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Hydrologic Investigations of Groundwater and Surface-water Interactions In Subarctic Alaska

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Dynamic interactions between rivers and adjacent aquifers can significantly affect near-bank geochemistry and processes associated with natural attenuation of contaminants by mixing water or introducing oxygen or nutrients. During 1997 and 1998 in a study near Fairbanks, Alaska U.S.A, the hydrologic conditions in the Chena River and in the adjacent groundwater were monitored. The river stage, groundwater elevations, and the water chemistry and temperature in both river and groundwater were measured. In the spring of 1997, the groundwater gradient close to the Chena River reversed causing surface water to enter the aquifer. Changes in temperature, specific conductance and alkalinity were used to determine the extent of bank recharge. For approximately one week during spring snowmelt of 1997, surface-water influx from the Chena River occurred approximately between the depths of 5.33 m and 9.1 m below ground surface. The effects of bank recharge extended at least 6.1 m but not to 30.5 m from the banks of the Chena River into the aquifer. Bank recharge caused 64 to 68 per cent of the groundwater, 6.1 m from the bank at a depth of 6.78 m to be displaced by surface water influx. Peak flows during 1998 were not high enough to cause flow reversals.

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Introduction

Interactions between groundwater and surface water systems with transient hydraulic conditions are not well understood. Transient groundwater and surface-water interactions complicate this mass exchange. A greater understanding of the processes associated with bank recharge is needed. The area surrounding the Chena River, in interior Alaska, is one such case, where surface water periodically migrates into the aquifer because of increasing river stages (Glass *et al.* 1996; Nakanishi and Lilly 1998; Nelson 1978).

There are several contaminated sites on the Fort Wainwright Army post near the Chena River where the investigation was sited. The effects of bank recharge on the contaminated aquifers have never been studied with respect to mass exchange. Bank recharge may enhance natural-attenuation processes, becoming important when considering natural attenuation as a remediation technique.

Several monitoring wells were installed between the depths of 3.81 m and 12.2 m below ground surface to bound the vertical limits of the influx. In addition to monitoring wells, thermistor strings with an even greater density of sensors were used to determine the vertical extent of mass influx. The horizontal extent was determined by installing well clusters in a line oriented perpendicular to the river and approximately parallel to the direction of groundwater flow. The range of extent of mass influx could be determined by detecting the magnitude of changes at sites near the river and at the more distant sites. Analyses of temperature and chemical data demonstrate the extent to which surface water influx readily mixes with groundwater.

Background

There are few investigations on groundwater and surface-water mass interaction in river systems. A variety of investigation methods have been used to study groundwater and surface-water interactions including analytical, chemical, numerical, and field methods (Winter 1995). Many investigations (Squillace *et al.* 1996; Squillace *et al.* 1997; Heimann *et al.* 1997) used the analyses of chemical concentrations and field parameters to determine the extent of bank recharge. Contamination of aquifers (Heimann *et al.* 1997) and movement of contaminants in bank-storage water (Squillace *et al.* 1996) are two reasons for the increase in groundwater and surface-water interaction studies. Other studies focused on conservation of groundwater resources (Lines 1996; Myers *et al.* 1996). Modica *et al.* (1997) characterized baseflow contributions for rivers. In addition, surface-water and groundwater data have been used in numerical simulations to estimate aquifer properties (Nakanishi and Lilly 1998).

Fort Wainwright and Fairbanks are located in interior Alaska near the confluence of the Chena and Tanana Rivers. Fairbanks has a continental climate with large seasonal temperature variations and annually averages 280 mm of precipitation (Plumb and Lilly 1996). The Chena River has a drainage area of approximately 5,180 km^2 (Glass *et al.* 1996). The Chena River flows through Fort Wainwright and Fairbanks. A major component of the Chena River's total discharge is from upper-basin rainfall or snowmelt. The discharge of the Tanana River is primarily due to glacial melt and snowmelt in the Alaska Range. The Tanana River is at its highest during the summer when glacial melt and snowmelt are at their greatest. Increases in Chena River stage generally occur during two periods annually, spring snowmelt and late-summer precipitation events (Nelson 1978). The river stage of the Chena River can vary as much as 2 to 3 m throughout the year due to these events (Glass *et al.* 1996).

The gradient of the Tanana River is steeper than that of the Chena River in the Fort Wainwright area. The Tanana River elevation in this area is higher than the Chena River. Groundwater typically flows northwest from the direction of the larger Tanana River into the Chena River in the Fort Wainwright area (Glass *et al.* 1996). Groundwater gradients reverse with high stage conditions on the Chena River, and water flows into the aquifer. An increase in river stage acts in much the same way as an injection well. The water table begins to rise near the river to compensate for the pressure perturbation on the system. A "pressure wave" characterized by an increase in water-table elevations propagates away from the river (Nakanishi and Lilly 1998). The "pressure wave" is attenuated with distance. Groundwater gradients resume normal trends toward the Chena River after the river stage drops. Groundwater then flows back into the Chena River. The hydraulic conductance of the system and the hydraulic gradient are the primary factors that affect the maximum extent of surface water flows into an aquifer during bank recharge (Squillace *et al.* 1996). The duration of high stage also contributes to the extent of bank recharge.

