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# Water Quality and Ground-Water/Surface-Water Interactions along the John River near Anaktuvuk Pass, Alaska, 2002–2003

Scientific Investigations Report 2005-5229

U.S. Department of the Interior
U.S. Geological Survey

**Cover Photograph.** Contact Creek at 400 meters below Main Street, looking upstream on June 19, 2003. Photograph taken by Daniel A. Long, U.S. Geological Survey.

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**U.S. Geological Survey**
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## CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| meter (m) | 1.094 | yard (yd) |
| | Area | |
| square meter ($m^2$) | 0.0002471 | acre |
| square kilometer ($km^2$) | 247.1 | acre |
| square kilometer ($km^2$) | 0.3861 | square mile ($mi^2$) |
| | Flow rate | |
| cubic meter per second ($m^3/s$) | 35.31 | cubic foot per second ($ft^3/s$) |
| cubic meter per day ($m^3/d$) | 35.31 | cubic foot per day ($ft^3/d$) |
| liter per second (L/s) | 15.85 | gallon per minute (gal/min) |
| cubic meter per day ($m^3/d$) | 264.2 | gallon per day (gal/d) |
| cubic meter per second ($m^3/s$) | 22.83 | million gallons per day (Mgal/d) |
| millimeter per year (mm/yr) | 0.03937 | inch per year (in/yr) |
| | Hydraulic conductivity | |
| meter per day (m/d) | 3.281 | foot per day (ft/d) |
| | Transmissivity | |
| meter squared per day ($m^2/d$) | 10.76 | foot squared per day ($ft^2/d$) |

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88/Geoid99)

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83)

Elevation, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

**Abbreviations and acronyms used in this report:**

GAAR–Gates of the Arctic National Park and Preserve

GPS–Global Positioning System

DOC–Dissolved Organic Carbon

NAD83–North American Datum of 1983

NAVD88–North American Vertical Datum of 1988

NPS–National Park Service

RTK–Real Time Kinematic

SSE–Sum of squared errors

USGS–U.S. Geological Survey

# Water Quality and Ground-Water/Surface-Water Interactions along the John River near Anaktuvuk Pass, Alaska, 2002–2003

By Edward H. Moran and Timothy P. Brabets

## Abstract

The headwaters of the John River are located near the village of Anaktuvuk Pass in the central Brooks Range of interior Alaska. With the recent construction of a water-supply system and a wastewater-treatment plant, most homes in Anaktuvuk Pass now have modern water and wastewater systems. The effluent from the treatment plant discharges into a settling pond near a tributary of the John River. The headwaters of the John River are adjacent to Gates of the Arctic National Park and Preserve, and the John River is a designated Wild River. Due to the concern about possible water-quality effects from the wastewater effluent, the hydrology of the John River near Anaktuvuk Pass was studied from 2002 through 2003.

Three streams form the John River at Anaktuvuk Pass: Contact Creek, Giant Creek, and the John River Tributary. These streams drain areas of 90.3 $km^2$, 120 $km^2$, and 4.6 $km^2$, respectively. Water-quality data collected from these streams from 2002–03 indicate that the waters are a calcium-bicarbonate type and that Giant Creek adds a sulfate component to the John River. The highest concentrations of bicarbonate, calcium, sodium, sulfate, and nitrate were found at the John River Tributary below the wastewater-treatment lagoon. These concentrations have little effect on the water quality of the John River because the flow of the John River Tributary is only about 2 percent of the John River flow.

To better understand the ground-water/surface-water interactions of the upper John River, a numerical ground-water-flow model of the headwater area of the John River was constructed. Processes that occur during spring break-up, such as thawing of the active layer and the frost table and the resulting changes of storage capacity of the aquifer, were difficult to measure and simulate. Application and accuracy of the model is limited by the lack of specific hydrogeologic data both spatially and temporally. However, during the mid-winter and open-water periods, the model provided acceptable results and was coupled with a particle-movement model to simulate the movement and possible extent of conservative particles from the wastewater-treatment-plant lagoon.

## Introduction

Gates of the Arctic National Park and Preserve (GAAR) contains 34,000 square kilometers ($km^2$) of Arctic wilderness straddling the crest of the central Brooks Range in northern Alaska (fig. 1). The park is home to far-ranging populations of caribou, Dall sheep, wolves, and grizzly bears. Anaktuvuk Pass, a Nunamiut Eskimo village settled in the 1950s, is the only community surrounded by the park and home to about 300 residents. The village is located along Contact Creek, one of three tributaries feeding the headwaters of the John River (fig. 2 and 3). No permanent roads connect Anaktuvuk Pass to the rest of Alaska. The nearest road is the Dalton Highway, which is about 97 kilometers (km) east of Anaktuvuk Pass (fig. 1), but a local gravel-pad airport allows daily access to the village.

Beginning on the south side of the Continental Divide, the John River originates on Soapak Mountain (fig. 2). The river flows southward approximately 233 km through alpine tundra and forested valleys. Arctic grayling, whitefish, burbot, and chum salmon are among the several fish species inhabiting the river. The John River was designated a Wild River in 1980 under the Alaska National Interest Lands Conservation Act, and the National Park Service (NPS) is responsible for management of the river corridor.

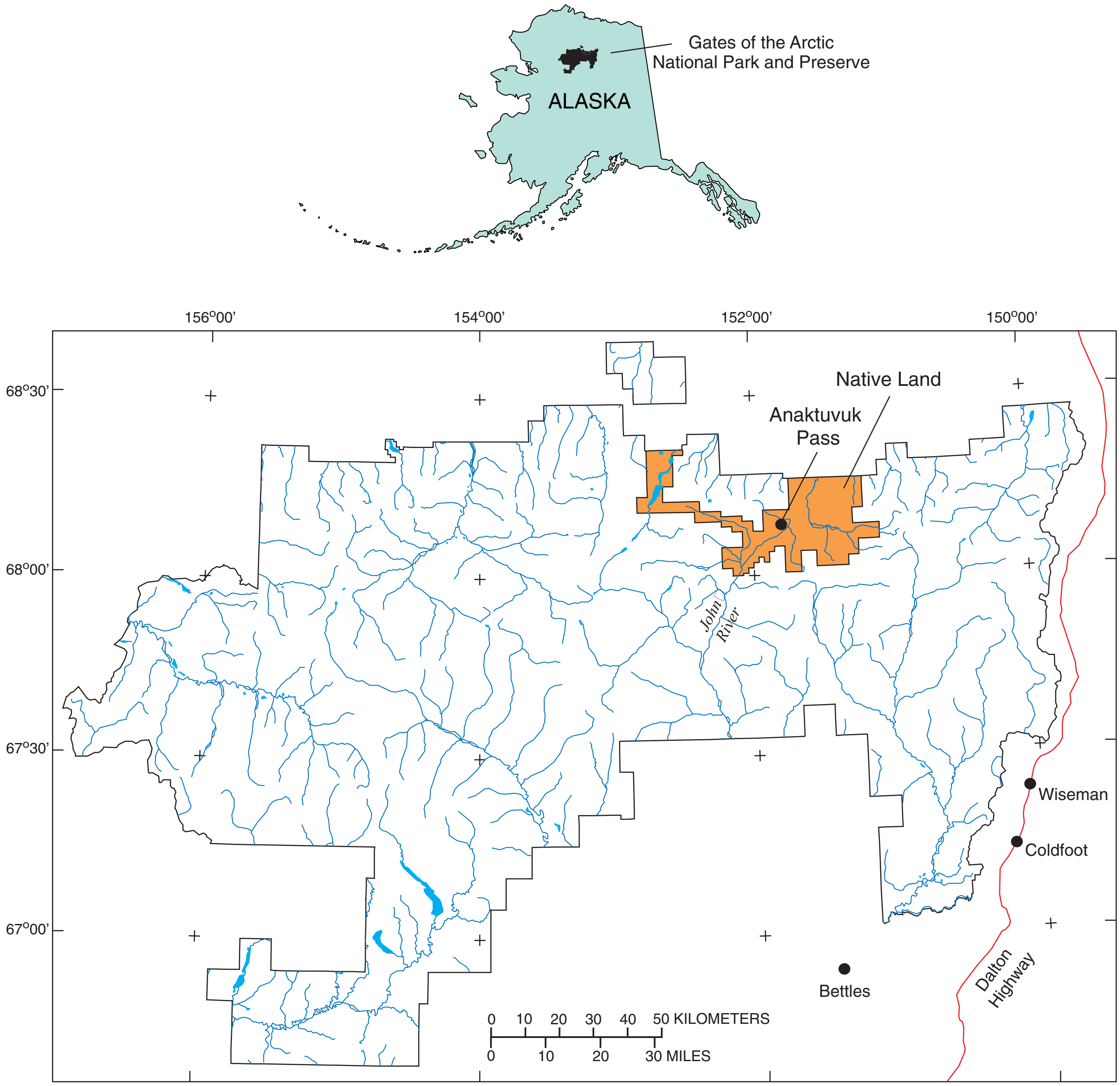



**Figure 1.** Location of Gates of the Arctic National Park and Preserve and Anaktuvuk Pass, Alaska.

Prior to the drilling of village-supply wells in 1974, residents of Anaktuvuk Pass obtained drinking water from nearby lakes. Before the construction of a wastewater-treatment plant in 2000, sewage and wastewater were disposed of in a now-abandoned pit just west of the current treatment-plant lagoon (fig. 3), which also served as the local landfill. Today, a modern landfill about 3 km northeast of town is used for disposal of all refuse. Most homes now have a direct hook-up to the new treatment plant. The treated effluent from the plant discharges into an unlined settling pond, where the liquids seep into an alluvial aquifer. The added convenience of the treatment plant as well as a growing population will likely increase the amount of treated effluent discharged into the settling pond and in turn, additional treated wastewater will enter the alluvial aquifer.

In the northern regions of Alaska, rivers generally have 100 percent ice cover for at least 6 months of the year (November to April). Because the ice cover eliminates direct gaseous exchange between the water column and the atmosphere, a significant lowering of the dissolved-oxygen concentration in these rivers and streams can occur (Chambers and others, 1997; Prowse, 2001a and 2001b). There is some concern about the effects of the treatment-

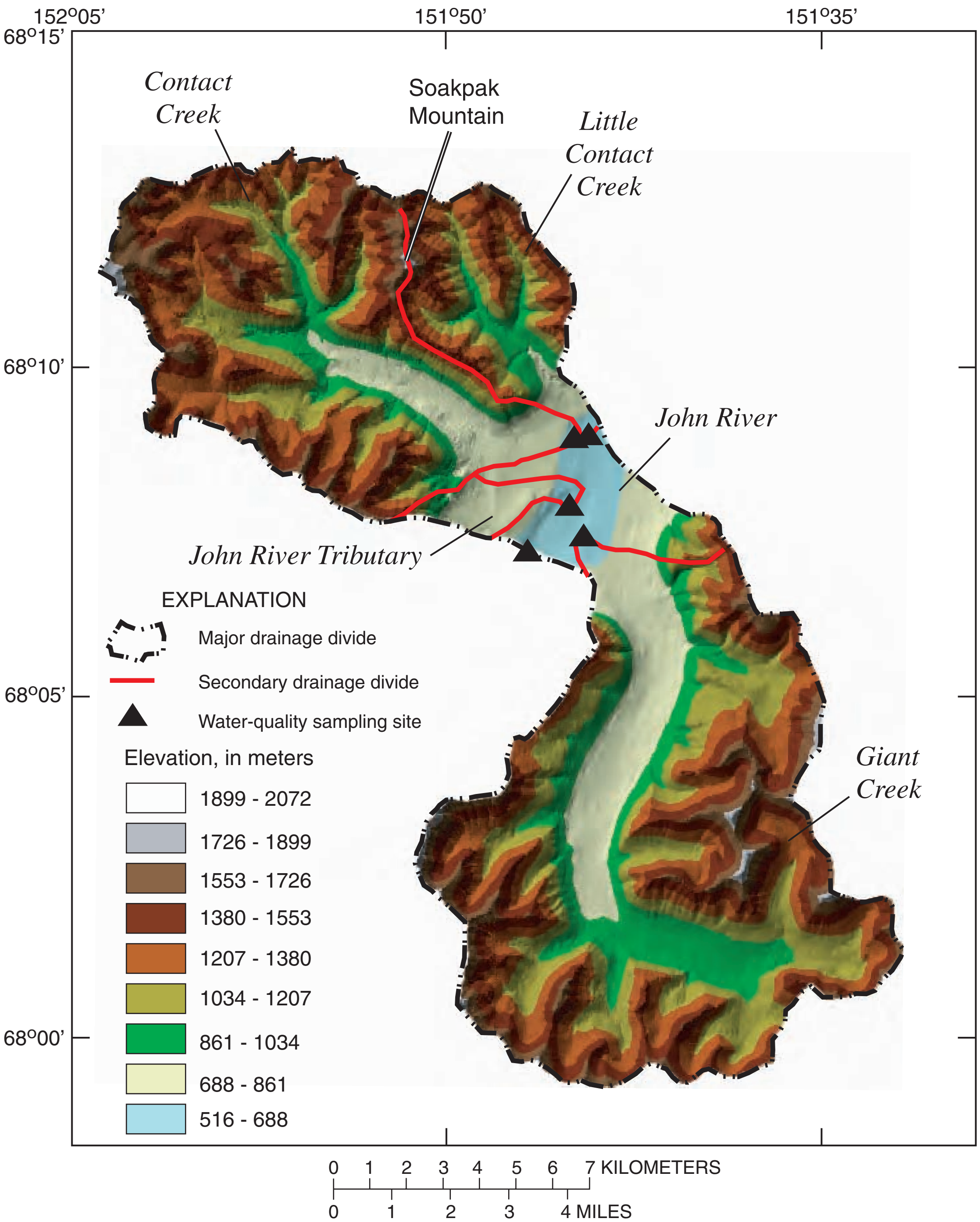



**Figure 2.** Shaded relief map of the Anaktuvuk Pass area.

plant effluent on the oxygen demand in the John River and the potential for lowering the dissolved-oxygen concentrations.

## Purpose and Scope

This report summarizes the results of a cooperative study by the NPS and the U.S. Geological Survey (USGS) from 2002–03 to study the water quality of the John River near Anaktuvuk Pass. The purpose of this study was to (1) evaluate the current water quality of the John River and the adjacent, inter-connected aquifer near Anaktuvuk Pass, (2) determine if the treatment-plant effluent affects the water quality of the John River, and (3) investigate the interaction between the surface-water and ground-water systems. The area of study was limited to the upper part of the John River near Anaktuvuk Pass (fig. 3).

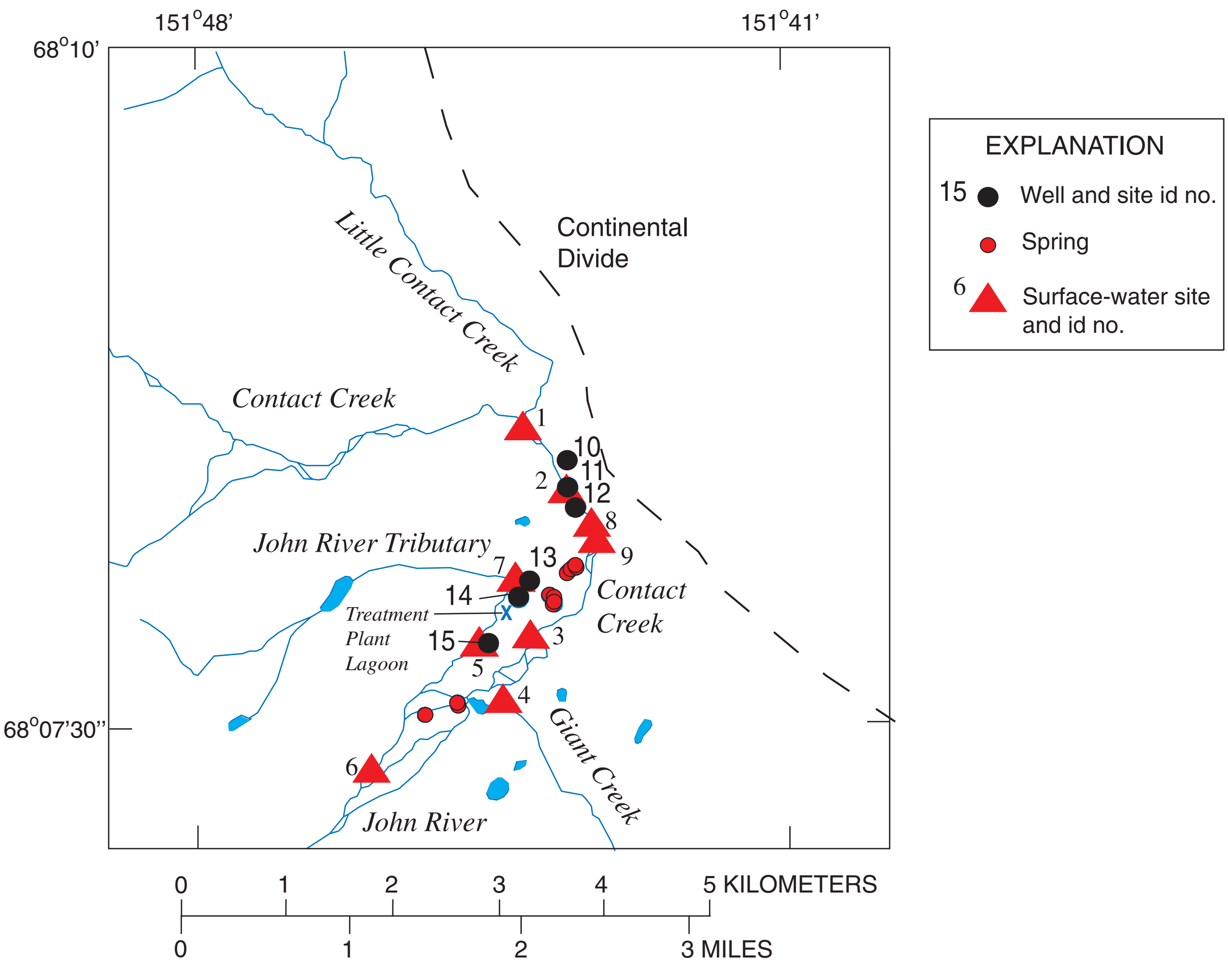



**Figure 3.** Locations of observation wells, springs, and surface-water sites at Anaktuvuk Pass. See table 1 for observation well and surface-water site information.

