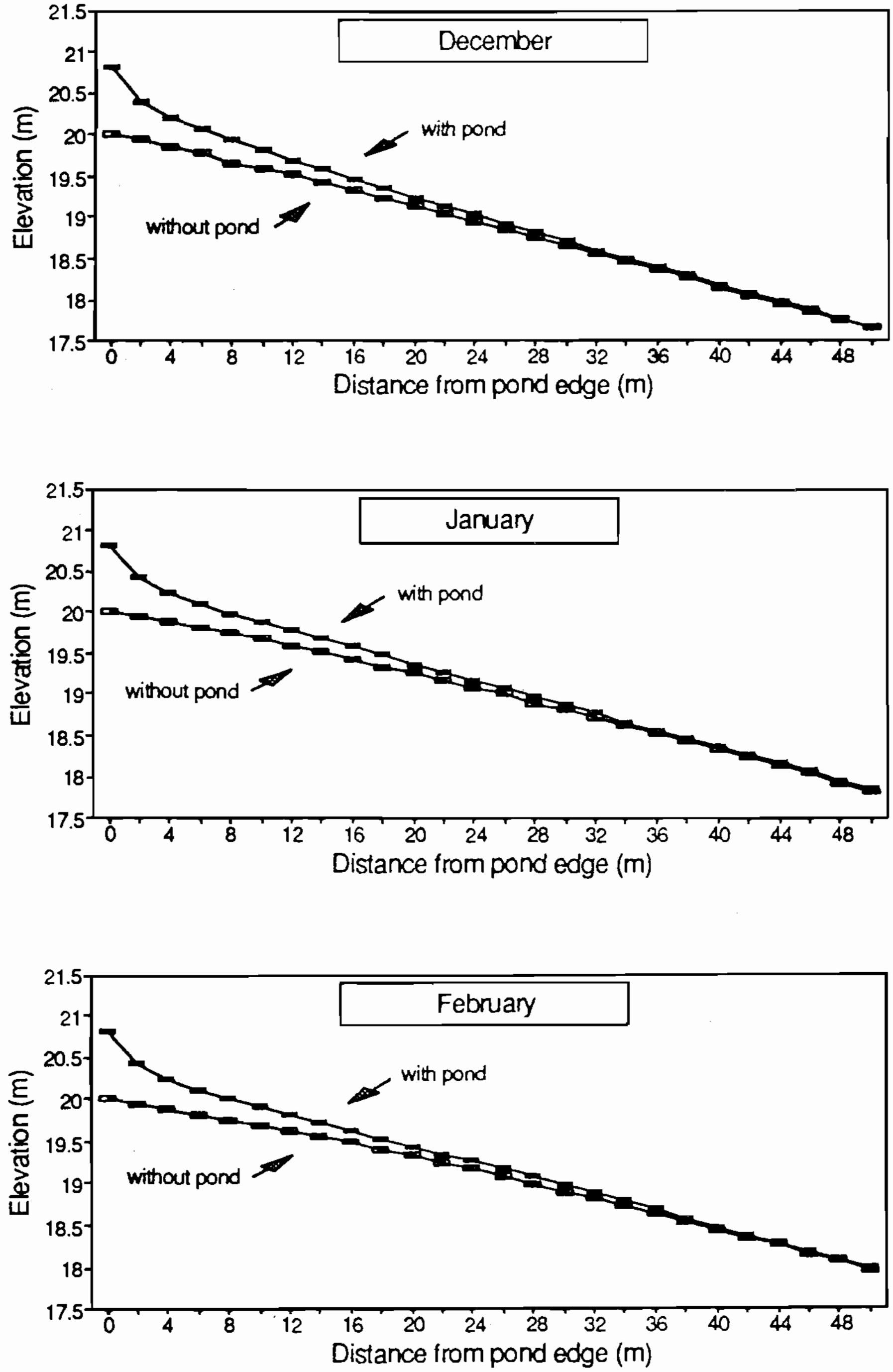


Figure D18. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CM during December, January and February.