The aquifer material in the study area is alluvial sand and gravel deposited by the Tanana River, described as Chena Alluvium (Péwé *et al.* 1976). The aquifer is laterally and vertically discontinuous like many braided-river facies (Rust 1978). Bedrock occurred 188 m below ground surface near Moose Creek Dam (Glass *et al.* 1996) and appr. 46 m below the Chena River (Nakanishi and Lilly 1998). Andreasen *et al.* (1964) estimated the basin depth south of the Tanana River as 610 m with aeromagnetic surveys.

Simulations by Nakanishi and Lilly (1998) showed that increases in Chena River stage caused detectable increases in the water table 300 m away from the river within a few days of the increase in stage. Changes in river stage were attenuated with distance from the river. At 300 m and 2.7 km from the river, the rise in water table was approximately 40 and 10 per cent, respectively, of the rise in river stage.

Temperature measurements have been a common tool in groundwater investigations. The use of temperature is a recommended technique for investigating artificial recharge due to the common differences in temperature that exist in groundwater and surface water (Schneider 1962). The use of water temperature as a tracer is advantageous, as it is inexpensive and easily measured. Thermistors or thermocouples can be used to measure temperatures with dataloggers for automated collection. Water has a relatively high specific heat capacity compared to aquifer materials. Because of this, the temperature of a thermal tracer changes slowly as it moves through an aquifer. Movement of water (convection) is believed by Davis *et al.* (1985) to be the dominant mechanism of heat transmission in groundwater. However, temperature does have its limitations as a tracer since it is a non-conservative tracer. Thermal effects on density and viscosity can make the use of a thermal tracer difficult (Davis *et al.* 1985). A difference in the densities of the tracer and groundwater can cause the tracer to rise or sink thus increasing breakthrough time. Different densities could potentially cause the tracer to not be detected at the monitoring wells. Effects of temperature on viscosity must also be considered since the viscosity can affect breakthrough time. Temperature differences between the tracer and in situ water can cause forced convection to occur (Combarnous and Bories 1975). This causes the tracer to lose its thermal difference with the aquifer or take a path that does not follow the groundwater gradient.

Changes in the viscosity of water due to temperature change can alter the hydraulic conductivity of a system (Rorabaugh 1956; Constantz *et al.* 1994). The hydraulic conductivity of a system with water at 25°C is twice that of water at 0°C. Regarding this study, a more pronounced bank recharge event would be expected in the later summer months when the Chena River is at its warmest.

The temperature of surface water could play a major role in inhibiting bank recharge. Density differences between groundwater and surface water are suspected of reducing vertical mixing during bank recharge. The density of water is dependent on temperature, dissolved solids and suspended solids. Suspended solids are low in both surface and groundwater at the site. Dissolved solids are greater in the groundwater than in the surface water. The maximum density of water occurs at 4.0°C. The temperature of groundwater at the site was measured to vary between 2 to 10°C over the course of a year. The temperature of the Chena River has been observed to vary between 0 and 19°C. During the summer when the difference in density is at its greatest, surface-water influx may override groundwater. A reduction in mixing limits the impact of bank recharge on natural attenuation processes. By closely monitoring parameters in a vertical profile it was possible to detect distinct layers through abrupt changes in groundwater temperature and field parameters.

Methods

The study area is located on the south side of the Chena River at Fort Wainwright. A line of monitoring wells and instrumented pits extended south approximately 91 m from the river's edge perpendicular to flow (Fig.1). Using a two dimensional cross-section, the study area coincides on the directional plane of groundwater flow. The ground surface in the study area is approximately 4.6 m above the surface of the Chena River at low stage. Since the bank of the Chena River is not vertical, a mea-

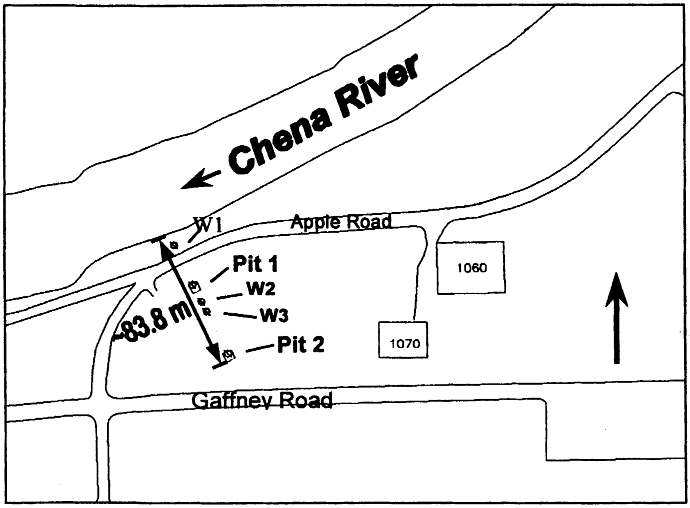

Fig.1. The research site is located adjacent to the Chena River near Fairbanks, Alaska, U.S.A.