## Previous Studies

Sloan (1972) and Seitz (1991) described the hydrology of the Anaktuvuk Pass area and Fish (1997) summarized available data and information on the water resources near the village. Porter (1966) described and mapped the local geology, and the Natural Resource Conservation Service mapped the soils (Schoephorster and Summerfield, 1969). J. D. LaPerriere (Alaska Fish and Wildlife Cooperative Unit, University of Alaska, written commun., 1994) collected water samples from John River, Contact Creek, and Little Contact Creek for analysis of metals, fecal coliform bacteria, total petroleum hydrocarbons, turbidity, and color. In the mid 1990s, Shiltec Alaska, Ltd. (1996) and Duane Miller and Associates (1995) performed geotechnical and geothermal studies as required for the construction of the village's water and sewer system.

## Methods of Data Collection and Analysis

The primary factors that could affect the water quality of the John River are high concentrations and loads of nutrients in treatment-plant effluent that might reach the river. Given the complexity of ground-water and surface-water interactions of the study area owing to the presence of permafrost, efforts were made to collect and analyze and interpret these types of data.

Hydrologic data collected by the USGS during the 2002–03 summer seasons consisted of water samples for chemical analyses, continuous water temperature, stream-discharge measurements, ground-water levels, and land-survey data. Hydrologic data concerning the design of the water system and treatment plant were provided to the USGS by LCMF Incorporated of Anchorage, Alaska. In order to estimate daily discharge for Contact Creek and Inukpasugruk Creek (needed for the construction of the numerical model), discharge measurements from Contact Creek were compared to flow data from a long-term stream-gaging station on the Sagavanirktok River Tributary (USGS station 15906000) to estimate runoff characteristics of the study area. (Note: Inukpasugruk Creek is commonly referred to as ‘Giant Creek’ by Anaktuvuk Pass residents and the name ‘Giant Creek’ is used for the remainder of this report).

Water samples collected from the streams and wells were analyzed for field parameters (pH, water temperature, specific conductance, and dissolved oxygen), major ions, dissolved solids, nutrients, and organic carbon. The field-collection and processing equipment used were made of Teflon, glass, or stainless steel to prevent sample contamination and to minimize analyte losses through adsorption. All sampling equipment was cleaned prior to use with a nonphosphate, laboratory detergent and then rinsed with deionized water and finally rinsed by stream or well water immediately prior to sample collection. Depth-integrated water samples were collected from streams using the equal-width-increment method (http://water.usgs.gov/owq/FieldManual/) and processed in the field (http://water.usgs.gov/owq/FieldManual/). Samples to be analyzed for dissolved constituents were filtered through 0.45 micrometer (μm) capsule filters. Water samples were sent to the USGS National Water-Quality Laboratory for analysis using standard USGS analytical methods (Fishman and Friedman, 1989; Patton and Truitt, 1992; Fishman, 1993). A Yellow Springs Instrument meter was used to measure water temperature, dissolved-oxygen concentration, specific conductance, and pH at the time of sampling. Discharge measurements also were made at the time of sampling using methods outlined by Rantz and others (1982).

In June and July 2003, locations of stream-sampling sites, observation wells, and springs were determined using a survey-grade global positioning system (GPS). The streambed of Contact Creek from Little Contact Creek to the John River also was surveyed to determine the gradient as accurately as possible. Static and Real Time Kinematic (RTK) GPS positioning methods were used to establish North American Datum of 1983 latitude and longitude coordinates and North American Vertical Datum of 1988 (NAVD88) elevations using Geoid99. All RTK points were corrected to a base station set over a static-established GPS control point at the NPS building in Anaktuvuk Pass and, relative to that point, are accurate to within 3 centimeters based on the datum.

To better understand the ground-water and surface-water systems and the potential migration of contaminants, a numerical ground-water-flow model, MODFLOW-2000 (Harbaugh and others, 2000), was constructed using the MODFLOW graphical user interface (Winston, 2000). MODFLOW-2000 simulates the flow of water through geologic material using numerical equations based on physical principles applied in a three-dimensional, finite-difference grid assuming fluid density is constant (Harbaugh and others, 2000). In this study, the simulation included the MODFLOW-2000 Lake (Merritt and Konikow, 2000) and Stream (Prudic, 1989) packages to investigate ground- and surface-water interactions. MODPATH (Pollack, 1994) was used to simulate the potential movement of conservative particles through the aquifer from beneath the treatment-plant lagoon.

## Acknowledgments

The authors thank Michael Haubert of the NPS for his hospitality during our field visits and for the use of NPS facilities; the residents of Anaktuvuk Pass for their hospitality and sharing their knowledge of the area; and LCMF Incorporated, Anchorage, Alaska, for providing historical hydrologic information of the study area. As part of the USGS Volunteer for Science program, Gordon Nelson shared his knowledge and insights of ground water of Alaska with the authors.

## Hydrogeologic Setting of Anaktuvuk Pass

Anaktuvuk Pass lies along the boundary of two major climatic zones in Alaska, the continental-climate zone and arctic-climate zone. The Brooks Range separates these two zones. The climate at Anaktuvuk Pass is characterized by short cool summers, long cold winters, and low amounts of annual precipitation. Average-annual precipitation for Anaktuvuk Pass is about 0.26 meters (m), of which 0.15 m occurs as snowfall from October to May (fig. 4). The mean annual temperature is -10$^{o}$C, with average temperatures of -24$^{o}$C in January and 10$^{o}$C in July. Local vegetation is typical for the climate zones: low-shrubs (willows), herbaceous plants, sedges, lichen, mosses, and grasses. Dense patches of willow grow within most of the riparian zones.

The generalized geology of the Anaktuvuk Pass area consists of two stratigraphic units: Quaternary unconsolidated glacial sediments overlying a metamorphic basement (Porter, 1966) (fig. 5). The metamorphic

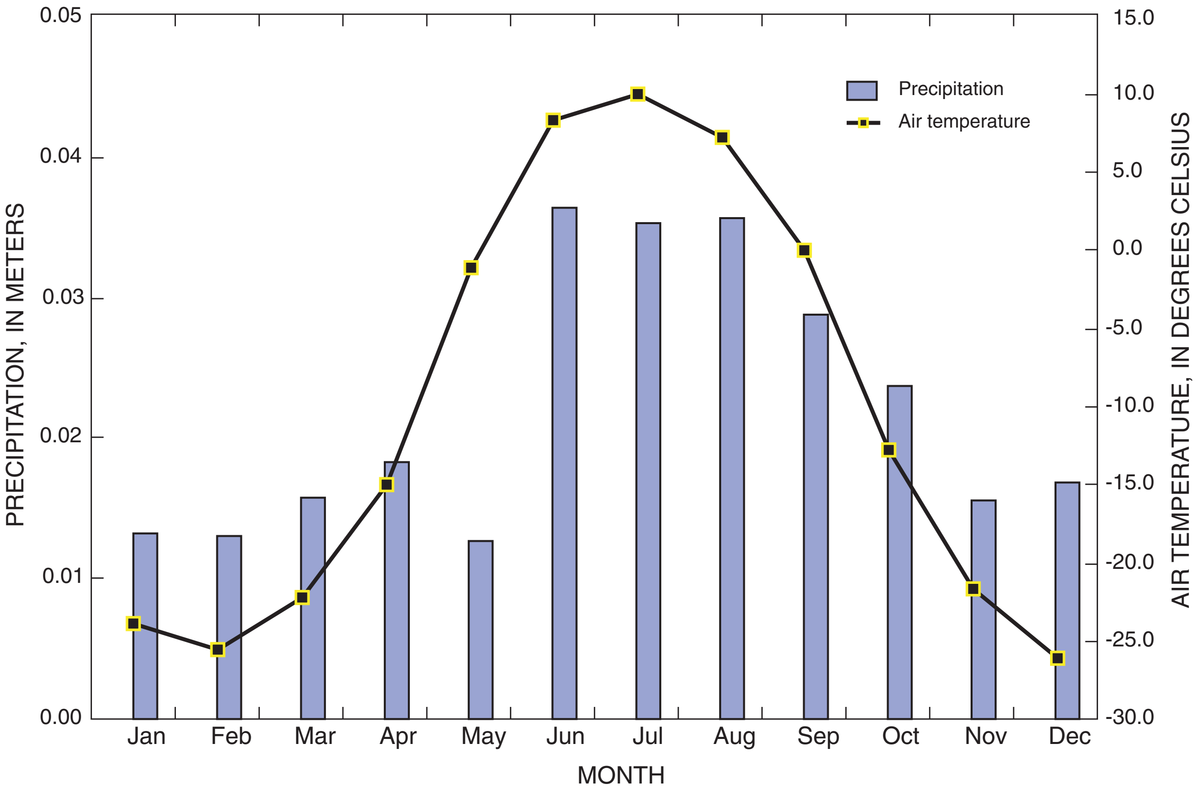



**Figure 4.** Average monthly precipitation and air temperature for Anaktuvuk Pass.

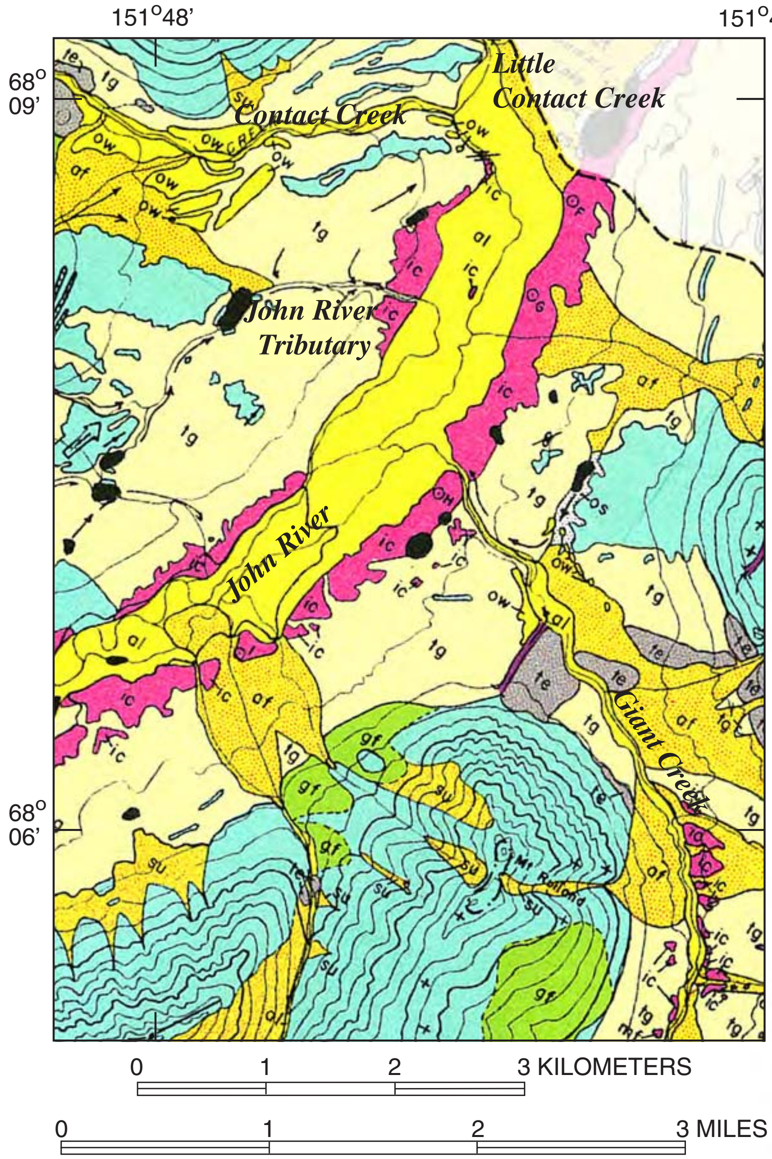
basement consists of Late Devonian- through Permian-age sedimentary marine clastic and carbonate bedrock that has undergone orogenic deformation and faulting. The quaternary deposits may range in thickness from 300 m in the southwestern part of the study area to 30 m in the northwestern part. In the flood plain of the John River and the larger tributaries (Contact and Giant Creeks), the unconsolidated materials predominately are alluvium bordered by benches of frozen ice-contact stratified drift and ground moraine that extend to the mountain slopes. Well logs and observations indicate the alluvium consists of boulders, cobbles, gravel, sand, and silt (Shiltec Alaska, Ltd., 1996). Alluvium cuts through layers of fine-grained sediments of the existing and abandoned stream channels.

Permafrost is present throughout the study area, commonly in the glacial-till benches (fig. 5), but generally is absent in the flood plain except near the John River headwaters where sediments are fine-grained and the shallower soils remain saturated prior to freeze-up. In permafrost areas, the active layer (the upper soil layer that annually thaws and freezes) can reach depths greater than 4 m as indicated by well-bore temperature profiles (Shiltec Alaska, Ltd., 1996).

Four major streams are located near Anaktuvuk Pass. Little Contact Creek drains 21 $km^2$, originates in the mountains north of Anaktuvuk Pass, and flows southeast into Contact Creek (fig. 2 and 3). The combined drainage of Little Contact Creek and Contact Creek is 90 $km^2$. Contact Creek flows southeast past the village and then turns southwest and merges with Giant Creek. Giant Creek originates in the mountains south of the village, flows northeast, and drains approximately 120 $km^2$. The confluence of Contact Creek and Giant Creek forms the John River. The John River Tributary drains approximately 4.6 $km^2$ southwest of the village proper, near the treatment-plant lagoon, and flows southwest into the John River (fig. 3).

Below the mouth of Little Contact Creek (fig. 3), Contact Creek has been diverted to the present-day channel (fig. 6). An aerial photograph, taken in August 1955, shows Contact Creek flowing where the airport runway now exists. As of 2002, the only lakes within the flood plain are two human-made lakes (fig. 12) near the diverted Contact Creek reach. Village personnel continually bulldoze the lake bottoms and the bed of this reach in efforts to alleviate flooding of the village.