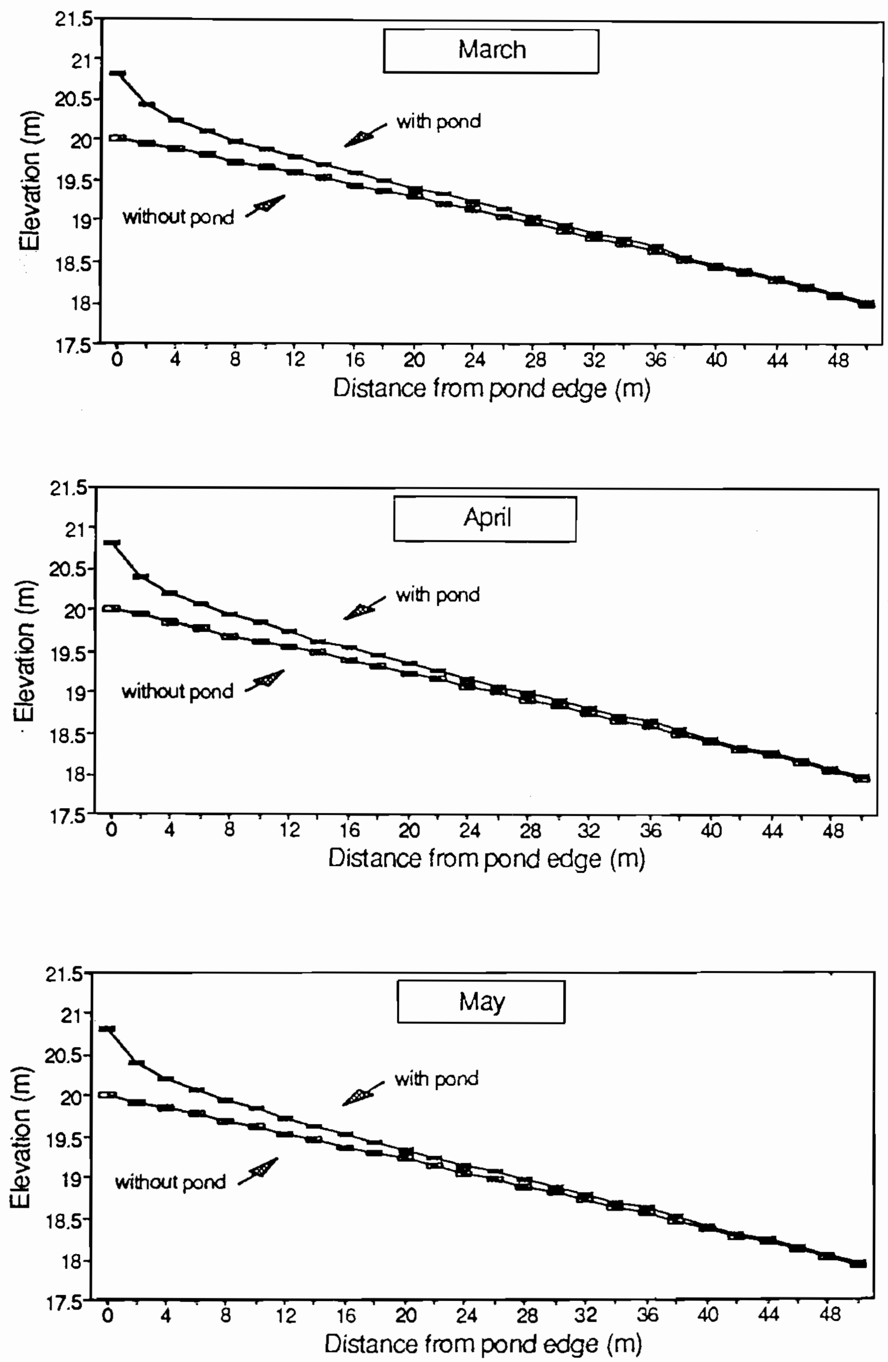


Figure D19. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CM during March, April and May.

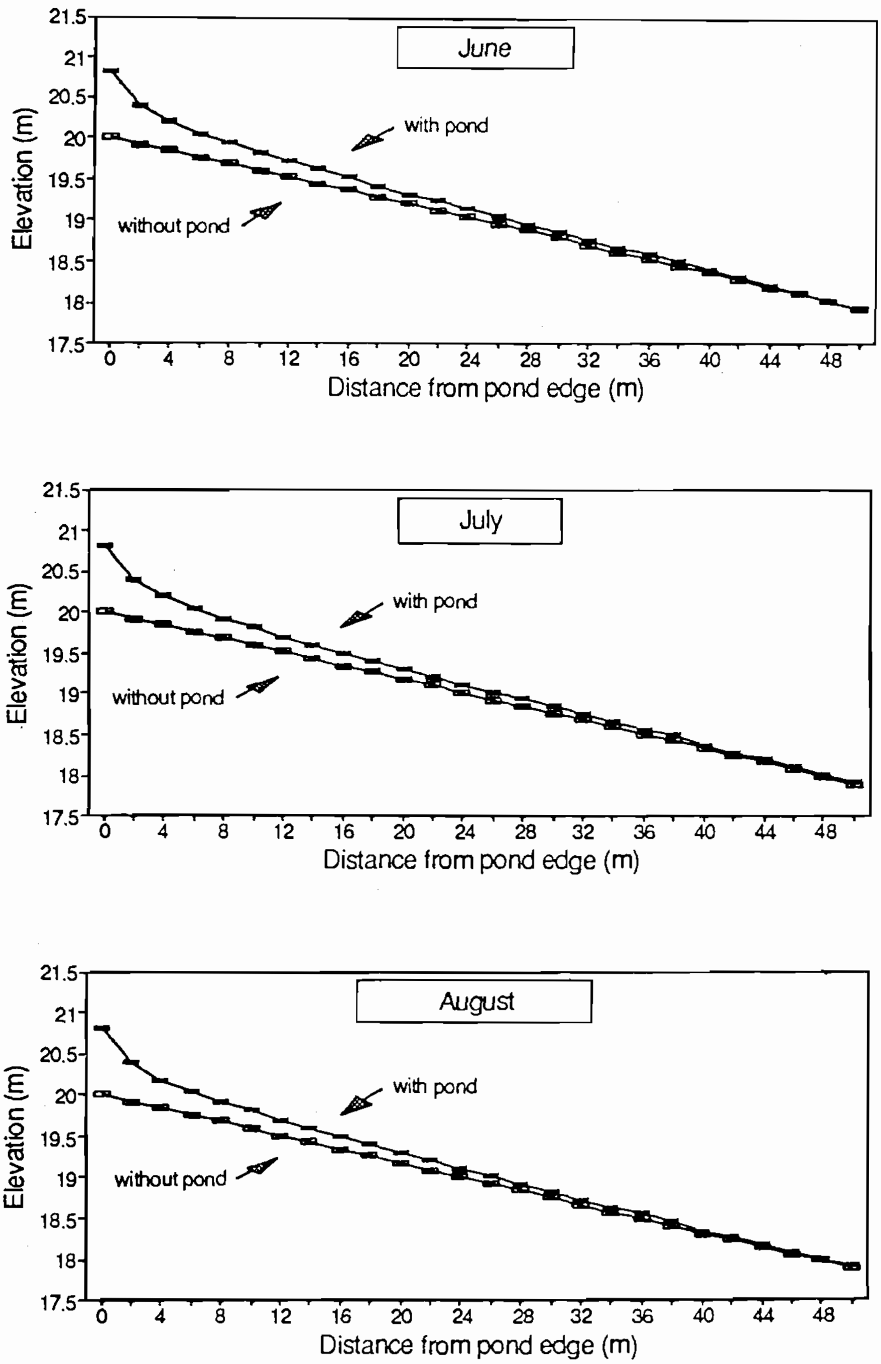


Figure D20. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CM during June, July and August.