Tabel 1 - Description of the number and depths of sampling screens in groundwater wells along a transect perpendicular to the river. W1, W2 and W3 had only groundwater sampling ports and temperature measurements. Pit 1 and Pit 2 included groundwater sampling ports, temperature measurements, unfrozen soil measurements and lysimeters.

W1	Pit 1	W2	W3	Pit 2
Screen Sampling Depths (m)				
3.8	3.8	6.1-WT	6.1-WT	3.8
4.6	3.9	9.1	7.6	3.9
5.3	4.1		9.1	4.1
6.1	4.2			4.2
6.9	4.4			4.4
6.9-WT	4.5			4.5
7.6	4.7			4.7
8.4	4.8			4.8
9.1	5.0			5.0
10.7	5.1			5.1
12.2	5.3			5.3
	6.9-WT			5.4
				5.6
				5.8-WT

WT: Water table well with 3.8 m screen, all other screens were 5 cm length.

suring point at the edge of the river during low stage was used to define horizontal distances from the river.

A series of wells were installed in two 7 m excavations (Pit 1 and Pit 2) as described in Table 1. Instrumentation and wells were installed and then the pits were back-filled with the excavated material. A collection of nested monitoring wells installed near the bank of the Chena River was denoted as W1. Two additional well clusters, W2 and W3, were drilled to the south of W1 in between Pit 1 and Pit 2. Campbell Scientific CR-10 dataloggers with AM416 multiplexors were used to record continuous data. The most concentrated instrumentation in this study occurred at Pit 1 and Pit 2. Instrumentation measured specific changes in groundwater properties over time. Probes are also located at regular intervals in the unsaturated zone (Table 1). The time domain reflectometry (TDR) probes, measuring unfrozen moisture content, in the unsaturated zone were installed to determine if water infiltrating as rainfall was a significant factor in groundwater and surface-water interactions. In addition to thermistors at Pit 1 and 2, thermistors were installed at W1 and in the Chena River. Three pressure transducers were installed to characterize how groundwater gradients were affected by changing stage elevations on the Chena River. Dataloggers recorded measurements hourly for thermistors and TDR probes and every half-hour for pressure transducers.

Field samples were collected on a regular basis to aid in the investigation of groundwater and surface-water mass interactions next to the Chena River. During periods of high stages and significant fluctuations of the Chena River, the sampling frequency interval decreased. The main emphasis of sampling occurred at a cluster of wells 6 m from the bank of the Chena River, referred to as W1. The wells were constructed to sample at the depths between 3.8 and 12.2 m below ground surface. Other wells sampled were at Pit 1, W2, W3 and Pit 2 (Fig. 1). Discrete sampling wells and water table wells were screened with 5 cm and 3.8 m length well screens, respectively.

Stagnant water in monitoring wells was removed prior to sampling to ensure samples are representative of the aquifer. Wells sampled were purged for at least three well volumes and until pH, dissolved oxygen, specific conductance, and temperature measurements were repeatable over a 5-minute time span. The water sampled was considered representative of the aquifer at that depth after measurements had stabilized. After the well stabilized in readings, samples were collected for alkalinity analyses and Winkler dissolved oxygen concentration analyses.

Results and Discussion

The Chena River and groundwater sampling at the project area was from September 1996 to September 1998. Intensive groundwater sampling occurred between April 1997 and October 1997. During those months, temperature, dissolved oxygen, pH, specific conductance and alkalinity measurements were collected on a regular basis. The summers of 1997 and 1998 were relatively dry and the only significant hydrologic events were spring snowmelt, and these were much less than almost each of the previous 30 years. The 1997 spring snowmelt provided enough of a groundwater gradient reversal to have the effects of bank recharge seen at W1. At no other time during the investigation did bank recharge occur.

Groundwater

Differences in water levels across a horizontal distance create hydraulic groundwater gradients. Other gradients affecting the transport of groundwater at this site are due to gravity, density and concentration. During the course of the investigation, only once was surface water detected flowing from the river into the aquifer. Although there were other hydrologic events that increased the stage of the Chena River, no other event was significant enough to cause measurable bank recharge. Previous years of hydrologic data show that 1997 and 1998 were rather atypical in terms of the very few number of high stage events. Other than hydraulically induced groundwater gradient reversal, density induced recharge was also examined. Theoretically, if the density of water in the Chena River is significantly greater than the density of groundwater, then surface water could mix into the system despite a hydraulic gradient toward the river. Analysis of data collected never showed a density-induced bank recharge.