Streambed and bank material consists of alluvium, with observed particle size decreasing in a downstream direction. At the confluence of Little Contact Creek and Contact Creek, sediments include boulders intermixed



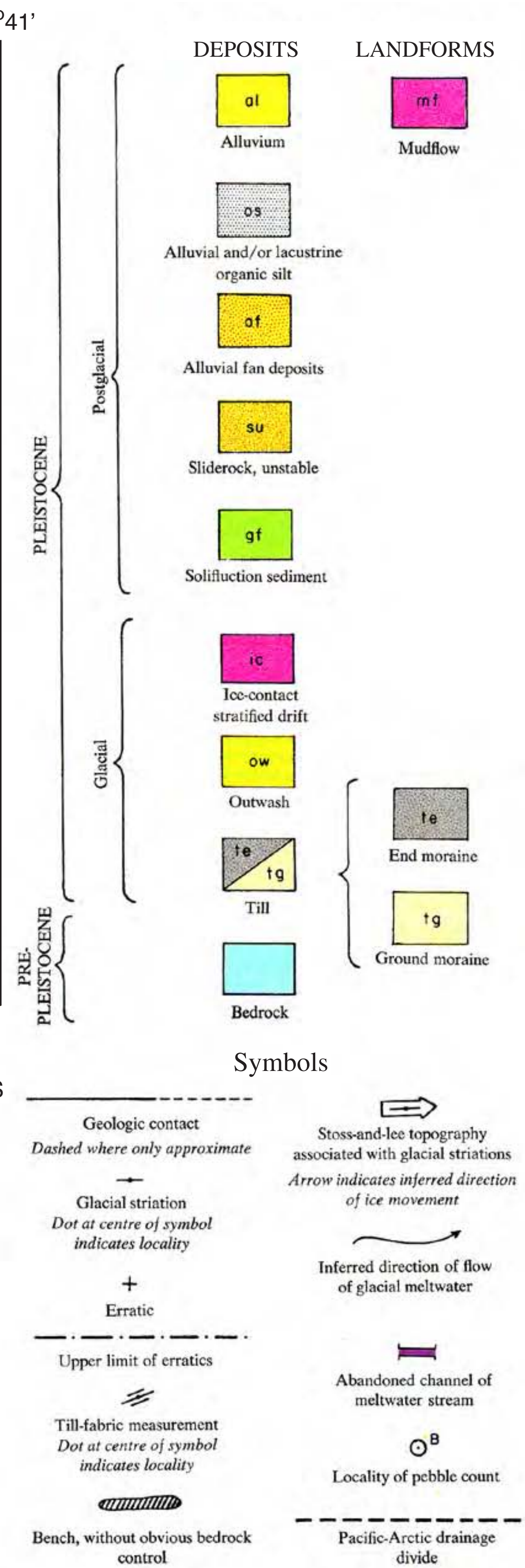




**Figure 5.** Surficial geology of the Anaktuvuk Pass area, Alaska. (Geology from Porter, 1966).

with cobble-size material. At Contact Creek at Main Street, bed sediments are cobbles and sand. Silt- and sand-size sediments dominate the streambed in the upper reach of the John River Tributary. Bed materials at Giant Creek range from cobbles to sand and at the confluence with Contact Creek, the streambed consists of sand with some cobbles. From this point downstream along the John River, sand dominates with minor amounts of silt, gravel, and cobbles.

As is typical for the region, flow occurs in the four tributaries only between May and October. Below the Contact Creek and Giant Creek confluence, however,

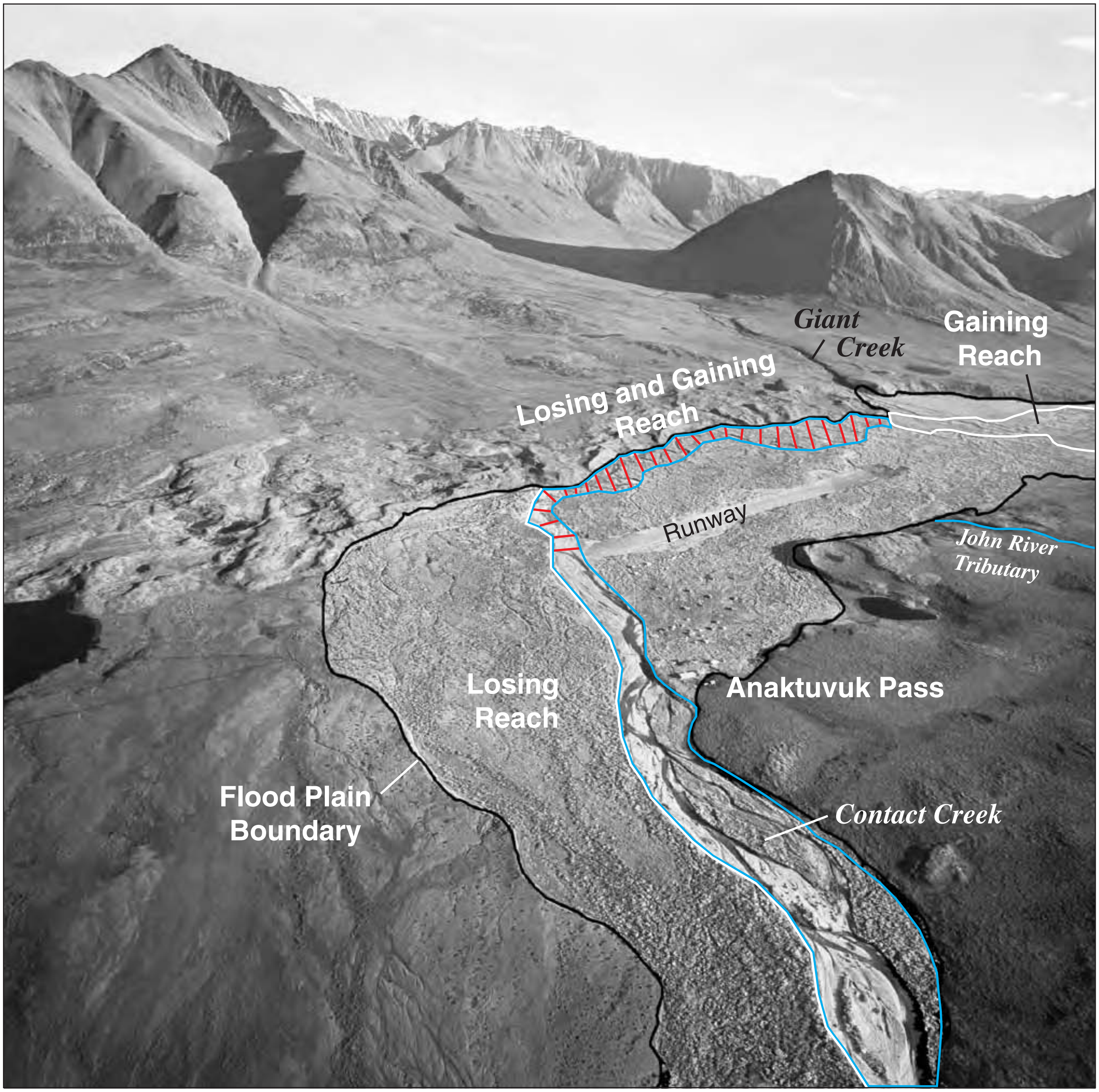



**Figure 6.** Aerial photograph of Anaktuvuk Pass (from Sloan, 1972).

several springs supply water to the John River (fig. 3), which flows year round. Such a large area of perennial springs is unusual, though not unique, in the Arctic. In mid to late May, streamflow begins and increases owing to melting snow. From June to mid September, baseflow, mountain snowmelt, and rainfall provide all flow. Permafrost substantially restricts the infiltration of precipitation into the aquifer and results in stream levels rapidly rising and falling during rainfall periods (fig. 7). Throughout the summer, streamflow in non-permafrost areas is rapidly lost to or gained from the aquifer.

Observations and well logs indicate that alluvial aquifer materials generally decrease in particle size downslope and perpendicular to stream channels, which is similar to the observed distribution of streambed and bank sediments. Ground water flows in the alluvial and fluvial sediments beneath and adjacent to the stream channels. Unconfined conditions exist just upstream from the John River headwaters (Shiltec Alaska, Ltd., 1996). Downstream in the transition area, between unconfined- and confined-flow conditions, lenses of coarser-grained stream-channel deposits are inter-bedded in a matrix of fine-grained

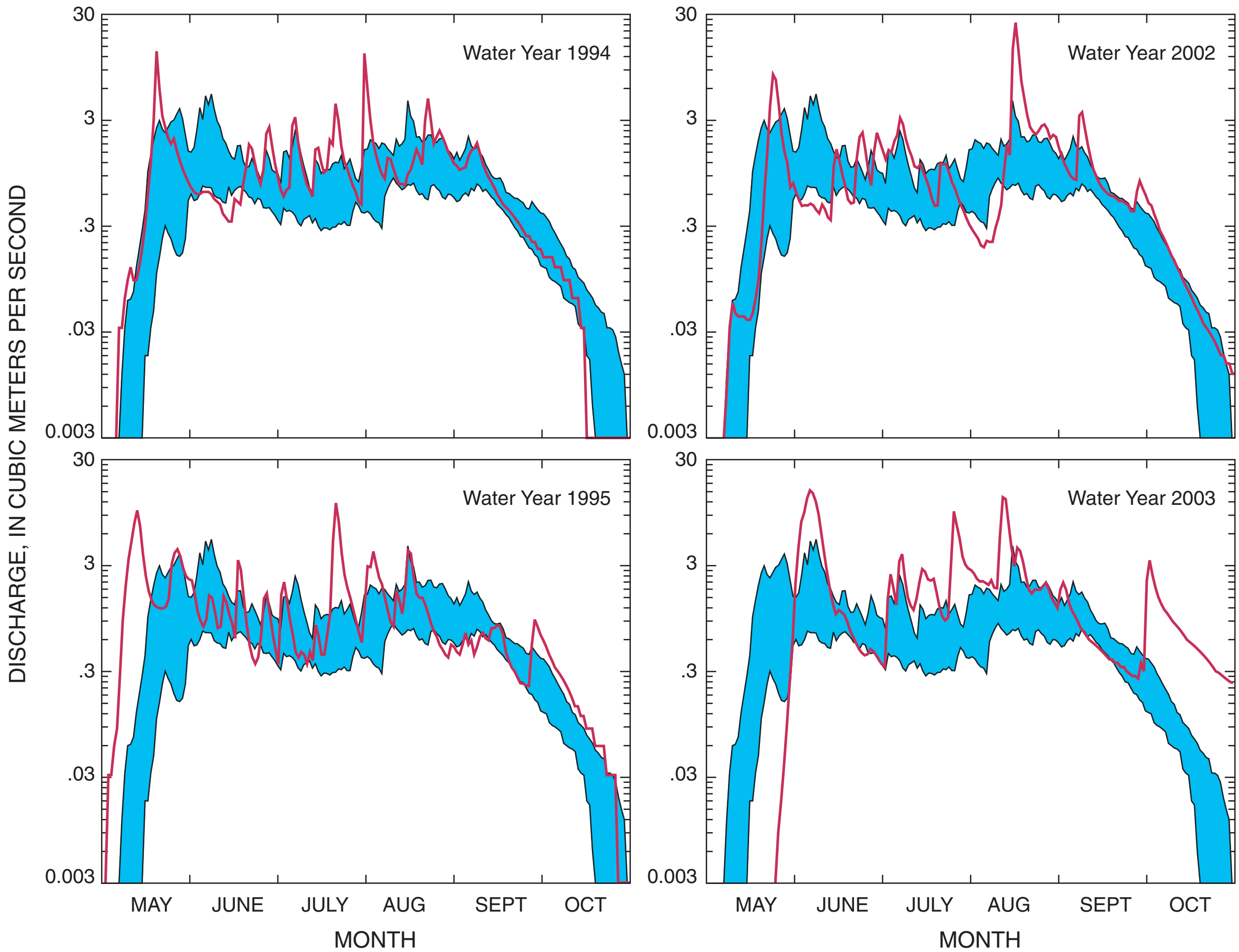



**Figure 7.** Daily streamflow and interquartile range (blue) of mean daily streamflows for Sagavanirktok River Tributary near Pump Station 3 (USGS ID 15906000, period of record 1979 to 2004). The interquartile range represents the range of the central 50 percent of the flow data. The upper boundary (quartile) is the flow value that is exceeded no more than 75 percent. The lower boundary (quartile) is the flow value that is exceeded no more than 25 percent.

sediments. The fine-grained sediments likely confine the deeper flowing ground water. During drilling of a well located northwest of the west-end of the runway, water levels rose above the land surface for a short time then dropped and remained below land surface (Shiltec Alaska, Ltd., 1996). During the summer and early fall, most of the transition area is fully saturated at or near the surface (Shiltec Alaska, Ltd, 1996), a result of upward ground-water movement through the confining sediments. At several locations, ground water discharges to the surface through springs, likely flowing through high-permeability pathways of coarse-grained material. However, because permafrost is present in the area, flow may follow fissures caused by the expansion and contraction of freezing and thawing soils (Duane Miller and Associates, 1995).

In observation-wells 3 and 4 (Sites 13 and 14, respectively, fig. 3, table 1), which are located between the treatment-plant lagoon and the runway, a 1 m water-level decline occurred immediately after induced thawing indicating the presence of perched ground water. In cold-climate regions, perched ground water commonly occurs seasonally, perched in saturated soils above frozen horizons. As interstitial pore-ice melts, perched water drains downward to the water table

Near Anaktuvuk Pass, winter and summer ground-water levels are notably different. During the winter of 1994–95, water levels in observation-wells 2 and 5 (Site 12 and 15, fig. 3) were more than 3 m lower than summer levels (fig. 8). At the beginning of spring runoff, seasonally frozen sediments limit the amount of recharge from surface sources. The relatively lower hydraulic conductivity of the upper horizons, owing to interstitial pore-ice formation, limits the infiltration of surface water to the water table. During the first few weeks of runoff, solar heat and heat from flowing stream water gradually melts the layers of ice and frozen soil on the streambed. The complete

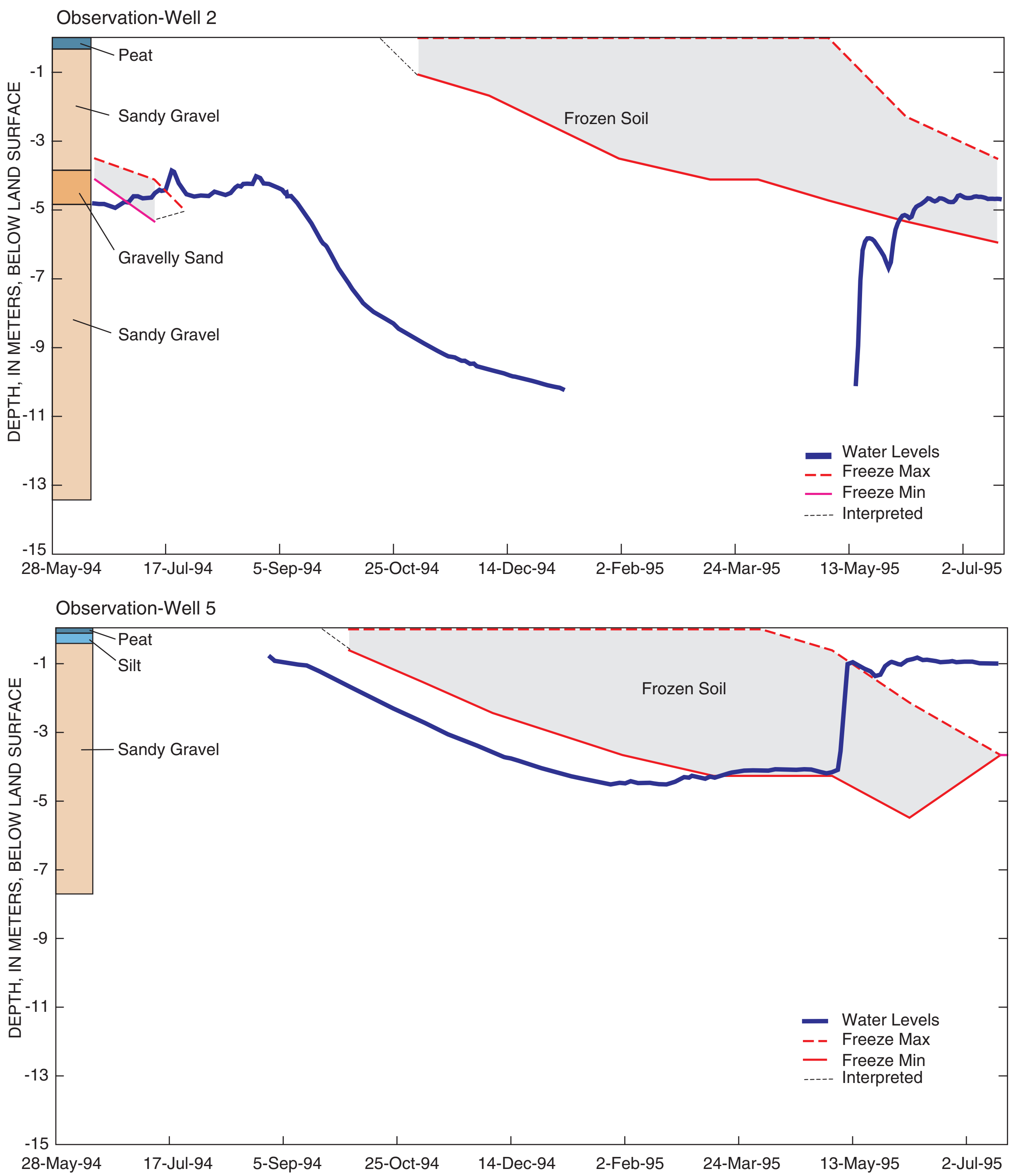



**Figure 8.** Ground-water levels, lithology, and depth of freezing for observation-wells 2 and 5 (Shiltec Alaska Ltd., 1996).

melting of streambed-sediment pore ice allows surface water to percolate downward through unfrozen sediments, thus recharging the water table.