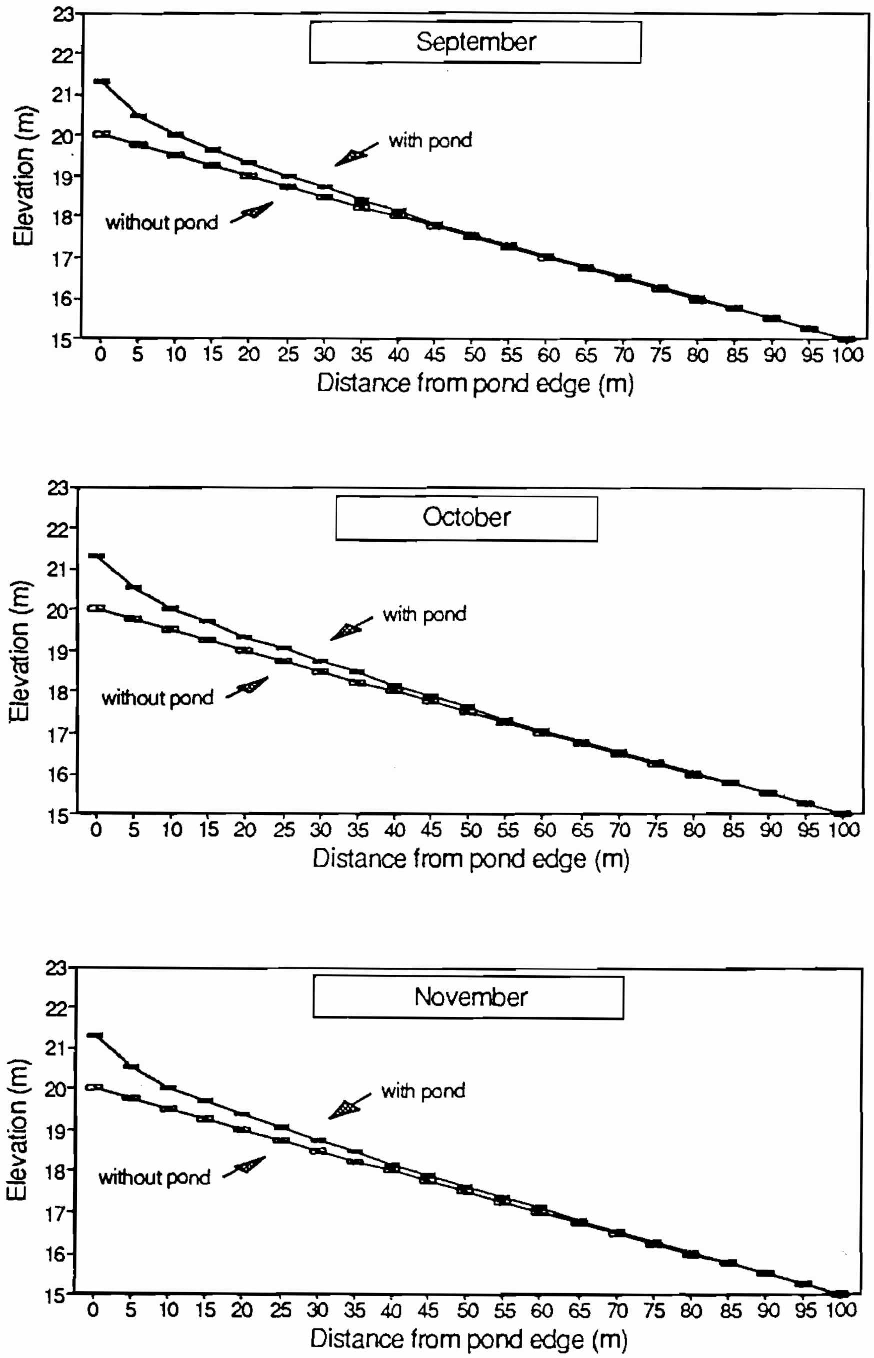


Figure D21. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CL during September, October and November.