In the last few days of April 1997, the ice cover of the Chena River began to break up and the river began to rise. An ice jam on the Chena River downstream of the site backed the river up. In the span of a day, the water level at W1 rose over 1.3 m. As the river rose, it soon was higher in elevation than the water table in the adjacent aquifer, resulting in a reversal of the groundwater gradient. At this point, river water began moving into the aquifer. The groundwater gradient maintained aquifer recharge from the river for appr. one week until the river stage dropped. Fig. 2 shows the water levels for W1, Pit 1, Pit 2 and the Chena River for April 1997 to October 1997.

Soil Moisture

Fig. 3 shows select data from the TDR probes for the spring melt event of 1997. Prior to break-up of the ice on the Chena River, soil water saturation was low, between 3.96 and 4.88 m below ground surface. With the increase of river stage, the water table rises, starting first at the riverbank and quickly propagating away from the river. As the water table rises, the soils quickly become saturated. As the water table begins to fall, the soils begin draining. One of the important factors to consider in bank recharge studies is whether infiltration from precipitation affects the aquifer chemistry and water levels. Since high river stages on the Chena River may or may not in general coincide with precipitation over the study site, it may seem proper to attribute changes in the aquifer characteristics and water table elevation to

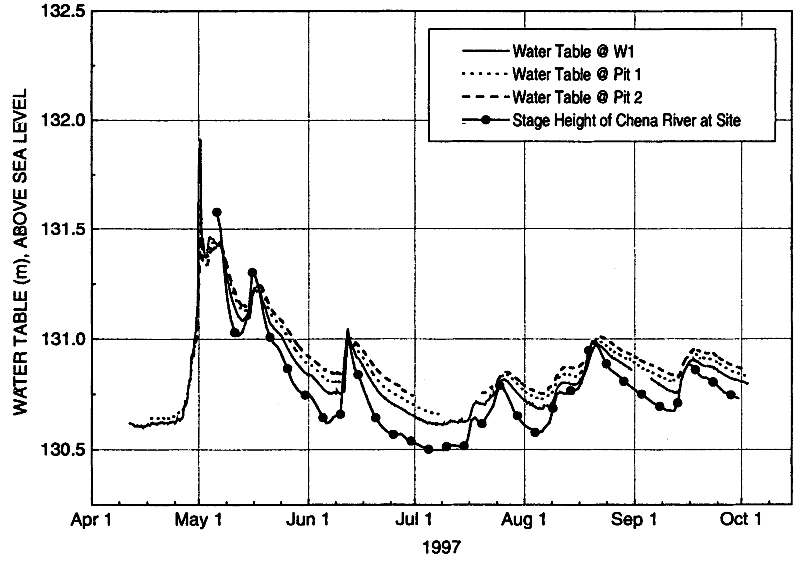

Fig.2. Water levels for W1, Pit 1, Pit 2 and the Chena River for April 1997 to October 1997 show a marked lack of high flow events.

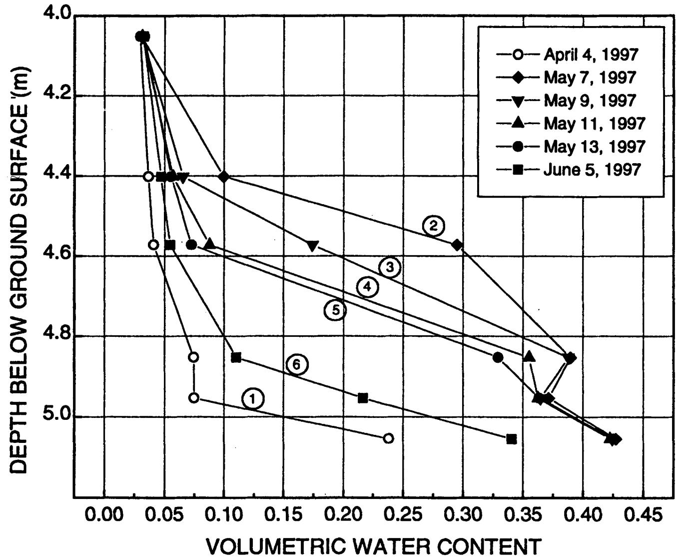

Fig.3. Soil moisture measurements obtained from TDR probes in Pit 1 show the water table rising due to the high stage of the Chena River during spring melt, but does not show infiltration reaching the water table.

infiltration. Infiltration into the aquifer from snowmelt at Pit 1 was found to be negligible from analyses of data collected from the TDR probes, probably due to the very thin snowpack during both years of the study. The volumetric water content of soil at 4.05 m below ground surface remained at 3 per cent over the span of the spring snowmelt event, never increasing in response to a wave of infiltrating water as one may expect. Fig. 3 shows the increasing soil moistures in the capillary fringe as the water table rises due to the higher stage of the Chena River during spring melt but does not show infiltration reaching the water table.