Coincident with the onset of streamflow in mid to late May, ground-water levels rise sharply and reach annual highs usually by mid June. Summer fluctuations in ground-water levels then reflect changes in streamflow. Freezing temperatures after August reduce streamflow, which results in less recharge to the water table. The release of ground water from storage results in a much slower and gradual decline in ground-water levels during the fall as compared to the rapid ground-water level rise during spring. Annual ground-water level lows occur in mid winter (fig. 8).


**Figure 9.** Aerial view of Anaktuvuk Pass looking south showing extent of aufeis. (Photograph by Timothy P. Brabets, U.S. Geological Survey, June 18, 2002).

Within the headwater area of the John River, the freezing of late-fall streamflow and the discharge of water from springs probably initiate the seasonal formation of aufeis, (fig. 9 and 12) which is the layering of ice caused by repeated overflowing of water onto frozen soil or ice (Ryan and Crissman, 1990). Aufeis remains in the area until mid June, which is well after most of the snow has melted from the mountains. The coupling of continuous, winter recharge from upgradient sources outside the study area and the process of aufeis formation possibly explains the gradual January to mid-May rise in ground-water levels just upgradient of the headwater area (fig. 8). In several areas, the observed thickness of aufeis during June 2003 was approximately 1 m and the discharge of water from springs within these areas was at the surface of the ice. This suggests that the altitude of ground water at the same location was 1 m lower when aufeis was absent. Because the ground-water level from sources outside the area was assumed to remain constant, the formation of aufeis resulted in a continuously decreasing slope of the water table upgradient of the headwater area.

# Water Quality of the Headwaters and Tributaries of the John River near Anaktuvuk Pass

In 2002, water samples were collected at six surface-water sites: Contact Creek below Little Contact Creek, Contact Creek at Main Street, Contact Creek above Giant Creek, Giant Creek, John River below Giant Creek, and the John River Tributary below Lagoons (Sites 1-6, fig. 3, table 1). After reviewing the 2002 water-quality data, the sampling scheme was modified for 2003. Only one site on Contact Creek was sampled, Contact Creek at Main Street, and a second site, John River Tributary above Lagoons (Site 7, fig. 3, table 1), was added. In 2003, the village-supply well (Site 10) and observation-wells 1, 3, and 4 (Sites 11, 13, 14, fig. 3, table 1) were sampled for water quality. Water-temperature probes were installed at Contact Creek below Little Contact Creek, Giant Creek, the John River Tributary below Lagoons, and John River below Giant Creek.

**Table 1.** Data collection sites at Anaktuvuk Pass, Alaska [see figure 3 for site locations]

| Site ID | USGS Station ID | Station Name | Site Type | Remarks |
|---|---|---|---|---|
| 1 | 1556488224 | Contact Creek below Little Contact Creek | Surface water | Observation, Model Boundary |
| 2 | 680837151435000 | Contact Creek at Main Street | Surface water | Observation |
| 3 | 680754151442100 | Contact Creek above Giant Creek | Surface water | Observation |
| 4 | 680735151444400 | Giant Creek | Surface water | Observation, Model Boundary |
| 5 | 680752151450200 | John River Tributary below Lagoons | Surface water | Observation |
| 6 | 680715151463000 | John River below Giant Creek | Surface water | Observation |
| 7 | 680811151443200 | John River Tributary above Lagoons | Surface water | Observation, Model Boundary |
| 8 | 680827151434300 | Contact Creek 200 m below Main Street | Surface water | Observation |
| 9 | 680822151433500 | Contact Creek 400 m below Main Street | Surface water | Observation |
| 10 | 680837151435301 | Village-Supply Well | Ground water | Water-quality sample |
| 11 | 680838151434901 | Observation-Well 1 | Ground water | Water-quality sample, Water levels |
| 12 | 680838151434301 | Observation-Well 2 | Ground water | Water levels |
| 13 | 680809151443101 | Observation-Well 3 | Ground water | Water-quality sample, Water levels |
| 14 | 680805151443001 | Observation-Well 4 | Ground water | Water-quality sample, Water levels |
| 15 | 680750151450501 | Observation-Well 5 | Ground water | Water levels |

## Specific Conductance

Specific conductance, a measure of the ability of water to conduct an electric current, is directly related to the concentration of ions dissolved in the water. Ground water, which flows slowly through saturated sediments, spends months or years in contact with sediments and has more time to dissolve solutes than surface water, which runs off quickly. As a result, ground water typically has a higher specific conductance than surface water. This effect is indicated by the specific conductance of samples collected from the village-supply well and observation-well 4. Both values were greater than 250 microsiemen per centimeter (µS/cm) at 25°C (table 3). For the surface-water sites on Contact Creek, Giant Creek, and the John River, specific conductance ranged (with one exception) from 100 µS/cm (Site 2) to 199 µS/cm (Site 6) at 25°C (table 2). A sample collected from Giant Creek during a low-flow period in May 2003, had a value of 371 µS/cm at 25°C. This was the highest specific conductance value noted in the study and probably was a mixture of ground water and surface water. Specific conductance at the John River Tributary above Lagoons was less than 50 µS/cm at 25°C for all samples (table 2) but at the John River Tributary below Lagoons, specific conductance values were 2 to 4 times higher than at the upstream site, indicating an increase in the dissolved-solids content of the water.

## pH

The pH of water is a measure of its hydrogen-ion activity and can range from zero (highly acidic) to 14 (very alkaline) standard units. The pH of river water not affected by contamination is typically between 6.5-and 8.0-standard units (Hem, 1985) and for fish growth and survival, the pH should remain in the 6.5 to 9.0-standard unit range. During the study period, measured values of pH in the study area ranged from 6.6 (Site 5) to 8.4 (Site 3) (tables 2 and 3).

## Water Temperature

Water temperature is important in physiochemical and biological processes such as oxygen solubility and fish metabolism and growth rates. Water temperature at the time of sampling at all sites ranged from 0.0 to 9.3°C (tables 2 and 3). In 2003, instruments that continuously sense and record water temperature were placed in Contact Creek, Giant Creek, John River Tributary, and at one spring to document fluctuations throughout the summer. Water temperature at all surface-water sites followed the same trend and was highly correlated with air temperature (fig. 10). The water temperature of the John River Tributary below the Lagoons was higher than Contact Creek and Giant Creek except for a short period from August 2–10. Water temperature of the spring remained fairly constant

**Table 2.** Physical properties measured in water samples collected from surface-water sites at Anaktuvuk Pass, Alaska

[$m^3/s$, cubic meters per second; mg/L, milligrams per liter; µS/cm at 25°C, microsiemen per centimeter at 25 degrees Celsius; --, no data]

| Station | Site ID | Date | Time | Discharge ($m^3/s$) | Dissolved Oxygen (mg/L) | pH (units) | Specific Conductance (µS/cm at 25 °C) | Water Temperature (°C) |
|---|---|---|---|---|---|---|---|---|
| Contact Creek below Little Contact Creek | 1 | 6/18/2002 | 1710 | 1.70 | 12.2 | 8.3 | 110 | 6.7 |
| | | 7/17/2002 | 940 | 3.03 | -- | 7.6 | 118 | 5.9 |
| | | 9/10/2002 | 1630 | 1.76 | 11.4 | 7.9 | 135 | 2.6 |
| Contact Creek at Main Street | 2 | 6/18/2002 | 2000 | 1.39 | 12.1 | 8.4 | 115 | 6.2 |
| | | 7/17/2002 | 1125 | 2.63 | -- | 8.0 | 112 | 7.3 |
| | | 9/10/2002 | 1900 | 0.65 | 10.8 | 8.0 | 133 | 2.6 |
| | | 6/17/2003 | 1515 | 6.03 | 11.5 | 8.1 | 100 | 4.9 |
| | | 7/15/2003 | 1810 | 3.71 | 12 | 7.9 | 133 | 4.7 |
| | | 8/14/2003 | 1510 | 8.18 | 11.5 | 7.9 | 127 | 4.9 |
| | | 9/9/2003 | 1130 | 0.88 | 9 | 8.3 | 150 | 0.3 |
| Contact Creek above Giant Creek | 3 | 6/19/2002 | 1350 | 0.99 | 12.6 | 8.4 | 139 | 5.3 |
| | | 7/16/2002 | 1635 | 3.03 | -- | 8.0 | 130 | 8.0 |
| | | 9/11/2002 | 1600 | 1.19 | 12 | 8.1 | 167 | 3.0 |
| Giant Creek | 4 | 6/19/2002 | 1155 | 2.63 | 13.1 | 8.2 | 148 | 4.4 |
| | | 7/16/2002 | 1445 | 4.56 | -- | 7.9 | 154 | 9.3 |
| | | 9/11/2002 | 1430 | 3.88 | 12.1 | 8.0 | 185 | 1.9 |
| | | 5/14/2003 | 1030 | 0.11 | 10.2 | 8.0 | 371 | 0.0 |
| | | 7/16/2003 | 1225 | 2.89 | 13 | 7.8 | 165 | 5.0 |
| | | 9/9/2003 | 1630 | 2.89 | 7.9 | 8.1 | 199 | 3.0 |
| John River Tributary below Lagoons | 5 | 9/11/2002 | 1100 | 0.02 | 11.4 | 6.6 | 94 | 2.9 |
| | | 6/17/2003 | 2115 | 0.04 | 10.2 | 8.1 | 106 | 4.7 |
| | | 7/17/2003 | 1600 | 0.09 | 10.6 | 7.6 | 87 | 7.1 |
| | | 8/13/2003 | 2125 | 0.21 | 11.1 | 7.3 | 80 | 6.2 |
| | | 9/11/2003 | 1115 | 0.03 | -- | 7.9 | 84 | 2.0 |
| John River below Giant Creek | 6 | 6/19/2002 | 1000 | 4.84 | 13.4 | 8.0 | 156 | 3.6 |
| | | 7/16/2002 | 1130 | 7.65 | -- | 8.0 | 150 | 8.7 |
| | | 9/11/2002 | 1230 | 5.07 | 11.8 | 7.8 | 185 | 2.4 |
| | | 7/16/2003 | 1513 | 6.57 | 12.2 | 8.1 | 158 | 6.6 |
| | | 8/14/2003 | 1145 | 17.0 | 9.9 | 7.8 | 148 | 5.5 |
| | | 9/9/2003 | 1415 | 3.82 | 8.2 | 8.2 | 195 | 3.3 |
| John River Tributary above Lagoons | 7 | 6/17/2003 | 1955 | 0.03 | 10.4 | 7.3 | 19 | 9.0 |
| | | 7/17/2003 | 1240 | 0.08 | 11.3 | 7.0 | 25 | 7.0 |
| | | 8/13/2003 | 1952 | 0.25 | 11.4 | 7.3 | 45 | 6.3 |
| | | 9/11/2003 | 1000 | 0.05 | -- | 7.0 | 38 | 0.8 |

**Table 3.** Concentrations of water-quality constituents measured in water samples collected from four wells at Anaktuvuk Pass, Alaska

[all values in milligrams per liter (mg/L) unless otherwise noted; µS/cm, microsiemen per centimeter at 25 degrees Celsius; <, less than; E, estimated]

| Station | Site ID | Date | Time | Dissolved Oxygen | pH (units) | Specific Conductance (µS/cm at 25 °C) | Water Temperature (°C) | Dissolved Solids | Magnesium | Potassium |
|---|---|---|---|---|---|---|---|---|---|---|
| Observation-Well 1 | 11 | 9/10/2003 | 945 | 7 | 7.0 | 87 | 3.5 | 40 | 4 | 0.8 |
| Observation-Well 3 | 13 | 9/10/2003 | 1215 | 14.3 | 8.1 | 160 | 2.8 | 94 | 4.4 | 0.2 |
| Observation-Well 4 | 14 | 9/10/2003 | 1330 | 12 | 7.8 | 252 | 1.7 | 151 | 6.2 | 0.2 |
| Village-Supply Well | 10 | 9/10/2003 | 1500 | 13.6 | 7.6 | 278 | 2.6 | 172 | 12.5 | 0.2 |

| Station | Site ID | Date | Time | Sodium | Alkalinity | Bicarbonate | Chloride | Fluoride | Silica | Sulfate | Calcium |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Observation-Well 1 | 11 | 9/10/2003 | 945 | 1 | 28 | 36 | 1.4 | 0.2 | 0.06 | 9.1 | 7.6 |
| Observation-Well 3 | 13 | 9/10/2003 | 1215 | 0.4 | 76 | 99 | 0.2 | <0.2 | 1.4 | 7.5 | 25 |
| Observation-Well 4 | 14 | 9/10/2003 | 1330 | 0.6 | 126 | 164 | 0.4 | <.2 | 1.9 | 8.6 | 43 |
| Village-Supply Well | 10 | 9/10/2003 | 1500 | 0.6 | 132 | 172 | 0.4 | <.2 | 4.2 | 20 | 40 |

| Station | Site ID | Date | Time | Ammonia Nitrogen ($NH_4$) | Nitrogen ($NH_4$+Org) | Nitrogen (Total) | Nitrogen ($NO_2+NO_3$) | Nitrogen ($NO_2$) | Phosphorus Dissolved |
|---|---|---|---|---|---|---|---|---|---|
| Observation-Well 1 | 11 | 9/10/2003 | 945 | 0.4 | 0.44 | 0.13 | <0.022 | <0.002 | E0.002 |
| Observation-Well 3 | 13 | 9/10/2003 | 1215 | <0.10 | 0.22 | <0.015 | 0.131 | <0.002 | <0.004 |
| Observation-Well 4 | 14 | 9/10/2003 | 1330 | E0.05 | 0.26 | <0.015 | 0.399 | <0.002 | E0.005 |
| Village-Supply Well | 10 | 9/10/2003 | 1500 | <0.10 | <0.10 | <0.015 | 0.056 | <0.002 | <0.004 |

| Station | Site ID | Date | Time | Phosphorus Ortho | Phosphorus Total | Dissolved Organic Carbon | Iron (µg/L) | Manganese (µg/L) |
|---|---|---|---|---|---|---|---|---|
| Observation-Well 1 | 11 | 9/10/2003 | 945 | <0.007 | 0.013 | 1 | 25 | 22 |
| Observation-Well 3 | 13 | 9/10/2003 | 1215 | <0.007 | 0.16 | 0.6 | <8 | 0.7 |
| Observation-Well 4 | 14 | 9/10/2003 | 1330 | 0.007 | 0.27 | 1 | <8 | <0.4 |
| Village-Supply Well | 10 | 9/10/2003 | 1500 | <0.007 | E0.002 | E0.3 | <8 | <0.4 |