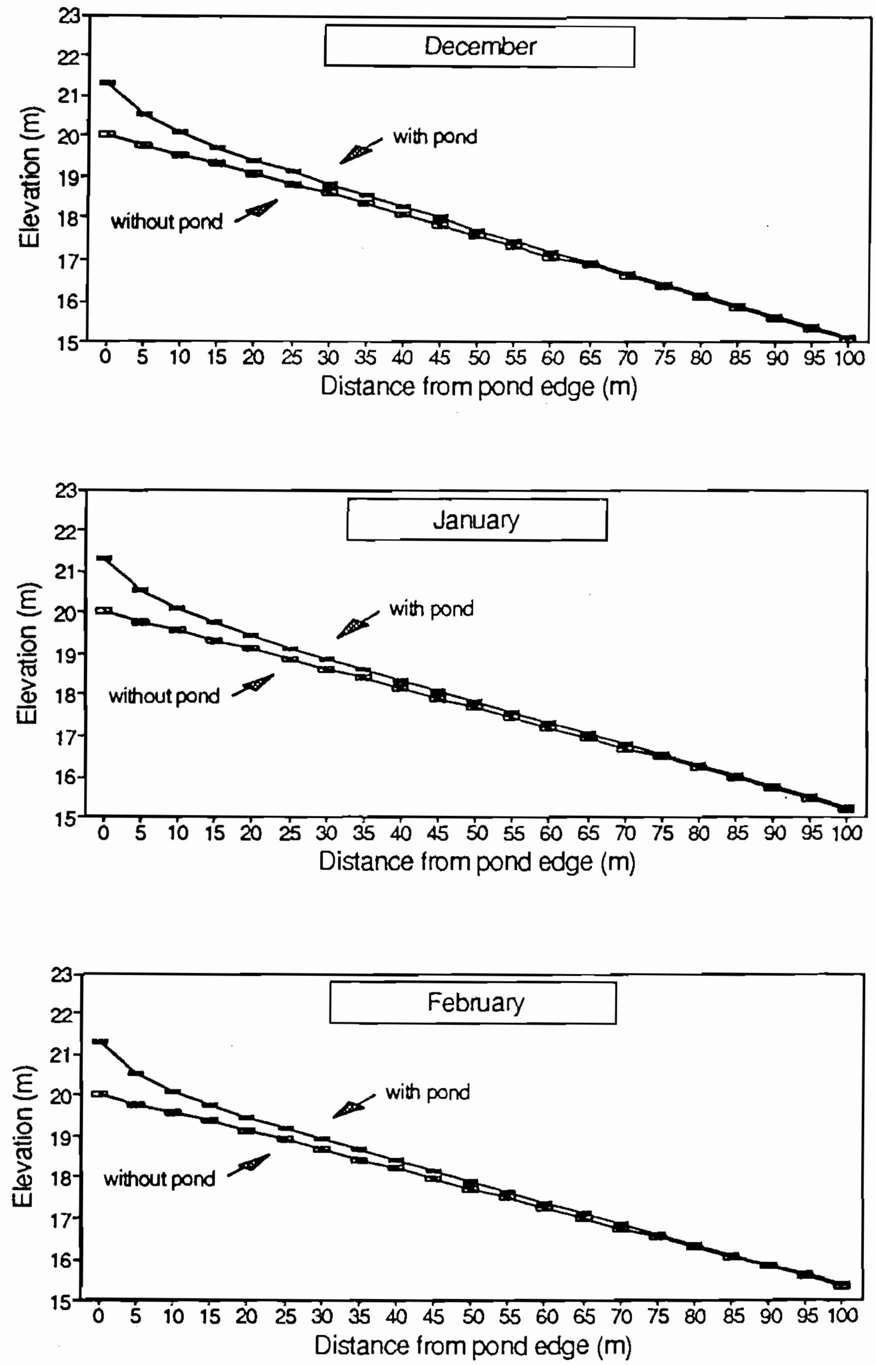
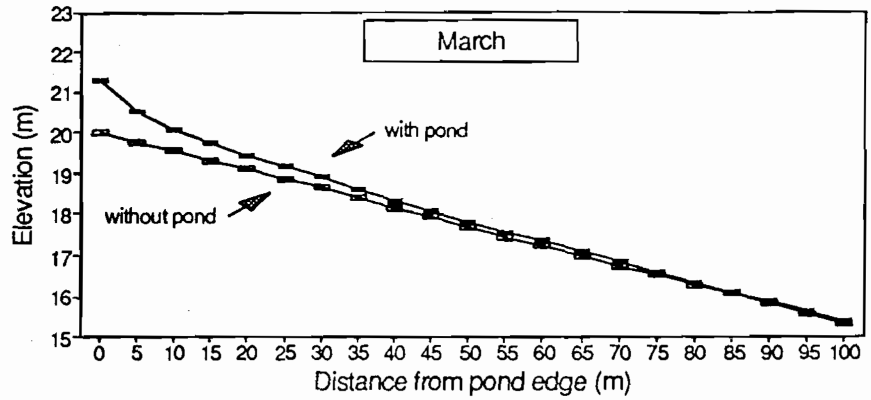
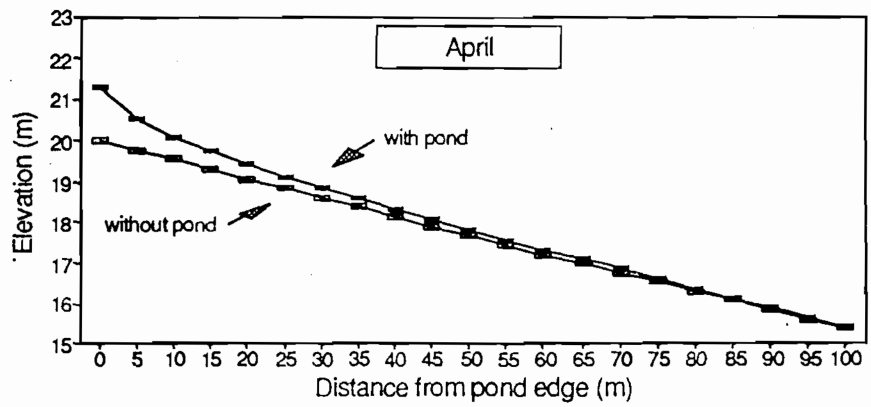


Figure D22. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CL during December, January and February.