Temperature

Collection of temperature data occurred from April 1997 to October 1998. Probes were located in the Chena River, at W1, Pit 1 and Pit 2. Temperature probes were used to detect temperature changes due to bank recharge and fluctuating water tables. In addition, mixing due to thermal processes could be identified by observing groundwater temperatures. Temperatures measured by thermistors at W1 proved that river water moved into the aquifer. The Chena River temperature was colder than the temperature of the groundwater during spring snowmelt. Soon after the rise of the river, the groundwater temperature suddenly decreased in response to aquifer recharge through the riverbank. Temperature differences were no longer observed after approximately one week, although the thermal profile never returned to its original form (Fig. 4). The greatest changes in temperature occurred between 4.3 m and 7.0 m below ground surface. The greatest change in temperature occurred at 5.94 m below ground surface on May 3, 1997, where the temperature decreased 1.6°C. Probes deeper than 8.5 m below ground surface showed very little change in temperature during bank recharge. Bank recharge occurred between the water table and 8.5 m below ground surface. Although the Chena River was colder than the groundwater, the density of the groundwater was greater because the temperature of the groundwater was close to 4.0°C and had a higher concentration of dissolved solids. Influx due to bank recharge did not occur uniformly with respect to depth. Differences in hydraulic conductance caused surface water influx to move into the system more rapidly at certain depths than at others.

Changes in ground temperature along the bank were due to two separate mechanisms, rising warmer groundwater from lower depths and bank recharge of cooler river water. Before the effects of surface water influx depressed the temperatures at W1, another process increased the temperature at the water table for a short time (Fig. 4). The first thermal change during the spring snowmelt event was due to the rising water table. As the water table rose in response to the increasing stage of the Chena River, groundwater warmer than the unsaturated soils above began to warm the overlying soil as those soils were saturated. By tracking the time the temperatures began to change at the different depths, it was apparent that the temperature wave was travelling upward. Between April 29 and May 1, 1997, an increase in temperature occurred around a depth of 4.3 m. A decrease in temperature due to the in-

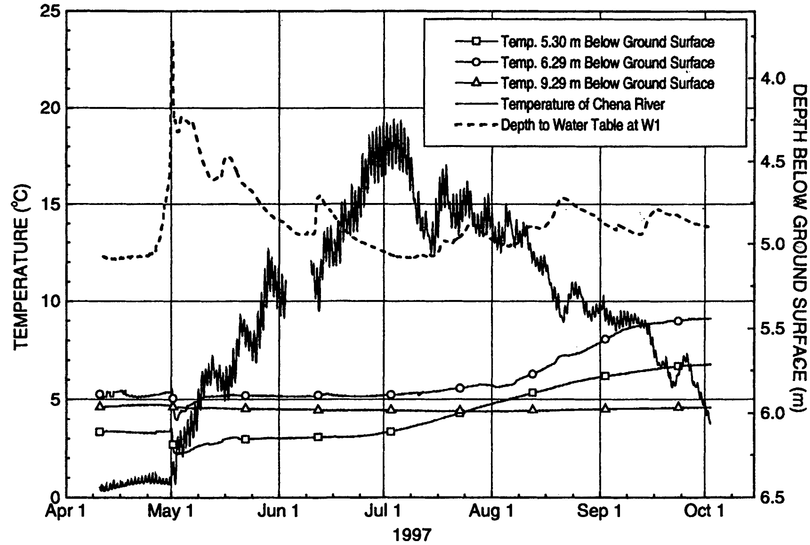

Fig.4. Temperature measurements at W1 demonstrate a brief period when bank recharge occurred, however, differences were not observed after appr. one week.

flux of cold river water was unobserved at that time. Effects of warming were apparent for a relatively short time because bank recharge soon caused temperatures to decrease. Prior to bank recharge, the temperature between 4.3 and 4.9 m was 1.8 to 2.3°C and 3.0 to 3.5°C between 4.9 and 5.5 m. The temperature of the probes between 4.3 and 4.9 m below ground surface briefly warmed up to 2.9°C. The increase in temperature is due to warmer groundwater moving upward and not due to the influx of the colder, 1.0°C, Chena River water.

Chemistry

During the 1997 spring melt event, changes in the aquifer chemistry attributed to river water were detected at W1, but not at Pit 1. Prior to spring melt a sampling routine was implemented to record the changes in the groundwater before, during and after spring melt. Specific conductance and alkalinity results showed that during the spring melt event, the river water moved into the aquifer between the depths of 5.3 and 9.1 m. Taking into account the magnitude of change, a majority of the influx occurred between 5.3 and 7.6 m.