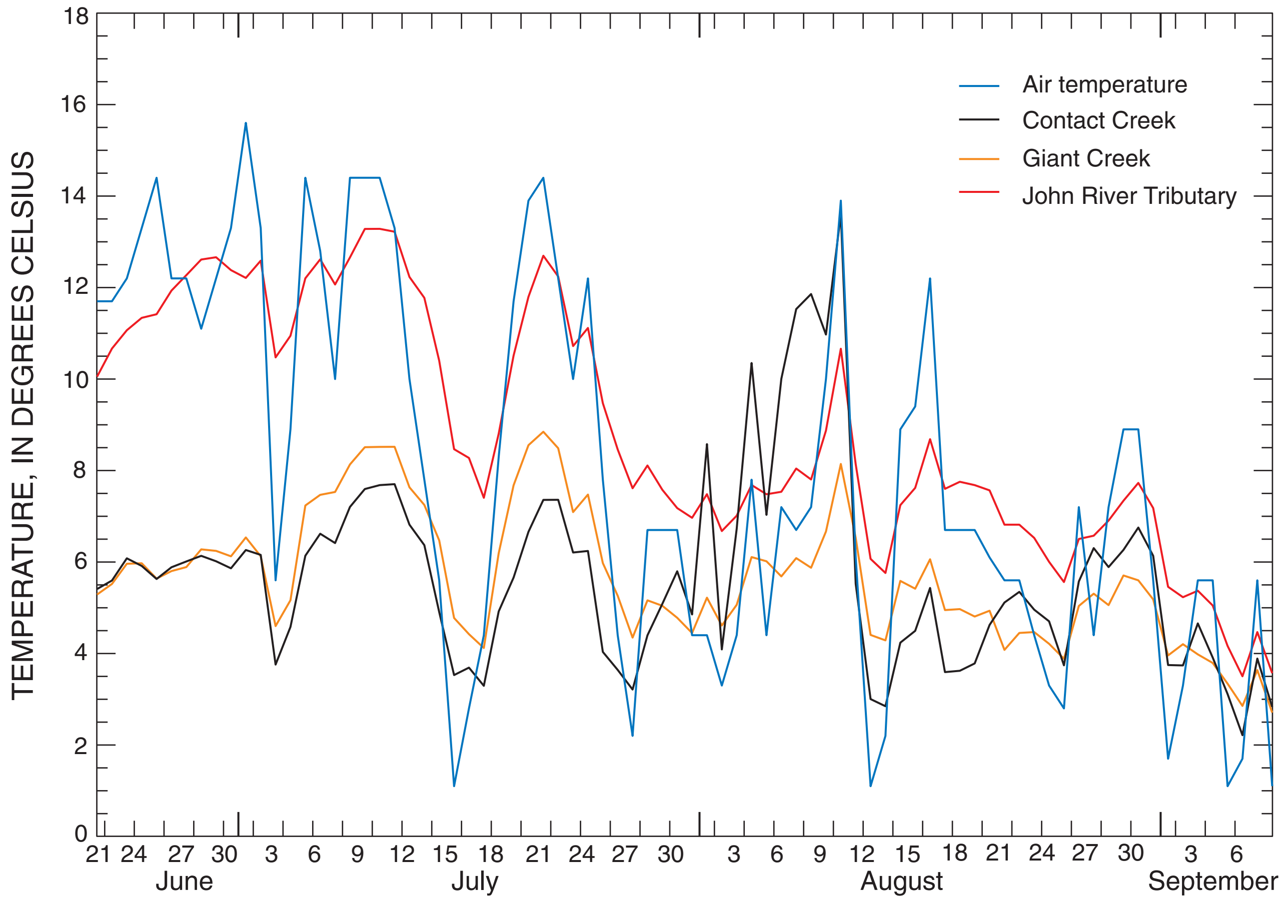



**Figure 10.** Daily air temperature and water temperature for streams at Anaktuvuk Pass, June through September 2003.

throughout the summer, ranging from 1.5 to 3.1°C. The relatively warm surface water that infiltrates into the alluvial aquifer during the summer carries an immense thermal load into the aquifer, which results in deeper sediments remaining unfrozen during the winter.

## Dissolved Oxygen

The dissolved-oxygen concentration in a stream is controlled by several factors, including water temperature, air temperature and atmospheric pressure, hydraulic characteristics of the stream, photosynthetic or respiratory activity of stream biota, and the quantity of organic matter present (Hem, 1985). Fish require well-oxygenated water at every stage in their life history, as do many aquatic invertebrates. Young fish tend to be more susceptible to oxygen deficiencies than adults. Measurements of dissolved oxygen at all surface-water sites during the study period ranged from 7.9 (Site 4) to 13.4 milligrams per liter (mg/L) (Site 6) (table 2). All measurements of dissolved oxygen indicate adequate concentrations to support populations of fish and aquatic invertebrates.

## Alkalinity

Alkalinity is a measure of the capacity of the substances dissolved in water to neutralize or buffer acid. In most natural waters, alkalinity is produced mainly by bicarbonate and carbonate ions, which are formed when carbon dioxide or carbonate rocks dissolve in water (Hem, 1985). Alkalinity concentrations of the water samples in the study area (reported as equivalent concentration of calcium carbonate) ranged from as low as 8 mg/L (an indication of low buffering capacity) at John River Tributary above Lagoons to as high as 132 mg/L (an indication of high buffering capacity) at the village-supply well for Anaktuvuk Pass (tables 3 and 4). The range of pH measured at these sites indicates that all of the alkalinity can be attributed to dissolved bicarbonate (Hem, 1985).

## Major Ions and Dissolved Solids

Water samples collected from the surface-water sites and the wells were analyzed for major ions and dissolved solids (tables 3 and 4). Major ions and dissolved solids in streams consist of inorganic minerals derived primarily

**Table 4.** Concentrations of water-quality constituents collected from surface-water sites at Anaktuvuk Pass, Alaska

[all values in milligrams per liter (mg/L) unless otherwise noted; <, less than; E, estimated;]

| Station | Site ID | Date | Time | Alkalinity | Bicarbonate | Calcium | Chloride | Fluoride | Magnesium |
|---|---|---|---|---|---|---|---|---|---|
| Contact Creek below Little Contact Creek | 1 | 6/18/2002 | 1710 | 50 | 65 | 18 | <0.3 | <0.1 | 2.5 |
| | | 7/17/2002 | 940 | 55 | 72 | 19 | <0.3 | <0.1 | 2.7 |
| | | 9/10/2002 | 1630 | 63 | 82 | 22 | <0.3 | E0.1 | 3.4 |
| Contact Creek at Main Street | 2 | 6/18/2002 | 2000 | 53 | 69 | 18 | <0.3 | <0.1 | 2.6 |
| | | 7/17/2002 | 1125 | 54 | 70 | 19 | <0.3 | <0.1 | 2.8 |
| | | 9/10/2002 | 1900 | 62 | 81 | 23 | <0.3 | E0.1 | 3.5 |
| | | 6/17/2003 | 1515 | 46 | 60 | 18 | | | 2.2 |
| | | 7/15/2003 | 1810 | 60 | 78 | 22 | 0.4 | <0.2 | 3.1 |
| | | 8/14/2003 | 1510 | 57 | 76 | 20 | E0.15 | <0.2 | 3.1 |
| | | 9/9/2003 | 1130 | 71 | 92 | 23 | 0.2 | <0.2 | 3.9 |
| Contact Creek above Giant Creek | 3 | 6/19/2002 | 1350 | 66 | 86 | 23 | <0.3 | <0.1 | 3.4 |
| | | 7/16/2002 | 1635 | 63 | 82 | 23 | <0.3 | <0.1 | 3.4 |
| | | 9/11/2002 | 1600 | 76 | 99 | 28 | <0.3 | <0.1 | 4.2 |
| Giant Creek | 4 | 6/19/2002 | 1155 | 47 | 61 | 19 | <0.3 | <0.1 | 5.6 |
| | | 7/16/2002 | 1445 | 49 | 64 | 21 | <0.3 | E0.06 | 6.1 |
| | | 9/11/2002 | 1430 | 56 | 73 | 25 | <0.3 | <0.1 | 7.4 |
| | | 5/14/2003 | 1030 | 110 | 143 | 43 | 0.4 | <0.2 | 23.0 |
| | | 7/16/2003 | 1225 | 55 | 72 | 22 | <0.2 | <0.2 | 6.0 |
| | | 9/9/2003 | 1630 | 60 | 78 | 23 | E0.2 | <0.2 | 7.6 |
| John River Tributary below Lagoons | 5 | 9/11/2002 | 1100 | 45 | 58 | 15 | 0.3 | <0.1 | 2.8 |
| | | 6/17/2003 | 2115 | 53 | 69 | 18 | 0.4 | <0.2 | 2.7 |
| | | 7/17/2003 | 1600 | 42 | 55 | 14 | 0.5 | <0.2 | 2.4 |
| | | 8/13/2003 | 2125 | 38 | 49 | 13 | 0.2 | <0.2 | 2.6 |
| | | 9/11/2003 | 1115 | 39 | 51 | 12 | 0.2 | <0.2 | 2.6 |
| John River below Giant Creek | 6 | 6/19/2002 | 1000 | 58 | 75 | 23 | <0.3 | <0.1 | 5.2 |
| | | 7/16/2002 | 1130 | 62 | 81 | 24 | <0.3 | E0.1 | 4.7 |
| | | 9/11/2002 | 1230 | 74 | 96 | 29 | E0.19 | <0.1 | 6.1 |
| | | 7/16/2003 | 1513 | 71 | 92 | 26 | E0.19 | <0.2 | 4.2 |
| | | 8/14/2003 | 1145 | 57 | 74 | 22 | E0.13 | <0.2 | 4.3 |
| | | 9/9/2003 | 1415 | 76 | 99 | 28 | 0.3 | <0.2 | 6.1 |
| John River Tributary above Lagoons | 7 | 6/17/2003 | 1955 | 8 | 10 | 2.2 | <0.2 | <0.2 | 0.8 |
| | | 7/17/2003 | 1240 | 12 | 15 | 3.8 | E0.12 | <0.2 | 1.3 |
| | | 8/13/2003 | 1952 | 19 | 24 | 6.9 | <0.2 | <0.2 | 1.8 |
| | | 9/11/2003 | 1000 | 15 | 20 | 5 | <0.2 | <0.2 | 1.8 |

**Table 4.** Continued.

[all values in milligrams per liter (mg/L) unless otherwise noted; <, less than; E, estimated;]

| Station | Site ID | Date | Time | Potassium | Silica | Sodium | Sulfate | Dissolved Solids | Iron (µg/L) | Manganese (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|
| Contact Creek below Little Contact Creek | 1 | 6/18/2002 | 1710 | E0.10 | 1.2 | 0.2 | 4 | 59 | <10 | <2.0 |
| | | 7/17/2002 | 940 | 0.11 | 1.3 | 0.2 | 4.5 | 62 | <10 | <2.0 |
| | | 9/10/2002 | 1630 | 0.14 | 1.4 | 0.3 | 7.9 | 77 | <10 | <2.0 |
| Contact Creek at Main Street | 2 | 6/18/2002 | 2000 | 0.11 | 1.1 | 0.2 | 4.2 | 60 | <10 | <2.0 |
| | | 7/17/2002 | 1125 | 0.11 | 1.2 | 0.2 | 4.5 | 69 | <10 | <2.0 |
| | | 9/10/2002 | 1900 | 0.14 | 1.5 | 0.3 | 7.8 | 79 | <10 | <2.0 |
| | | 6/17/2003 | 1515 | E0.12 | 0.8 | 0.2 | | | 9 | 0.9 |
| | | 7/15/2003 | 1810 | 0.27 | 1.3 | 0.4 | 5.6 | 75 | E6 | E0.4 |
| | | 8/14/2003 | 1510 | <0.16 | 1.3 | 0.3 | 5.3 | 75 | <8 | 0.4 |
| | | 9/9/2003 | 1130 | E0.16 | 1.5 | 0.3 | 8.7 | 86 | E5 | 0.6 |
| Contact Creek above Giant Creek | 3 | 6/19/2002 | 1350 | 0.12 | 1.3 | 0.2 | 5.8 | 76 | <10 | <2.0 |
| | | 7/16/2002 | 1635 | 0.14 | 1.4 | 0.3 | 5.8 | 80 | <10 | <2.0 |
| | | 9/11/2002 | 1600 | 0.15 | 1.6 | 0.4 | 9.9 | 91 | <10 | E0.9 |
| Giant Creek | 4 | 6/19/2002 | 1155 | 0.25 | 1.7 | 0.8 | 26 | 86 | <10 | <2.0 |
| | | 7/16/2002 | 1445 | 0.32 | 1.9 | 1 | 28 | 98 | <10 | <2.0 |
| | | 9/11/2002 | 1430 | 0.32 | 2.1 | 1.1 | 37 | 117 | <10 | <2.0 |
| | | 5/14/2003 | 1030 | 1.9 | 5.4 | 4.2 | 100 | 274 | E8 | 15.1 |
| | | 7/16/2003 | 1225 | 0.42 | 2.0 | 1.1 | 27 | 99 | E5 | 1.3 |
| | | 9/9/2003 | 1630 | 0.29 | 2.1 | 1 | 36 | 114 | <8 | 1.2 |
| John River Tributary below Lagoons | 5 | 9/11/2002 | 1100 | 0.5 | 1.6 | 0.8 | 19 | 91 | <10 | <2.0 |
| | | 6/17/2003 | 2115 | 0.2 | 1.7 | 0.7 | 14 | 94 | E8 | <2.0 |
| | | 7/17/2003 | 1600 | 0.2 | 1.9 | 0.9 | 23 | 115 | <10 | E0.9 |
| | | 8/13/2003 | 2125 | 0.3 | 1.6 | 0.7 | 9.3 | 89 | E6 | 0.6 |
| | | 9/11/2003 | 1115 | 0.2 | 1.8 | 0.5 | 13 | 91 | E5 | 1.4 |
| | | | | 0.2 | 1.8 | 0.8 | 19 | 115 | <8 | 0.6 |
| John River below Giant Creek | 6 | 6/19/2002 | 1000 | | | | | | | |
| | | 7/16/2002 | 1130 | 0.2 | 1.0 | 0.1 | 1.0 | 11 | 222 | 2.1 |
| | | 9/11/2002 | 1230 | 0.2 | 1.3 | 0.3 | 1.3 | 29 | 206 | 3.8 |
| | | 7/16/2003 | 1513 | E0.08 | 1.9 | 0.1 | 1.6 | 40 | 128 | 1.8 |
| | | 8/14/2003 | 1145 | E0.10 | 2.2 | 0.1 | 2.3 | 37 | 113 | 10.4 |
| | | 9/9/2003 | 1415 | | | | | | | |
| | | | | 0.2 | 1.8 | 0.5 | 3.8 | 66 | 46 | E1.6 |
| John River Tributary above Lagoons | 7 | 6/17/2003 | 1955 | <0.2 | 1.2 | 0.4 | 2.2 | 67 | 57 | E0.3 |
| | | 7/17/2003 | 1240 | 0.3 | 1.4 | 0.6 | 2.6 | 65 | 100 | 0.7 |
| | | 8/13/2003 | 1952 | 0.2 | 2.2 | 0.3 | 2.4 | 65 | 83 | 0.7 |
| | | 9/11/2003 | 1000 | 0.2 | 2.0 | 0.3 | 2.9 | 59 | 31 | 1.2 |

from the weathering of soil and rock. Dissolved-cations content in natural waters include calcium, magnesium, sodium, and potassium. The major anions are usually sulfate, chloride, fluoride, nitrate, carbonate, and bicarbonate (Hem, 1985). Streams draining basins with rocks and soils containing insoluble minerals contain lower concentrations of dissolved solids. Concentrations of dissolved solids in samples from the surface-water sites and wells ranged from a low of 11 mg/L at John River Tributary above Lagoons to as high as 274 mg/L at Giant Creek. The low concentrations at John River Tributary above Lagoons are representative of basins containing shallow soils and rocks that are not easily dissolved or of water that has been in contact with more easily dissolved rocks for only a brief time.

Calcium and magnesium are common alkaline-earth metals that are essential elements in plant and animal nutrition and the major cations in most natural waters (Hem, 1985). Concentrations of these metals in samples collected for this study ranged from 2.2 (Site 7) to 43 mg/L (Site 4) for calcium and from 0.8 (Site 7) to 23 mg/L (Site 4) for magnesium (table 3 and 4). Sodium and potassium also are present in most natural waters, but usually in low concentrations in rivers. Sodium concentrations ranged from 0.1 (Site 6) to 4.2 mg/L (Site 4) and potassium concentrations ranged from values below detection limits of 0.16 to 1.9 mg/L (Site 4) (table 3 and 4).

Bicarbonate was the dominant anion in samples from all sites. Concentrations ranged from 10 mg/L at John River Tributary above Lagoons (table 4) to 172 mg/L at the village-supply well (Site 10, table 3). Sulfate was the next most abundant anion, with concentrations ranging from 1.0 (Site 6) to 100 mg/L (Site 4) (table 4). Silica concentrations ranged from 0.06 mg/L at observation-well 1 (Site 11, table 3) to 5.4 mg/L at Giant Creek (Site 4, table 4). Chloride concentrations ranged from less than the detection limit of 0.3 mg/L to 1.4 mg/L (observation-well 1), and fluoride concentrations were all equal to or less than the detection limit of 0.2 mg/L (tables 3 and 4).