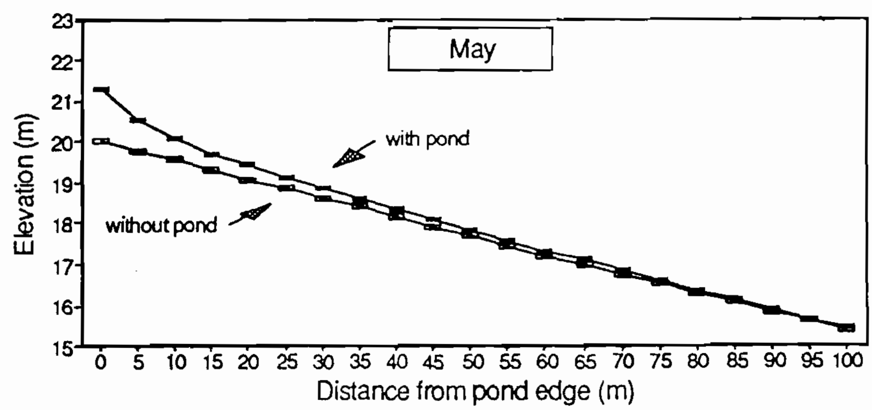


Figure D23. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CL during March, April and May.

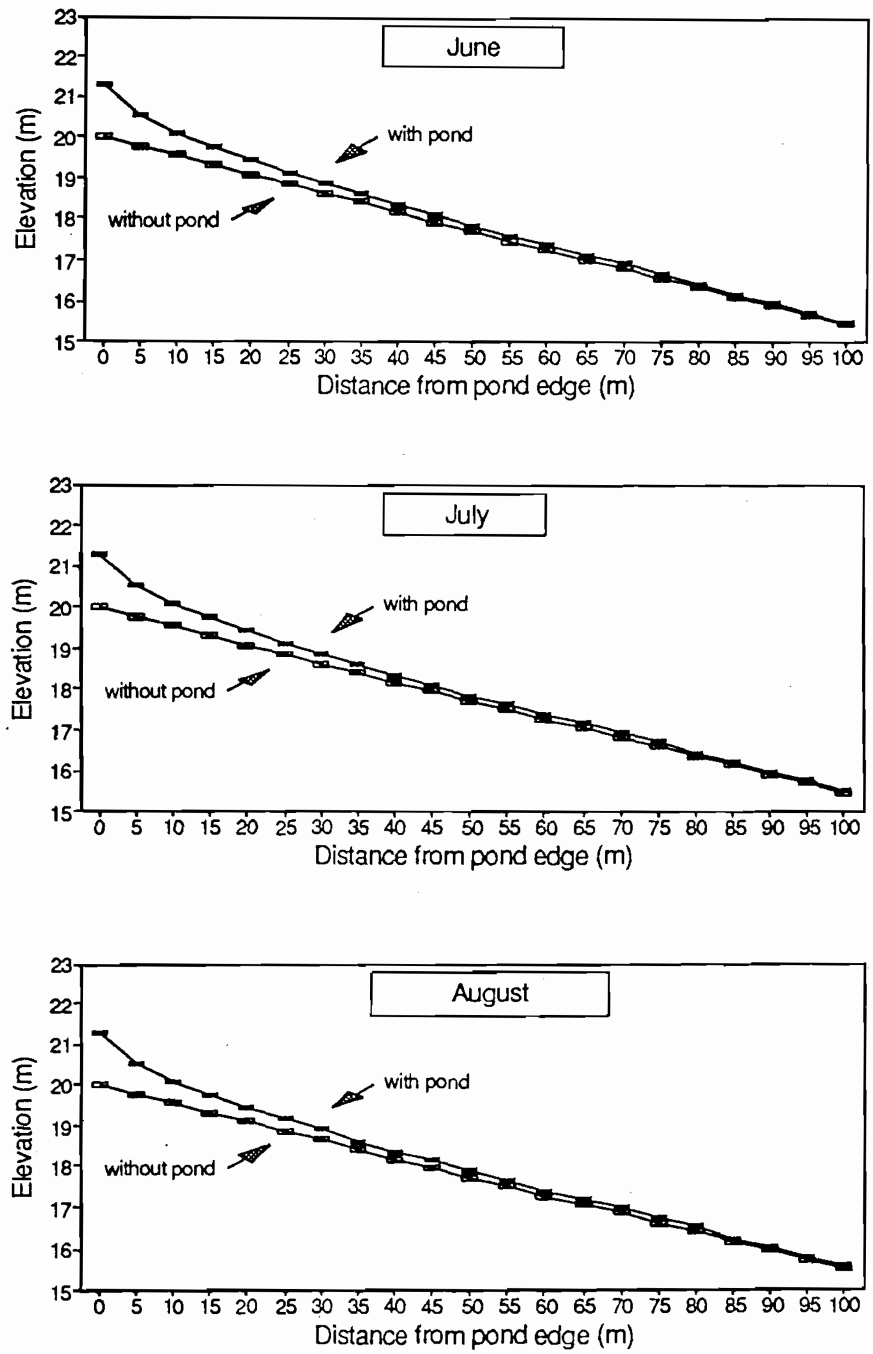


Figure D24. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for Case CL during June, July and August.