The specific conductance data proved to be the most valuable physical parameter. The specific conductance was measured multiple times on the Chena River because it does vary throughout the year. To determine the effects of bank recharge, using the specific conductance of the surface water at the time of the event is most appropriate. Prior to the spring snowmelt event, the specific conductance was measured to be 210 μS/cm on April 18, 1997 and 156 μS/cm on April 29, 1997. The specific con-

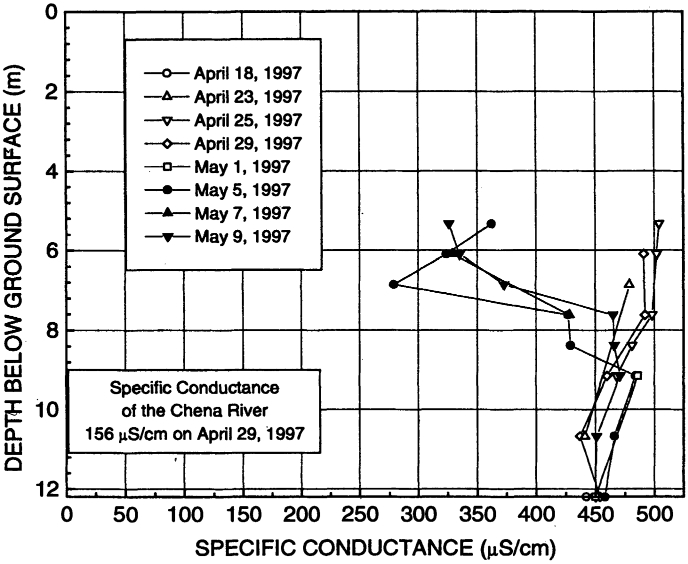

Fig.5. The specific conductance of the groundwater profile at W1 provided good evidence of river water influx to the groundwater system.

ductance of the groundwater at W1 was between 450 and 500 μS/cm prior to bank recharge. As river water moved into the aquifer, the specific conductance dropped due to river water mixing with groundwater (Fig. 5). The greatest change in specific conductance was observed at 6.86 m below ground surface. Collected groundwater samples at 6.86 m had a specific conductance of 279 μS/cm. Data shows vertical mixing occurred even at close proximity to the river, such as at W1. Changes in specific conductance may be due to dilution of the groundwater with surface water or through precipitation of reduced metals. Reduced metals in the groundwater may precipitate with the addition of oxygen-rich surface water. Consequently, the precipitated metals decrease the total dissolved solids and the observed specific conductance at the wells (Heimann *et al.* 1997).

Alkalinity measurements were used in the same way as specific conductance measurements. Analysis of alkalinity values show that bank recharge occurred between 5.3 and 9.1 m (Fig. 6). The greatest change in alkalinity values occurred at 6.86 m suggesting that the greatest amount of recharge happened at that depth. Alkalinity measurements at 6.86 m below ground surface decreased from 238 to 114 mg/L as $CaCO_3$ during bank recharge. The alkalinity of the Chena River was measured to be 92 and 56 mg/L as $CaCO_3$ on April 25 and April 29, 1997, respectively.

The concentration of dissolved oxygen was quite different between the Chena River and groundwater. The concentration of dissolved oxygen was near 0.0 mg/L for most groundwater sites and the concentration in the river remained near satura-

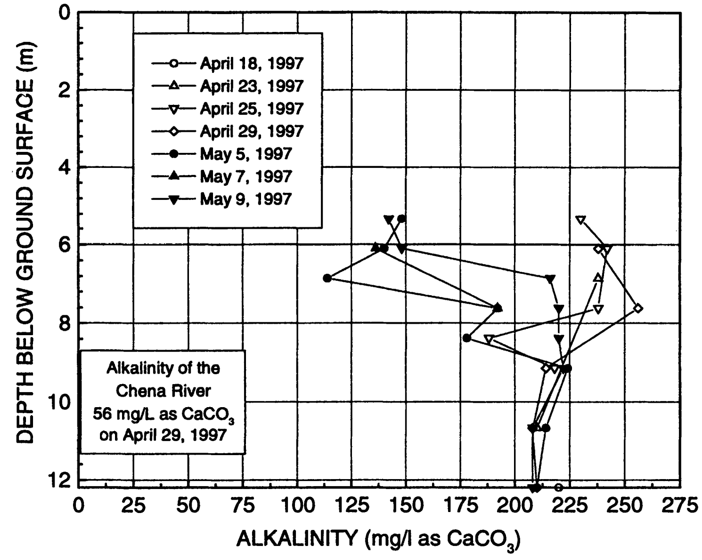

Fig.6. Analysis of alkalinity values at W1 show that bank recharge occurred between 5.3 and 9.1 m.

tion around 11 mg/L during springmelt. The influx of river water did not significantly change the concentration of dissolved oxygen in the groundwater at any site. Considering that the aquifer is predominately in a chemically reduced condition, the addition of dissolved oxygen is most likely depleted quickly. The aquifer contains relatively high concentrations of reduced iron. It is assumed that dissolved oxygen entering the system is consumed by the oxidation of reduced metals. In similar investigations, dissolved oxygen was not useful in determining whether groundwater and surface-water interactions occurred (Heimann *et al.* 1997).