Results of the analyses of the samples collected from streams and wells were plotted on a trilinear diagram such as that developed by Piper (1944). The trilinear diagram permits the chemical composition of multiple samples to be presented on a single graph, and facilitates classification of overall water chemistry. On the basis of samples collected during this study, both surface and ground water can be classified as a calcium bicarbonate type (fig. 11). The trilinear diagram further indicates that Giant Creek contributes a sulfate component to the John River.

## Nutrients and Dissolved Organic Carbon

Nitrogen is an important water-quality constituent as a component of the protoplasm in aquatic biota, and thus is an essential nutrient in lakes, streams, and rivers. In aquatic ecosystems, nitrogen commonly occurs in three ionic forms: nitrite, nitrate, and ammonium. Nitrite and nitrate are oxidized forms of inorganic nitrogen that make up most of the dissolved nitrogen in the well-oxygenated streams at Anaktuvuk Pass. Nitrate generally is more abundant than nitrite in natural waters because nitrite readily oxidizes to nitrate in oxygenated water. In the laboratory, ammonium is analyzed as ammonia; thus nitrogen concentrations are reported as total and dissolved ammonia plus organic nitrogen, dissolved ammonia, dissolved nitrite plus nitrate, and dissolved nitrite. The concentrations of total ammonia plus organic nitrogen represent the ammonium and organic-nitrogen compounds in solution and associated with colloidal material. The dissolved concentrations represent the ammonium or nitrite plus nitrate in solution and associated with material capable of passing through a 0.45-µm filter.

All concentrations of the various nitrogen forms were less than 1 mg/L (tables 3 and 5). Because of the toxicity of ammonia to freshwater-aquatic organisms, the U.S. Environmental Protection Agency (http://www.epa.gov/waterscience/standards/ nh3_rpt.pdf) suggests a limitation of 0.02 mg/L of ammonia in un-ionized form for waters to be suitable for fish propagation. Concentrations of ammonia (both ionized and un-ionized) detected in samples for this study were all below this level

Phosphorus is an element vital to all forms of aquatic biota because it is involved in the capture and transfer of chemical energy and it is an essential element in nucleic acids (Gaudy and Gaudy, 1988). It occurs as organically-bound phosphorus or as phosphate. Elevated concentrations of phosphorus in water are not considered toxic to human or aquatic life. Elevated concentrations, however, can stimulate the growth of algae in lakes and streams. Phosphorus concentrations are reported as total phosphorus and dissolved orthophosphate. Total phosphorus concentrations represent the phosphorus in solution, associated with colloidal material, and contained in or attached to biotic- and inorganic-particulate matter. Dissolved concentrations are determined from the filtrate that passes through a 0.45-µm pore filter. The orthophosphate ion is a significant form of phosphorus because it is directly available for metabolic use by aquatic biota. Concentrations of total phosphorus, dissolved phosphorus and orthophos-

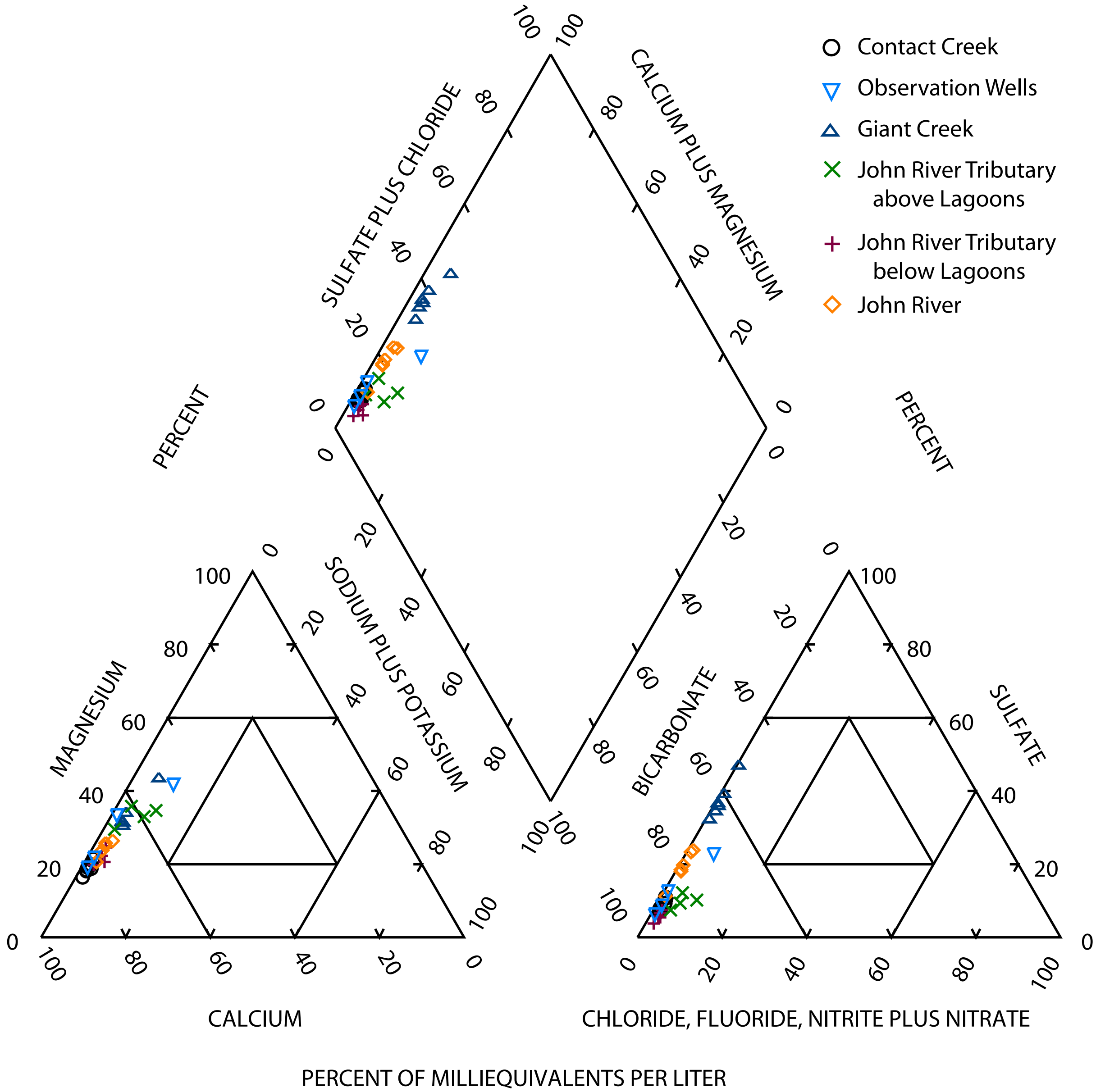



**Figure 11.** Trilinear diagram showing chemical composition of surface-water and ground-water samples collected from streams and wells at Anaktuvuk Pass.

phate were typically low in the samples collected for this study, with values near or below minimum detection levels in all samples with the exception of samples from observation-wells 3 and 4 in which total-phosphorus concentrations were 0.16 and 0.27 mg/L, respectively (table 3 and 5).

For the nutrients nitrogen and phosphorus, loads were calculated for the surface-water samples (table 5). Nutrient loads were calculated to assess the relative contribution to the John River from the treatment-plant effluent. Comparison of nitrogen and phosphorus loads from the John River Tributary with loads from the John River indicate that only a small part of the total nutrient load in the John River is contributed by the John River Tributary. (NOTE: The nitrogen load comprises the nitrate plus nitrite nitrogen, and the total ammonia plus organic nitrogen).

Dissolved organic carbon (DOC) is a major component of organic matter in aquatic ecosystems. DOC is defined as organic carbon in the filtrate (dissolved and colloidal phases) that has passed through a 0.45-µm filter. Generally, DOC is in greater abundance than particulate organic carbon, accounting for about 90 percent of the total organic carbon of most waters (Aiken and Cotsaris, 1995). For the surface-water sites on Contact Creek, Giant

**Table 5.** Concentrations and loads of nutrients and dissolved organic carbon in water samples collected from surface-water sites at Anaktuvuk Pass, Alaska

[all values in milligrams per liter (mg/L) unless otherwise noted; <, less than; E, estimated; --, no data]

| Station | Site ID | Date | Ammonia Nitrogen (Dissolved) | Nitrogen Ammonia+ Org (Dissolved) | Nitrogen Ammonia+ Org (Total) | Nitrogen Nitrite + Nitrate (Dissolved) | Nitrogen Nitrite (Dissolved) | Nitrogen (Total) | Nitrogen Load (kg/day) |
|---|---|---|---|---|---|---|---|---|---|
| Contact Creek below Little Contact Creek | 1 | 6/18/2002 | <0.015 | <0.10 | E0.08 | 0.029 | <0.002 | 0.11 | 16.0 |
| | | 7/17/2002 | <0.015 | <0.10 | E0.05 | 0.014 | <0.002 | 0.06 | 16.8 |
| | | 9/10/2002 | <0.015 | E0.08 | <0.10 | 0.054 | <0.002 | 0.15 | 23.4 |
| Contact Creek at Main Street | 2 | 6/18/2002 | <0.015 | <0.10 | E0.06 | 0.03 | <0.002 | 0.09 | 10.8 |
| | | 7/17/2002 | <0.015 | <0.10 | E0.06 | 0.013 | <0.002 | 0.073 | 16.6 |
| | | 9/10/2002 | <0.015 | E0.07 | E0.06 | 0.049 | <0.002 | 0.11 | 6.1 |
| | | 6/17/2003 | <0.015 | <0.10 | E0.05 | 0.042 | <0.002 | 0.092 | 48.0 |
| | | 7/15/2003 | <0.015 | <0.10 | E0.06 | E0.014 | <0.002 | 0.074 | 23.7 |
| | | 8/14/2003 | <0.015 | <0.10 | <0.10 | 0.035 | <0.002 | 0.14 | 95.6 |
| | | 9/9/2003 | <0.015 | <0.10 | <0.10 | <0.022 | <0.002 | 0.12 | 9.3 |
| Contact Creek above Giant Creek | 3 | 6/19/2002 | <0.015 | <0.10 | <0.10 | 0.063 | <0.002 | 0.16 | 14.0 |
| | | 7/16/2002 | <0.015 | <0.10 | <0.10 | 0.04 | <0.002 | 0.14 | 36.7 |
| | | 9/11/2002 | <0.015 | E0.08 | <0.10 | 0.07 | <0.002 | 0.17 | 17.5 |
| Giant Creek | 4 | 6/19/2002 | <0.015 | <0.10 | <0.10 | 0.052 | <0.002 | 0.15 | 34.6 |
| | | 7/16/2002 | <0.015 | <0.10 | <0.10 | 0.033 | <0.002 | 0.13 | 52.4 |
| | | 9/11/2002 | <0.015 | E0.06 | <0.06 | 0.044 | <0.002 | 0.10 | 34.9 |
| | | 5/14/2003 | <0.015 | 0.19 | 0.21 | E0.013 | 0.003 | 0.22 | 2.1 |
| | | 7/16/2003 | <0.015 | <0.10 | <0.10 | 0.027 | <0.002 | 0.13 | 31.7 |
| | | 9/9/2003 | <0.015 | <0.10 | <0.10 | 0.024 | <0.002 | 0.12 | 31.0 |
| John River Tributary below Lagoons | 5 | 9/11/2002 | <0.015 | <0.10 | <0.10 | 0.068 | <0.002 | 0.17 | 0.6 |
| | | 6/17/2003 | <0.015 | <0.10 | <0.10 | 0.068 | <0.002 | 0.17 | 1.2 |
| | | 7/17/2003 | <0.015 | E0.06 | E0.08 | 0.084 | <0.002 | 0.16 | 3.4 |
| | | 8/13/2003 | <0.015 | <0.10 | E0.06 | 0.065 | <0.002 | 0.13 | 5.6 |
| | | 9/11/2003 | <0.015 | <0.10 | 0.11 | 0.05 | <0.002 | 0.16 | 0.9 |
| John River below Giant Creek | 6 | 6/19/2002 | <0.015 | <0.10 | <0.10 | 0.066 | <0.002 | 0.17 | 70.4 |
| | | 7/16/2002 | <0.015 | 0.15 | 0.16 | <0.022 | <0.002 | 0.18 | 111.1 |
| | | 9/11/2002 | <0.015 | 0.16 | 0.23 | <0.022 | <0.002 | 0.25 | 71.9 |
| | | 7/16/2003 | <0.015 | 0.2 | 0.22 | <0.022 | <0.002 | 0.22 | 71.0 |
| | | 8/14/2003 | <0.015 | 0.14 | 0.19 | <0.022 | <0.002 | 0.21 | 235.1 |
| | | 9/9/2003 | <0.015 | 0.14 | 0.17 | 0.18 | <0.002 | 0.35 | 54.9 |
| John River Tributary above Lagoons | 7 | 6/17/2003 | <0.015 | 0.1 | 0.12 | 0.27 | <0.002 | 0.39 | 0.5 |
| | | 7/17/2003 | <0.015 | 0.13 | 0.18 | 0.26 | <0.002 | 0.44 | 1.7 |
| | | 8/13/2003 | <0.015 | 0.17 | 0.2 | 0.11 | <0.002 | 0.31 | 4.8 |
| | | 9/11/2003 | <0.015 | 0.16 | 0.21 | 0.09 | <0.002 | 0.3 | 0.9 |

**Table 5.** Continued.

[all values in milligrams per liter (mg/L) unless otherwise noted; <, less than; E, estimated; --, no data]

| Station | Site ID | Date | Phosphorus Dissolved | Phosphorus Ortho | Phosphorus Total | Phosphorus Load (kg/day) | Dissolved Organic Carbon |
|---|---|---|---|---|---|---|---|
| Contact Creek below Little Contact Creek | 1 | 6/18/2002 | E0.003 | <0.007 | 0.009 | 1.32 | 1 |
| | | 7/17/2002 | E0.003 | <0.007 | 0.006 | 1.57 | 1 |
| | | 9/10/2002 | <0.004 | <0.007 | 0.003 | 0.46 | 1.1 |
| Contact Creek at Main Street | 2 | 6/18/2002 | E0.003 | <0.007 | 0.006 | 0.72 | 0.9 |
| | | 7/17/2002 | E0.003 | <0.007 | 0.006 | 1.37 | 0.9 |
| | | 9/10/2002 | <0.004 | <0.007 | 0.003 | 0.17 | 1 |
| | | 6/17/2003 | E0.003 | <0.007 | 0.028 | 14.6 | 0.8 |
| | | 7/15/2003 | E0.002 | <0.007 | 0.003 | 0.96 | 1.1 |
| | | 8/14/2003 | <0.004 | <0.007 | 0.009 | 6.37 | 1.1 |
| | | 9/9/2003 | <0.004 | <0.007 | 0.003 | 0.23 | 1.2 |
| Contact Creek above Giant Creek | 3 | 6/19/2002 | <0.004 | <0.007 | 0.006 | 0.51 | 0.7 |
| | | 7/16/2002 | <0.004 | <0.007 | 0.006 | 1.57 | 0.9 |
| | | 9/11/2002 | <0.004 | <0.007 | 0.003 | 0.31 | 0.8 |
| Giant Creek | 4 | 6/19/2002 | <0.004 | <0.007 | 0.008 | 1.82 | 0.7 |
| | | 7/16/2002 | <0.004 | <0.007 | 0.004 | 1.58 | 0.8 |
| | | 9/11/2002 | <0.004 | <0.007 | 0.002 | 0.67 | 1 |
| | | 5/14/2003 | 0.006 | <0.007 | 0.014 | 0.13 | 4.8 |
| | | 7/16/2003 | <0.004 | <0.007 | 0.002 | 0.50 | 0.8 |
| | | 9/9/2003 | <0.004 | <0.007 | 0.004 | 1.0 | 1 |
| John River Tributary below Lagoons | 5 | 9/11/2002 | <0.004 | <0.007 | 0.003 | 0.01 | 4.7 |
| | | 6/17/2003 | <0.004 | <0.007 | 0.005 | 0.02 | 3 |
| | | 7/17/2003 | <0.004 | <0.007 | 0.003 | 0.02 | 4.4 |
| | | 8/13/2003 | 0.005 | <0.007 | 0.004 | 0.07 | 6.3 |
| | | 9/11/2003 | <0.004 | <0.007 | 0.009 | 0.03 | 4.9 |
| John River below Giant Creek | 6 | 6/19/2002 | <0.004 | <0.007 | 0.01 | 4.19 | 0.7 |
| | | 7/16/2002 | E0.003 | <0.007 | 0.004 | 2.65 | 0.9 |
| | | 9/11/2002 | <0.004 | <0.007 | 0.002 | 0.88 | 1.1 |
| | | 7/16/2003 | 0.009 | <0.007 | 0.004 | 2.27 | 1.1 |
| | | 8/14/2003 | E0.003 | <0.007 | 0.056 | 82.3 | 1.3 |
| | | 9/9/2003 | <0.004 | <0.007 | 0.003 | 0.99 | 1.2 |
| John River Tributary above Lagoons | 7 | 6/17/2003 | E0.003 | <0.007 | 0.006 | 0.02 | 4.1 |
| | | 7/17/2003 | E0.004 | <0.007 | 0.004 | 0.03 | 5.5 |
| | | 8/13/2003 | E0.004 | <0.007 | 0.004 | 0.09 | 6.9 |
| | | 9/11/2003 | E0.002 | <0.007 | 0.004 | 0.02 | 5.5 |

Creek, and the John River and the wells, DOC concentrations were less than or equal to 1.3 mg/L, with the exception of the May 2003 sample from Giant Creek, in which the DOC concentration was 4.8 mg/L (table 5). The consistently highest concentrations of DOC were detected at the two surface-water sites on the John River Tributary. Concentrations of DOC at these two sites ranged from 3 to 6.9 mg/L, with slightly lower concentrations at John River Tributary below Lagoons.