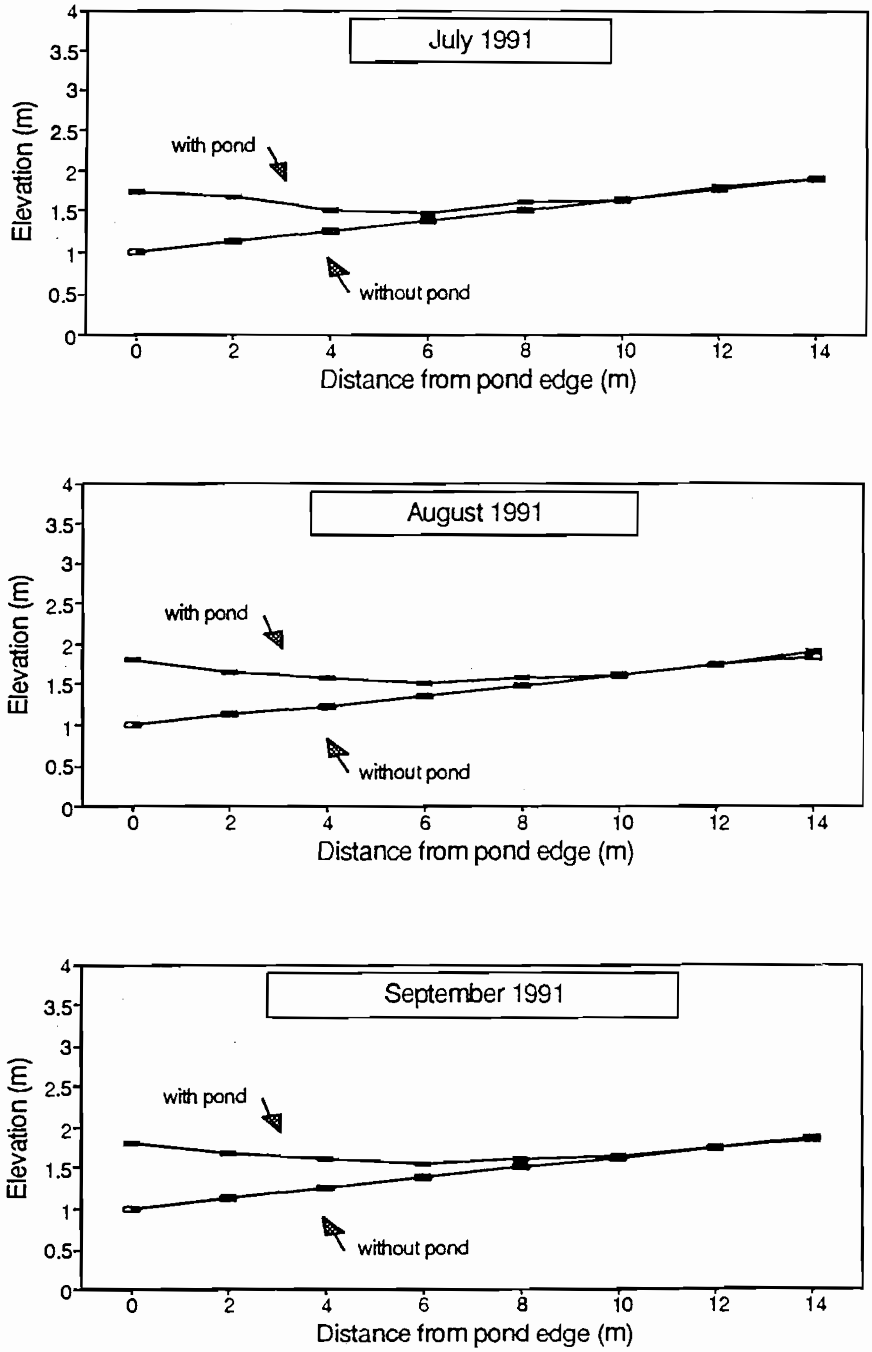


Figure D25. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for the Oak Creek site during July, August and September 1991.