Density Effects

The density of water is dependent upon the temperature and the amount of dissolved and suspended solids. The effects of suspended solids on the density of water are assumed insignificant when turbidity is low. There are many correlations for specific conductance and total dissolved solids (TDS). The Hach Model 44600 Conductivity/TDS meter estimates the total dissolved solids (mg/L) in the groundwater assuming that TDS is equal to 0.5 times the specific conductance (μS/cm at 25°C). Using this relationship and neglecting volumetric change, a 500 μS/cm water sample at 4°C would have the density 1.00025 g/cm^3. Although the effect on density is slight, it is quite important when working with water samples around 4°C. The density of water varies with temperature, with maximum density occurring at 4°C. The river and groundwater densities were calculated based upon measurements of water tem-

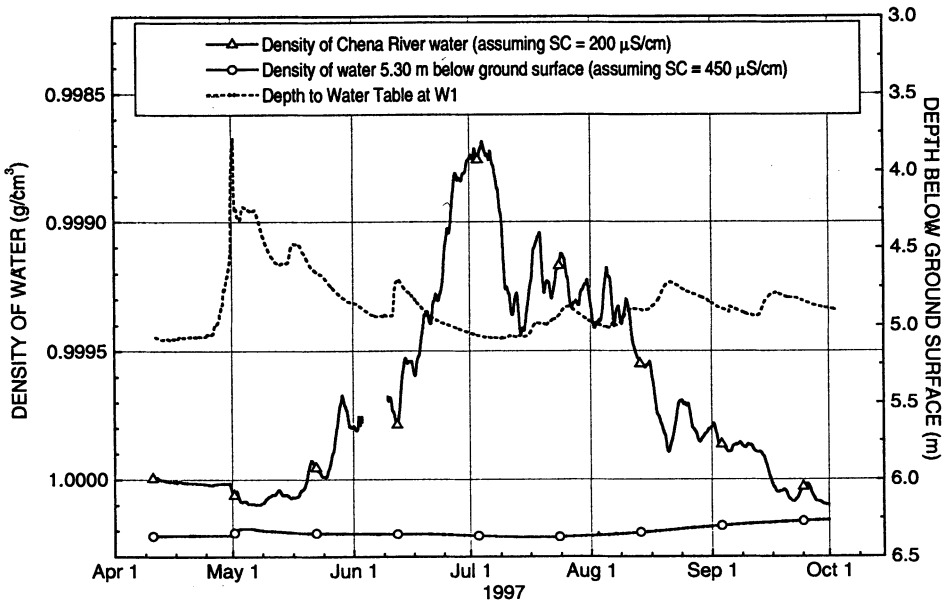

Fig.7. The water in the Chena River was never more dense than the groundwater at W1 between April 1 and October 31, 1997.

perature and dissolved solids (Wegner 1997 adapted from Dorsey 1940).

The water in the Chena River was never more dense than the groundwater between April 1 and October 31, 1997 (Fig. 7). For purposes of calculating the density of Chena River water and groundwater throughout the year, a specific conductance of 200 µS/cm and 450 µS/cm, respectively, were used. The change in density between pure water and water with dissolved solids considered was summed with the density due to temperature. Twice a year the temperature of the river is 4.0°C. Even when the river is at maximum density, the higher concentration of dissolved solids in groundwater make the river water less dense. The groundwater temperature would have to be greater than 10°C when the river was at 4.0°C in order for the density of the river to be greater than the groundwater. The only time this might occur would be during autumn. In the event that bank recharge occurred while the river water was denser than the groundwater, the influx may tend to move downward. At other times of the year, when the river water is less dense it may attempt to override the groundwater.

During spring melt, bank recharge occurred between the depths of the water table and approximately 9.1 m below ground surface. It is difficult to determine if density-driven mixing occurred during bank recharge. The differences in densities of groundwater and surface water were relatively small at this time. At that scale, any uncertainties in measurements would cause major changes in calculated densities.

Denser water moves downward until the water below it is denser, stopped by a confining layer or until the thermal difference is attenuated. Analyses of additional bank recharge events are needed to fully understand the effects of density differences.