# Ground-Water/Surface-Water Interactions along the headwaters of the John River

## Simulation of the Hydrologic System

Throughout the summer and early fall, the ground-water and surface-water systems beneath the flood plain of the John River headwaters are hydraulically connected, as suggested by rising ground-water levels after streamflow begins (fig. 8). Comparison of the discharge measurements made during 2002–03 indicated that Contact Creek from the junction with Little Contact Creek downstream to Contact Creek at Main Street (fig. 12) lost streamflow to the ground-water system. At and below the headwaters, the discharge measurements indicated streamflow was gained from ground water discharging into the stream. The many springs in this area (fig. 3) also indicate the discharge of ground water to the surface. The reach between Contact Creek at Main Street and the headwaters (fig. 12), however, progressively changes upgradient from a losing reach to a gaining reach.

Given the complex hydrogeology of the study area, further efforts were focused on examining the ground-water/surface-water interactions of the John River at Anaktuvuk Pass. A numerical model, which can simulate and incorporate the features, flow properties, and hydraulic processes of the ground- and surface-water flow systems, provided a better understanding of the interaction between those systems.

## Model Specifications

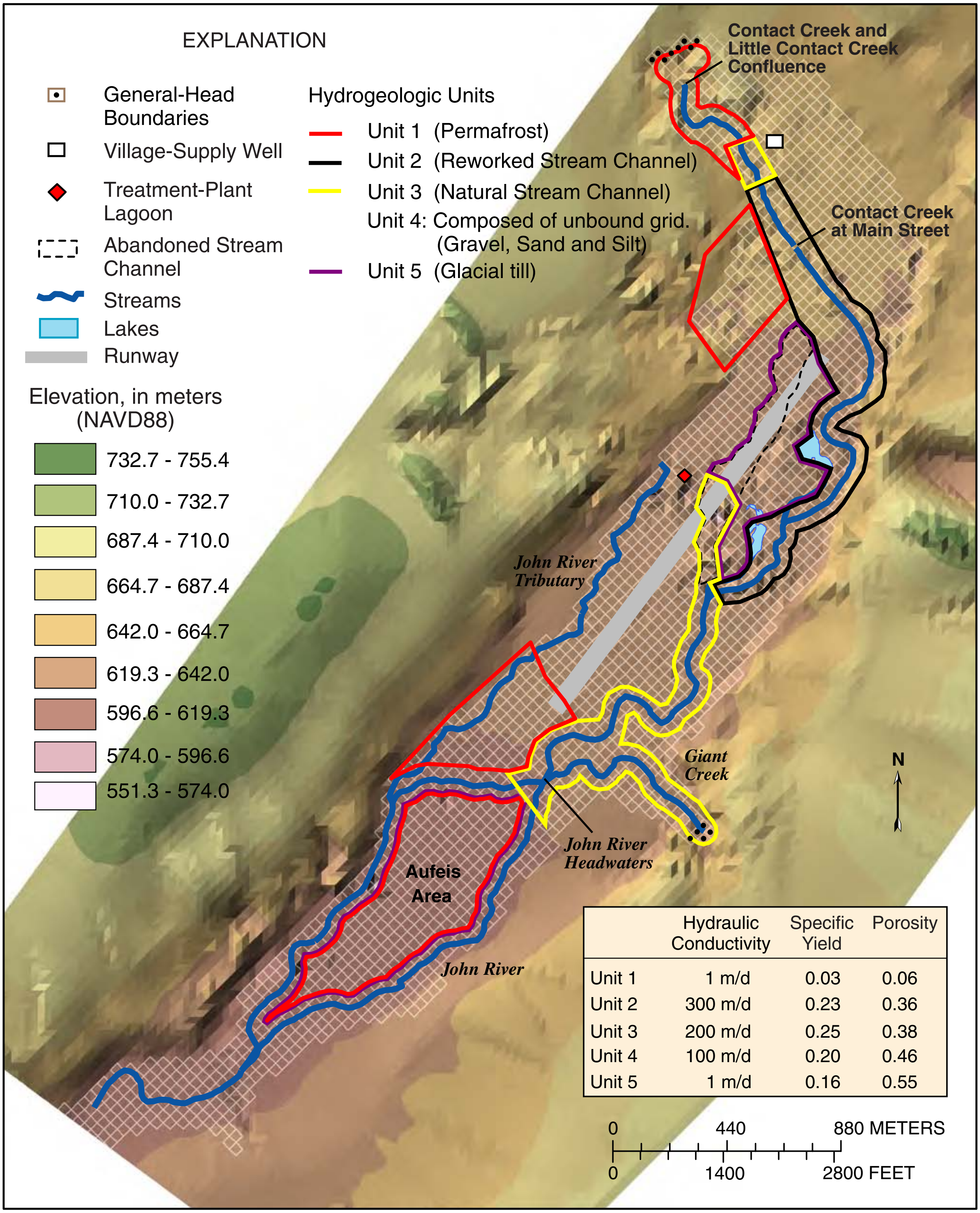
Numerical models of ground-water flow, such as MODFLOW-2000 (Harbaugh and others, 2000) used in this study, are based on partial-differential equations that are developed from physical principles and solved using computers. Solutions to the equations require defining and identifying 1) boundary conditions, 2) the amount of water flowing into and out of the systems (water balance or budget), and 3) the distribution of hydraulic properties.

The aquifer system of the John River at Anaktuvuk Pass was overlain by a rectangular grid and extended in the vertical (depth) to form a single layer of three-dimensional blocks or cells (fig. 12). The grid consisted of 2,378 active cells (99 rows and 159 columns), each oriented 55-degrees north-northeast and representing 1,225 square meters ($m^2$) but varying in thickness (fig. 13). Each model cell represents a block of earth material within the aquifer system, which may contain one or more types of materials but with uniform hydraulic properties within a model cell. The extent of the modeled area was selected to include or nearly coincide with interpreted natural-flow boundaries. All ground-water and surface-water flow occurs in one model layer, which represents an unconfined aquifer. The Layer Property Flow Package was used for the model, which assigns hydraulic properties to the center of each model cell independent of cell dimension (Harbaugh and others, 2000). The hydraulic properties used in the model were based on field observations, Porter's (1966) surficial geologic map, and well logs and geotechnical and geothermal reports by Shiltec Alaska, Ltd. (1996) and Duane Miller and Associates (1995).

A major source of error in ground-water flow simulations is insufficient knowledge of the true distribution of ground-water fluxes and hydraulic-property values assigned as parameters in the model. Given the set of observations and fluxes, once the boundaries of the modeled system are defined, simulation errors are minimized by adjusting the hydraulic-parameter values during the model-calibration phase. For this study, the calculated errors of interest were the residuals between observed and simulated ground-water levels (heads) and observed and simulated streamflow values (discharge). Because of uncertainties in model boundaries, the sparsity of observed heads and fluxes to constrain the calibration, and the nonunique set of hydraulic parameters that result from minimizing the residuals, there is a high degree of uncertainty in the model.

## Calibration of the Model

Calibration is a procedure by which differences between observed and simulated values of hydrologic factors are mathematically minimized so that the model will replicate as closely as possible the behavior of the aquifer during steady-state and (or) transient conditions. This is accomplished by adjusting the input data such as aquifer parameters, hydraulic stresses, and by adjusting model-boundary conditions. Because of the many interrelated factors affecting ground-water flow, calibration is a subjective procedure. The degree of allowable adjustment of any parameter is generally determined by the modeler and is directly related to the uncertainty of its value. For example, because withdrawal rates from the village-supply well and discharge of treatment-plant effluent into the aquifer at Anaktuvuk Pass are well documented, those values




| | Hydraulic Conductivity | Specific Yield | Porosity |
|---|---|---|---|
| Unit 1 | 1 m/d | 0.03 | 0.06 |
| Unit 2 | 300 m/d | 0.23 | 0.36 |
| Unit 3 | 200 m/d | 0.25 | 0.38 |
| Unit 4 | 100 m/d | 0.20 | 0.46 |
| Unit 5 | 1 m/d | 0.16 | 0.55 |

**Figure 12.** Grid layout of the numerical model of the John River at Anaktuvuk Pass.

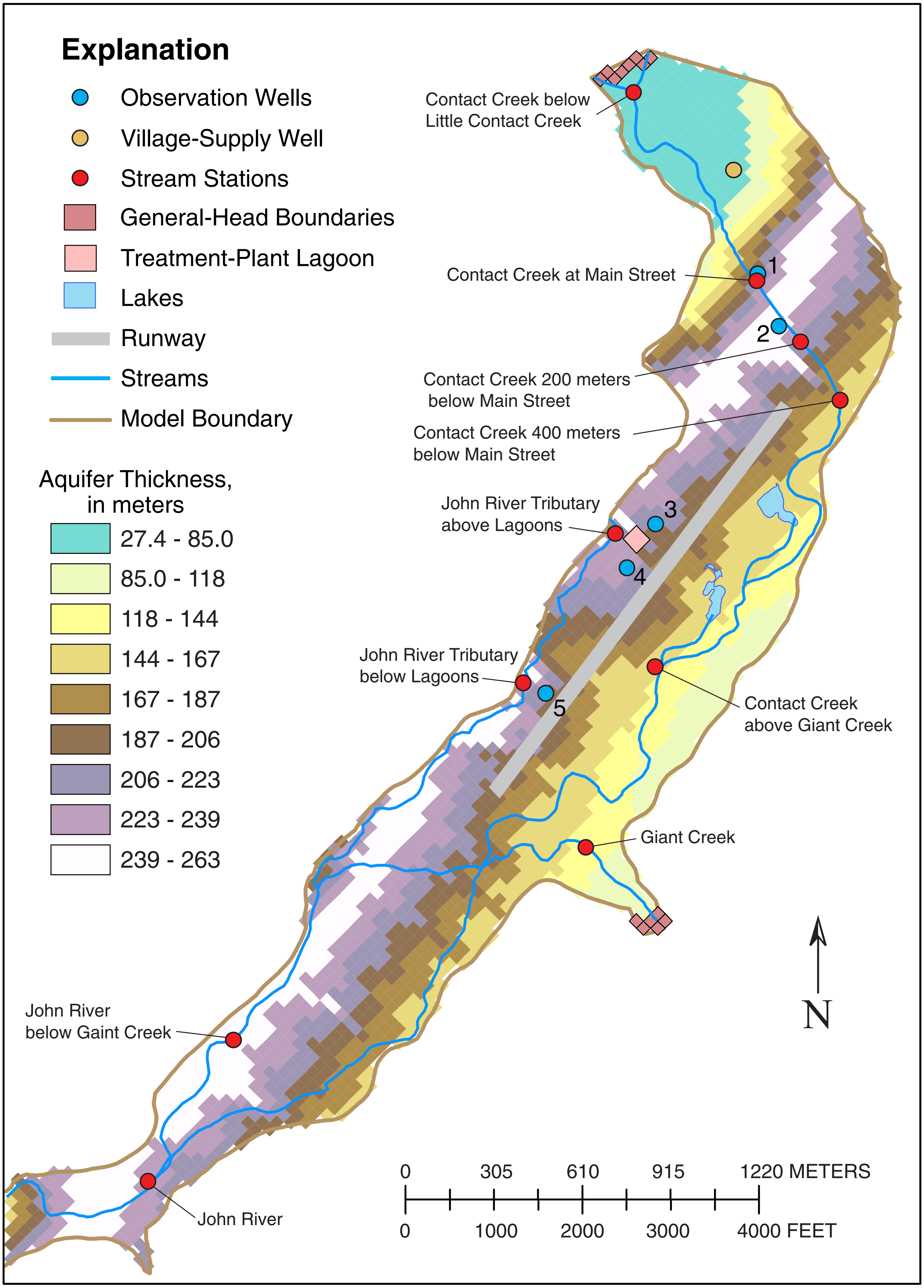



**Figure 13.** Unconfined-aquifer thickness of the numerical model of the John River at Anaktuvuk Pass.

were not adjusted. Hydraulic conductivity, specific yield, and porosity, however, generally are imprecisely known because lithologic variation usually is not well defined and because the methods by which they are determined are subject to many limitations.

In this study, the goal of calibration was to determine the most reasonable hydraulic-parameter values and recharge rates from sources outside the study area that minimized simulated ground-water-head errors (less than 0.5 m) and stream-discharge errors (+/- 10 percent). For calibration, the observed-heads and-discharge values were not weighted, therefore, each observation was deemed equally important. Acceptable simulated ground-water-head errors were approximated on the basis of water-level variations observed in wells proximal to streams throughout each field-visit period and simulated-streamflow errors were based on errors assigned for the quality of the discharge measurement.

Model calibration incorporated steady-state and transient conditions; however, the Lake Package (Merritt and Konikow, 2000) did not allow for both steady-state and transient simulations to occur in a single simulation. Calibration data used for the steady-state model included the slope of the water table in early May between observation-wells 3 and 5 (Shiltec Alaska, Ltd., 1996), which were the only data available for winter conditions. Calibration data used in the transient simulations included 25 discharge measurements made during 2002–03 (table 6). Calibration discharge measurements were taken during 2002 at two locations on Contact Creek and one on the John River. During 2003, additional locations for discharge measurements included one along Contact Creek and two on the John River Tributary. Calibration data for the transient simulation included continuous ground-water levels collected at observation-wells 2, 3, and 5 during 1994–95 by Shiltec Alaska, Ltd. (1996) and 16 water levels collected in 2003 at observation-wells 1, 2, 3, 4, and 5 by the USGS (fig. 3 and 13, table 1 and 6).

Simulation was begun with the system in a steady state, under which constant recharge equals constant discharge, no water taken into or released from storage, and ground-water heads do not vary over time. Because of discrepancies between the observation-well elevations reported by Shiltec Alaska, Ltd. (1996) and the USGS, owing to different vertical datums used for land-surveying, the resulting steady-state heads represent as closely as possible the slope of the winter water table observed between observation-wells 3 and 5 (fig. 14) by Shiltec Alaska, Ltd. (1996). The only stresses applied during the steady-state simulation were recharge from sources outside the study area, the discharge of wastewater into the treatment-plant lagoon, and pumping from the village-supply well. Hydraulic properties were adjusted to obtain the best fit between the observed and simulated ground-water heads. The purpose of the steady-state simulation was to obtain reasonable initial conditions and hydraulic parameters for the transient-model simulation. Once the steady-state conditions of the model reasonably matched the steady-state slope of the water table as observed between observation-wells 3 and 5 by Shiltec Alaska, Ltd. (1996), the values used for hydraulic properties were considered to be acceptable.

A number of transient-model simulations were then made to fully calibrate the model. The fully-calibrated-transient simulation incorporated as initial values all boundary conditions, hydraulic parameters, and heads from the steady-state simulation. During the transient-model calibration, flow into stream segments at the model boundary (Contact Creek below Little Contact Creek, John River Tributary above Lagoon, and Giant Creek) remained fixed (fig. 12 and 13, table 1). Since the quantity of inflow or recharge from the sources outside the model domain were unknown, constant-head elevations and hydraulic conductivity for the general-head boundaries placed at Contact and Giant creeks (fig. 12 and 13) were adjusted during calibration to simulate trends in ground-water levels as observed from late September to early May, as shown in the three 1994–95 well hydrographs (fig. 14) (Shiltec Alaska, Ltd., 1996).