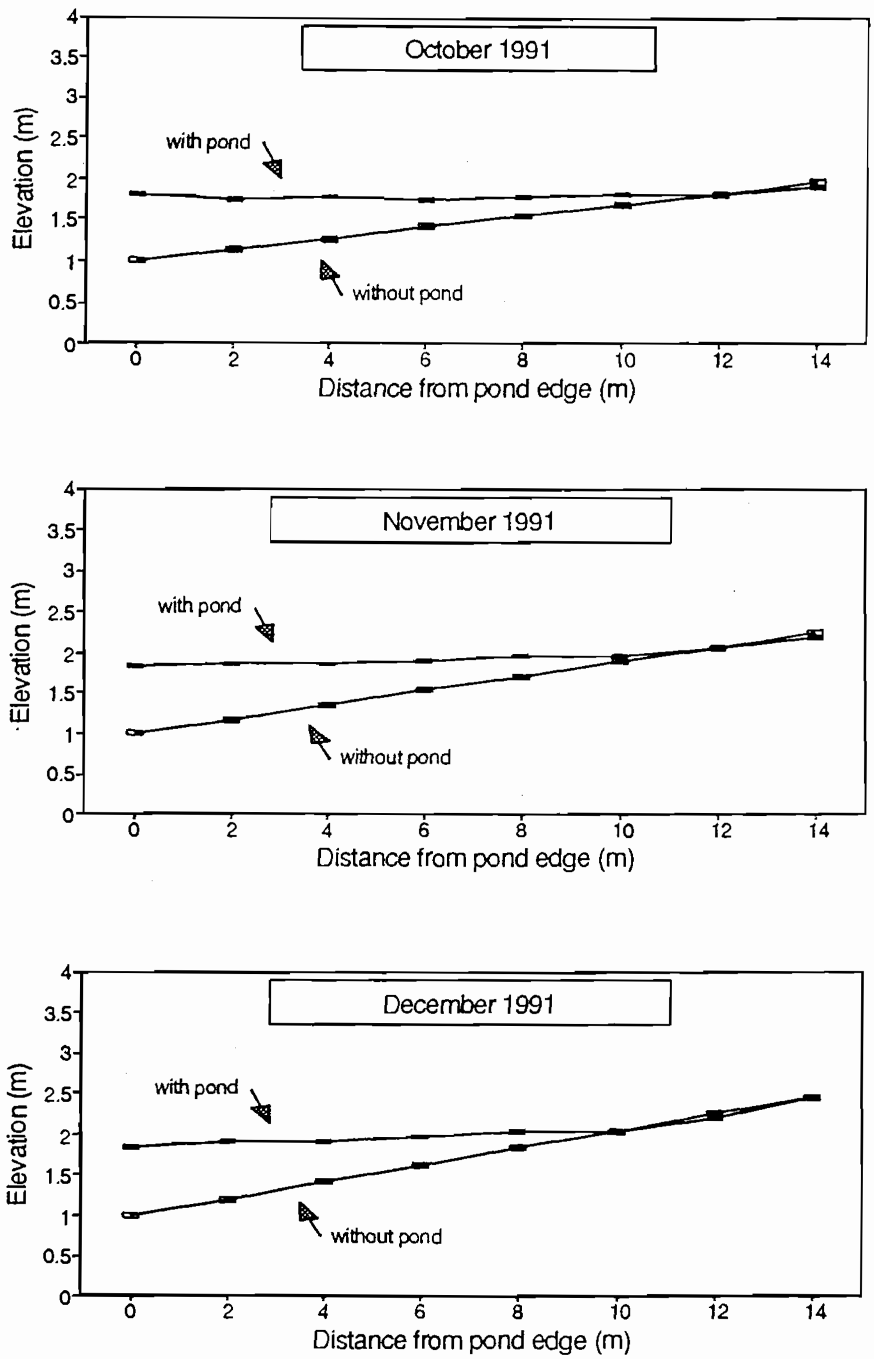


Figure D26. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for the Oak Creek site during October, November and December 1991.

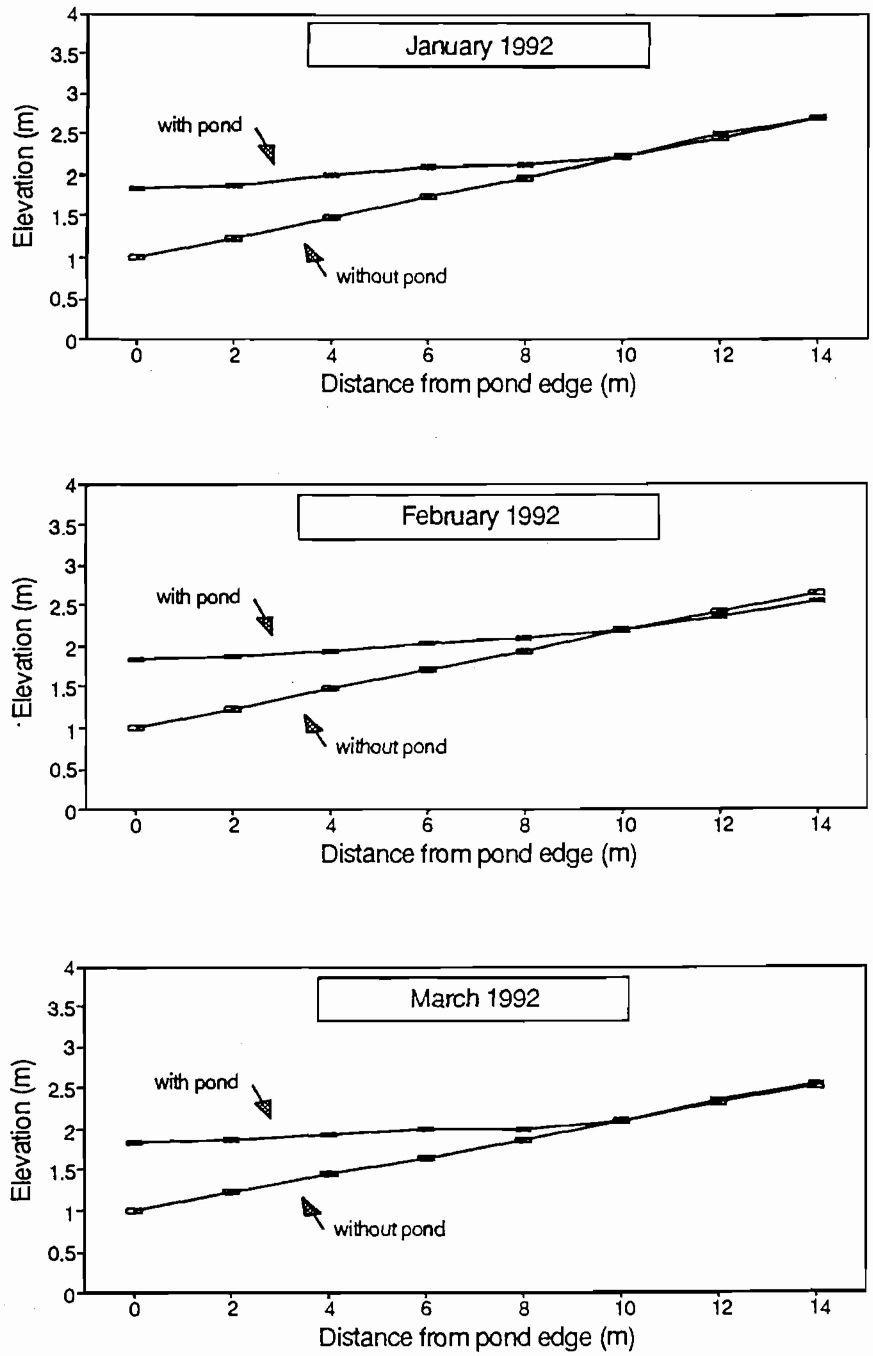


Figure D27. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for the Oak Creek site during January, February and March 1992.