Groundwater Displacement

Specific conductance and alkalinity data showed that the greatest amount of surface water influx occurred 6.86 m below ground surface at W1. Temperature data suggests that bank recharge most affected W1 at a depth of 5.94 m. If bank recharge completely displaced all the groundwater at W1, and the indicator tracers were conservative, the alkalinity and specific conductance in the groundwater should be the same as in the river. In the same way, groundwater temperature may approach that of the river, though temperature is the most non-conservative of the three parameters that were used to track bank recharge. Thus, the temperature of the groundwater is expected to change the least (*i.e.* percentage of parameter change before and after bank recharge). The specific conductance changed the most (from 500 µS/cm to 279 µS/cm) at a depth of 6.86 m. The specific conductance of the river was 156 µS/cm during the spring snowmelt event. If 100 per cent of the groundwater was displaced the specific conductance would be 156 µS/cm. Using Eq.(1), the per cent of groundwater displaced can be determined.

$$GW_{\text{displaced}}(\%) = \frac{(P_0 - P_1)}{(P_0 - P_r)} \qquad (1)$$

where

$GW_{\text{displaced}}$ – Per cent of groundwater displaced by surface water
P_0 – Parameter measured prior to event
P_1 – Parameter measured at its greatest change
P_r – Parameter measured at river

The decrease in specific conductance suggests 64 per cent of the groundwater was displaced by river water at a depth of 6.86 m. The alkalinity dropped from 238 to 114 mg/L as $CaCO_3$ at a depth of 6.86 m at W1, while the river had an alkalinity of 56 mg/L as $CaCO_3$ on April 29, 1997. Using the above approach, river water displaced 68 per cent of the water. The greatest change in temperature occurred when the temperature dropped from 3.9°C to 2.3°C at a depth of 5.94 m, with the river at 1.0°C. The resulting change would predict a displacement of 55 per cent of the groundwater. The coldest temperature at that depth occurred on May 3, 1997. These calculations represent the minimum amount of bank recharge that occurred. If the maximum displacement occurred on May 3, then the displacement numbers for specific conductance and alkalinity might be underestimated since both readings were taken on May 5. The temperature method probably underestimated the amount of mixing due to heat exchange with soil matrix. During bank recharge, it was estimated that 64 to 68 per cent of the groundwater was displaced at a depth of 6.86 m at

W1. In contaminated areas near the Chena River, this would correspond to a significant amount of contaminated water that is moved away from the river.

Natural Attenuation

Many processes associated with bank recharge affect the natural attenuation of contaminants. Specific conductance and alkalinity data suggest that 64 to 68 per cent of the groundwater was displaced at a depth of 6.86 m at W1. In addition to displacement, the influx of water from bank recharge will dilute contaminant levels. Groundwater-gradient reversals will increase the time it takes contaminant plumes to reach the river. An increase in dissolved oxygen from bank recharge influx was never observed in groundwater samples. It is believed that as water moved into the aquifer, microorganisms and oxidation of reduced metals quickly utilized all the dissolved oxygen present in the surface-water influx.

During high stages on the Chena River, the extent of bank recharge was between 6.1 m and 30 m from the river's edge. Nakanishi and Lilly (1998) observed increases in water tables 2.7 km from the bank during 1995, because of the increase in Chena River stage. Considering the scale, natural attenuation processes are more affected by fluctuating water tables than bank recharge. During times of increasing water-table elevations, contamination is smeared into the newly saturated areas. As water tables drop and water begins to drain, some contaminants are left in the unsaturated zone. The large smear zone, resulting from fluctuating water tables, may be a more favorable environment for biodegradation processes. It is possible that the soils, as they drain, act similarly to trickling filters used to treat wastewater. The true effects of contaminant smearing as an aid to natural attenuation in this area are still unknown.

Summary and Conclusions

There were very few high river stage events during this study so it was not possible to fully investigate all effects of bank recharge caused by groundwater flow direction reversals that occurred when the water level elevation of the Chena River was greater than the water surface elevation of the surrounding groundwater. Hydraulic conductance, hydraulic gradient, duration and suddenness of the event all affect the extent and magnitude of bank recharge. This study demonstrated that bank recharge occurred when the water level elevation of the Chena River was greater than that of the surrounding groundwater for one week during spring melt. In 1997, the amount of groundwater displaced by surface water influx was estimated to be at least 64 to 68 per cent, 6.1 m from the bank at a depth of 6.78 m. Peak flows in the river during 1998 were not high enough to reverse the normal flow direction, from groundwater into the river.

In the characterization of groundwater aquifers, processes of recharge due to high-river stage complicate matters. This is especially the case when trying to understand how groundwater and surface-water interactions can affect natural attenuation of contaminants. In the studies on natural attenuation at Fort Wainwright, it is not completely understood how changes in the Chena River will affect the degradation process of contaminant plumes. Elevated levels of dissolved oxygen in the groundwater were not observed during bank recharge. Additional dissolved oxygen introduced into the groundwater though surface-water influx is suspected to be quickly utilized by chemical and biological processes. Although no increase in dissolved oxygen was seen, bank recharge still affects natural attenuation through the processes of dispersion, dilution and vertical smearing.

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