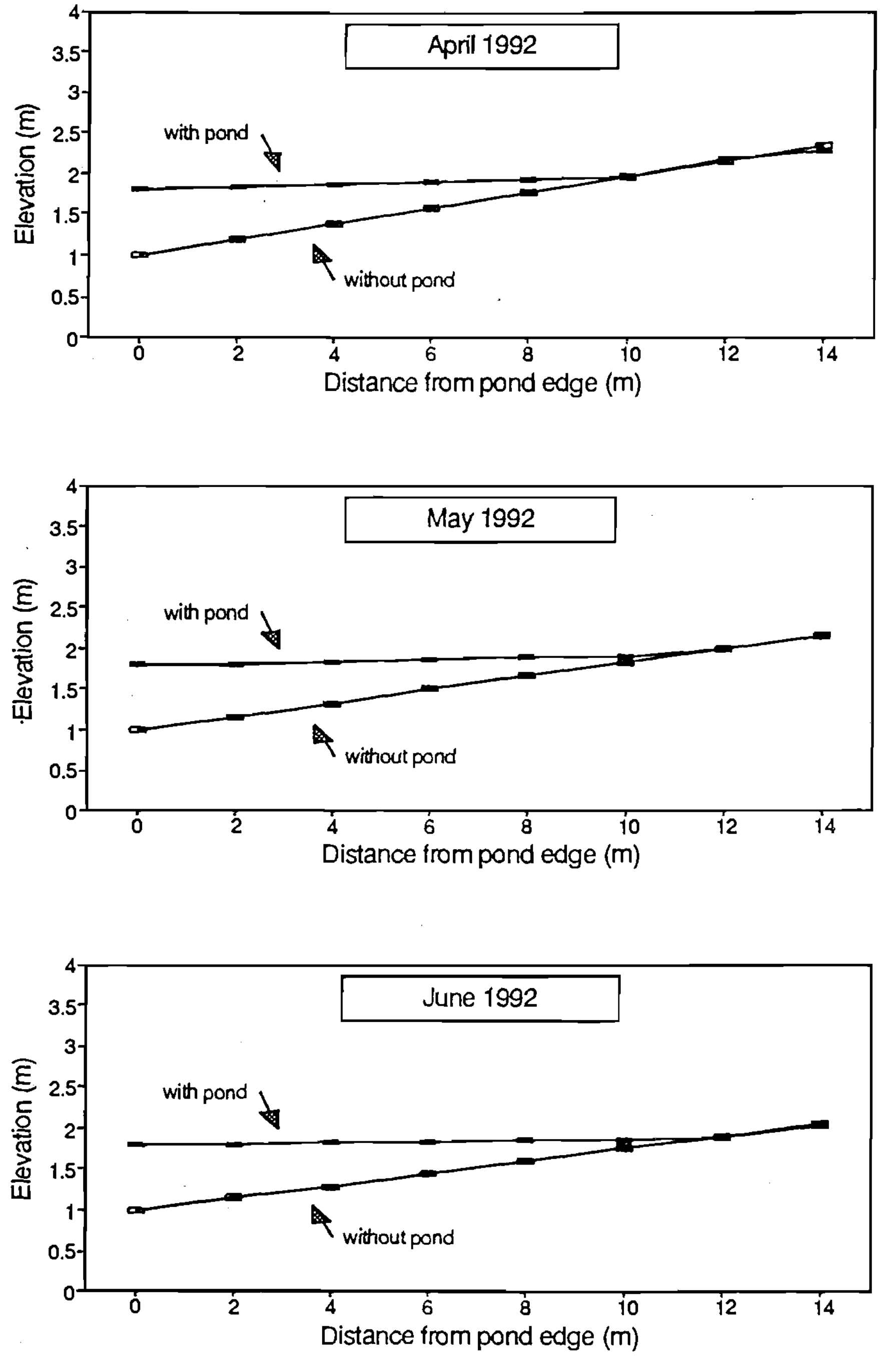


Figure D28. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for the Oak Creek site during April, May and June 1992.

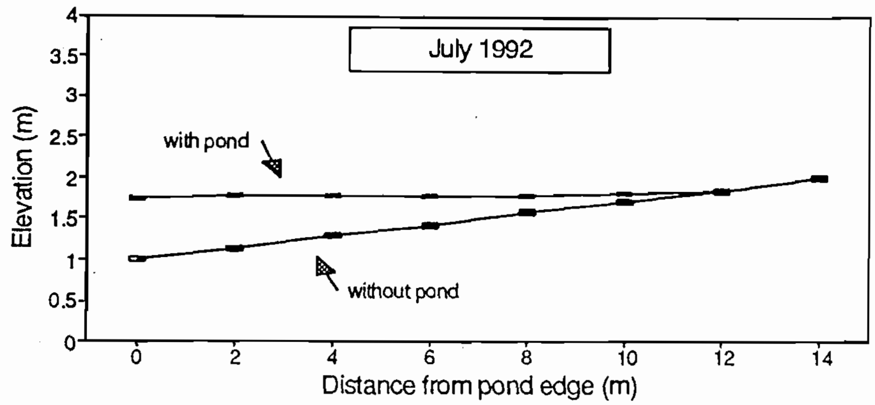


Figure D29. Comparison of riparian groundwater table elevations with and without the presence of a beaver pond for the Oak Creek site during July 1992.