## Boundary and Initial Conditions

Boundary conditions are physical features that 1) correspond to identifiable hydrogeologic features at which some characteristics of ground water can be described, 2) may be static or vary over time, and 3) define the amount of water entering or leaving the system at that location or grid cell. The land surface was considered to be the upper boundary of the unconfined aquifer, or model layer, and was determined from contour maps (Shiltec Alaska, Ltd., 1996 and Duane Miller and Associates, 1995) and GPS RTK points (fig. 12). The bottom of the unconfined aquifer is a no-flow boundary representing a U-shaped bedrock valley as interpreted from Porter's (1966) geologic map with the thickness of the aquifer (fig. 13) varying throughout the model domain. A lateral no-flow boundary, the Model Boundary as shown in figure 13, separates the more permeable alluvium from the much-less permeable

**Table 6**. Observed and simulated stream-discharge (cubic meters per second) and ground-water elevations (meters above NAVD88)

| Stream-Discharge Station | Date | Observed Discharge | Simulated Discharge | Error |
|---|---|---|---|---|
| Contact Creek at Main Street | 6/18/2002 | 1.4 | 1.3 | -0.1 |
| Contact Creek above Giant Creek | 6/19/2002 | 0.99 | 0.73 | -0.26 |
| Contact Creek at Main Street | 7/17/2002 | 2.6 | 2.6 | 0 |
| Contact Creek above Giant Creek | 7/16/2002 | 3.0 | 2.1 | -0.9 |
| Contact Creek at Main Street | 9/10/2002 | 0.65 | 1.4 | 0.75 |
| Contact Creek above Giant Creek | 9/11/2002 | 1.2 | 0.99 | -0.21 |
| Contact Creek at Main Street | 6/17/2003 | 6.0 | 4.3 | -1.7 |
| John River tributary below Lagoons | 6/17/2003 | 0.04 | 0.02 | -0.02 |
| Contact Creek at Main Street | 6/19/2003 | 2.1 | 2.0 | -0.11 |
| Contact Creek 200 m below Main Street | 6/19/2003 | 1.4 | 1.4 | 0 |
| Contact Creek 400 m below Main Street | 6/19/2003 | 2.8 | 1.5 | -1.3 |
| Contact Creek at Main Street | 7/15/2003 | 3.7 | 4.5 | 0.8 |
| Contact Creek 200 m below Main Street | 7/15/2003 | 3.7 | 3.8 | 0.1 |
| Contact Creek 400 m below Main Street | 7/15/2003 | 4.3 | 4.0 | -0.3 |
| John River below Giant Creek | 7/16/2003 | 7.7 | 7.7 | 0 |
| John River tributary below Lagoons | 7/17/2003 | 0.06 | 0.07 | 0.01 |
| Contact Creek 400 m below Main Street | 8/14/2003 | 8.2 | 7.2 | -1.0 |
| Contact Creek above Giant Creek | 8/14/2003 | 7.9 | 7.2 | -0.7 |
| John River tributary below Lagoons | 8/13/2003 | 0.21 | 0.24 | 0.03 |
| Contact Creek at Main Street | 9/09/2003 | 0.89 | 0.68 | -0.21 |
| Contact Creek 200 m below Main Street | 9/09/2003 | 0.79 | 0.05 | -0.73 |
| Contact Creek 400 m below Main Street | 9/09/2003 | 0.76 | 0.21 | -0.55 |
| Contact Creek above Giant Creek | 9/09/2003 | 0.95 | 0.37 | -0.58 |
| John River below Giant Creek | 9/09/2003 | 3.8 | 4.2 | 0.4 |
| John River tributary below Lagoons | 9/11/2003 | 0.04 | 0.04 | 0 |
| **Observation Well** | **Date** | **Observed Water Elevation** | **Observed Water Elevation** | **Error** |
| 1 | 6/19/2003 | 638.85 | 641.88 | 3.03 |
| 2 | 6/19/2003 | 638.82 | 640.92 | 2.10 |
| 5 | 6/19/2003 | 624.64 | 625.00 | 0.36 |
| 1 | 7/17/2003 | 641.61 | 641.94 | 0.33 |
| 2 | 7/18/2003 | 640.59 | 641.00 | 0.41 |
| 3 | 7/18/2003 | 628.47 | 628.93 | 0.46 |
| 4 | 7/18/2003 | 627.51 | 627.92 | 0.41 |
| 1 | 8/13/2003 | 641.58 | 641.97 | 0.39 |
| 5 | 8/13/2003 | 624.79 | 625.07 | 0.28 |
| 2 | 8/15/2003 | 640.65 | 641.04 | 0.39 |
| 3 | 8/15/2003 | 629.13 | 628.92 | -0.21 |
| 4 | 8/15/2003 | 628.06 | 627.94 | -0.12 |
| 1 | 9/10/2003 | 641.02 | 641.84 | 0.82 |
| 2 | 9/10/2003 | 640.13 | 640.88 | 0.75 |
| 3 | 9/10/2003 | 628.44 | 628.85 | 0.41 |
| 4 | 9/10/2003 | 627.50 | 627.85 | 0.36 |

glacial-till benches. Although few geologic materials are completely impermeable, negligible flow occurs through a layer of material when the hydraulic conductivity of an adjacent layer is several orders of magnitude higher.

Head-dependent boundaries occur at the creeks and lakes (fig. 12 and 13). The vertical direction of flow between the aquifer and these surface-water bodies depends on the relative difference of ground-water heads and stream or lake stage. Surface-water bodies lose water to an aquifer when stage is higher than ground-water heads. Conversely, surface-water bodies gain water from an aquifer when ground-water heads are higher than surface-water stage.

General-head boundaries were used to simulate the seepage of ground water from sources outside the study area that recharge the alluvial aquifer (fig. 13). Constant-flux boundaries were assigned to cells that represent locations of constant withdrawal and recharge: the village-supply well and the discharge of treatment-plant effluent into the aquifer at the treatment-plant lagoon, respectively (fig. 13).

## Aquifer Recharge

For the ground-water model of the John River, recharge to the aquifer was from sources outside the study area and from streamflow. In many ground-water models, precipitation is considered a principal means of recharge. However, extensive permafrost in the study area inhibits direct infiltration of rain and snowmelt to the aquifer. Additionally, frozen soils occur throughout the flood plain and inhibit direct infiltration of most spring and fall precipitation. Generally, precipitation during these times flows as runoff to nearby streams. In addition, the study area is considered arid and has a water-balance deficit (potential evaporation and transpiration is greater than precipitation) (Patrick and Black, 1968). For these reasons, precipitation was not simulated in the ground-water model.

The type and location of the boundary conditions and the rates of recharge to the aquifer from sources outside the study area were not precisely known. These sources are assumed to provide all the recharge necessary to maintain ground-water heads from mid winter to late spring. Water from these sources likely originates from unfrozen sediments below permafrost and (or) from bedrock. To represent these sources in the model they were simulated using general-head boundaries where Contact and Giant Creek enter the flood plain. Simulated recharge rates from the Contact and Giant Creek sources varied from 0.21 to 0.36 $m^3/s$ (4.9 to 8.2 million gallons per day (Mgal/d)) from October thru mid May and from 0.19 to 0.20 $m^3/s$ (4.3 to 4.5 Mgal/d) from mid May thru September. The simulated Contact Creek general-head boundary accounted for 86 percent of the total recharge from external sources.

The general-head boundary was assigned to eight grid cells for the Contact Creek source and six cells for the Giant Creek source (fig. 12 and 13). The altitude of both constant heads was set at least 2 m below land surface at 660 and 626 m, respectively, above NAVD88. Hydraulic conductivity values for the Contact Creek general-head boundary cells ranged from 95 to 320 meters per day (m/d) and from 3 to 10 m/d for the Giant Creek boundary cells. These values were based on a cell area of 1,225 $m^2$ and an average boundary length within a cell of 23 m. The total lengths of the Contact Creek and Giant Creek boundaries were 184 and 136 m, respectively.

In the study area, the rapid rise and fall of ground-water heads are correlated directly to recharge rates from Contact Creek, Giant Creek, and the John River Tributary streamflow, which provides the primary source of summer recharge to the aquifer. Thus determining starting and ending streamflow dates was critical for constructing a representative ground-water flow model. As shown in the 1994–95 well hydrographs (fig. 14), the rise of ground-water heads from winter to summer may take approximately 1 month (from mid May to mid June), whereas the drop from summer to winter is longer (from the end of August to the end of January) but begins immediately after the cessation of streamflow.

Starting and ending streamflow dates for the John River tributaries were determined on the basis of observations made within the study area and from flow data from the streamgaging station on the Sagavanirktok River Tributary (fig. 7). Field visits report that flow begins first and ends last in Giant Creek, but the exact dates were unknown. Flow likely starts in Contact Creek and the John River Tributary 1–2 weeks after flow begins in Giant Creek and ends 1–2 weeks before flow ends in Giant Creek.

Flow in the John River tributaries can vary considerably (table 6) and changes in ground-water heads coincide with these variations (fig. 14). To simulate these changes, the length determined for the model stress periods representing spring through fall was based on the time between measurements made during each field visit. Several discharge measurements needed for particular stress periods, however, were not available but were estimated by correlation of existing Contact Creek data with daily streamflow for the Sagavanirktok River Tributary (fig. 7). In June and July, discharge in Contact Creek was esti-

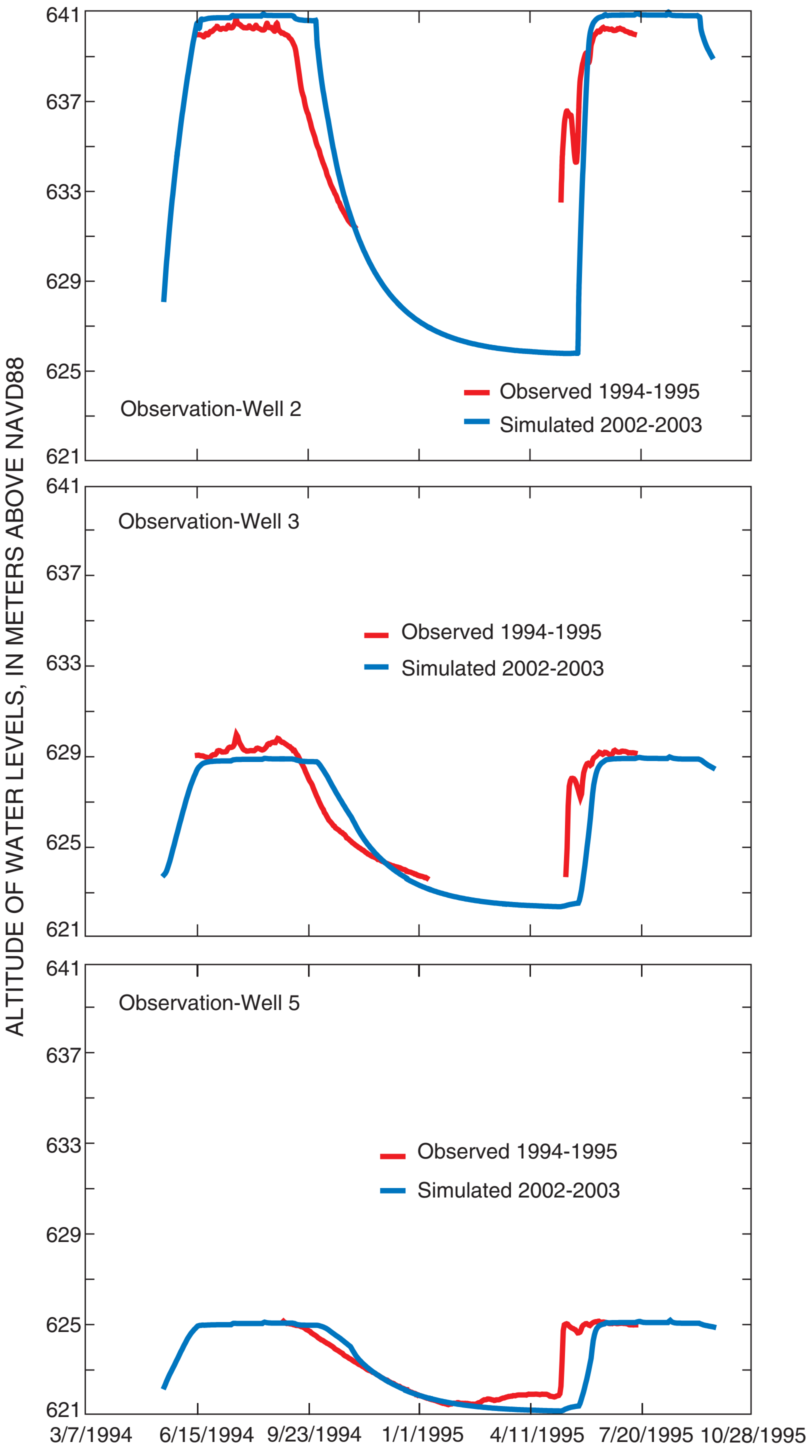



**Figure 14.** Simulated versus observed water levels for observation-wells 2, 3, and 5.

mated to be approximately twice that of the Sagavanirktok River Tributary. Discharges for the remaining periods of streamflow were estimated to be equal between the two streams. During 2002, flow in the John River Tributary was equal to that in 2003 and assumed to increase progressively from June to August and then similarly decrease toward September.

More streamflow and thus more recharge to the aquifer and, likely, higher ground-water heads occurred in 2002–03 than in 1994–95, but these differences were difficult to both qualify and quantify. The largest known errors contributing to differences between the observed and simulated hydrographs (fig. 14) were due to land-survey datum differences and alterations to the well casings. Due to lost or destroyed benchmarks, no well-defined points existed at the time of the 2003 survey to tie the two surveys together. Several well casings were altered by man and (or) heaved by frost. A close approximation showing the potential difference between land-survey datums is the reported NAVD88 elevation for observation-well 2 by the USGS and Shiltec Alaska, Ltd. (1996). This well appeared unaltered. Shiltac Alaska, Ltd. (1996) reported the top of the casing at 645.5 m above NAVD88, whereas the USGS reported an elevation of 644.5 m above NAVD88. Because of inconsistent differences in elevations at other points and suspect alterations of the well casings, no attempt was made to reconcile any differences between the reported ground-water heads in 1994–95 and in 2002–03.

The cessation of streamflow generally results in steadily declining ground-water heads throughout the fall and winter months. The sustained and slight increase in winter to spring ground-water heads measured in observation-well 5 (fig. 14) could be due to the rising altitude of the discharge locations of the headwater springs caused by aufeis formation and freezing soils.

## Hydraulic Properties

Hydraulic conductivity, specific yield, and porosity are hydraulic properties that describe an aquifer's ability to transmit and store ground water. Lithologic data for wells in the study area and various references were used to estimate these properties throughout the modeled area. Knowledge of local geohydrologic conditions, well-log information, and geologic reports were used to make initial estimates of aquifer hydraulic properties. Final values were determined by minimizing the residuals between the observed and simulated heads and stream discharge through the process of model calibration.

To simplify the hydrogeology of the John River aquifer, the model used five distinct hydrogeologic units each having different hydraulic properties (fig 12). Unit 1 has hydraulic properties that are influenced by permafrost. Unit 2 encloses the reworked stream channel and consists of coarse gravel and sand. Unit 3 encloses the natural stream channels above the headwater area and has more fines than the reworked stream channels. Unit 4 consists of gravel with sand and silt and Unit 5 represents areas of glacial till dominated by cobbles and (or) gravel.

Parameter values for hydraulic conductivity, specific yield, and porosity were distributed on the basis of streamflow- and flood-plain-sediment deposition principles and observations. Shifting stream velocities result in a systematic sorting of sediments in the downcurrent direction where larger particles are deposited upcurrent and finer particles are deposited downcurrent (Friedman and Sanders, 1978). Another factor that influenced the choice of parameter values is that freezing of interstitial-pore water can reduce soil hydraulic conductivity by two orders of magnitude (Liang and others, 1983). While maintaining the principle of streamflow- and flood-plain-sediment deposition, the properties of frozen soils, and accounting for human modifications to the terrain, model calibration resulted in final values of horizontal hydraulic conductivity of 1 m/d in Units 1 and 5, 300 m/d in Unit 2, 200 m/d in Unit 3, and 100 m/d in Unit 4 (fig. 12).

To simulate the interactions of surface-water with the John River aquifer an estimate of the vertical hydraulic conductivity of the stream-and lake-bed material was required. A vertical hydraulic conductivity of stream-and lake-bed material of one order of magnitude lower than horizontal hydraulic conductivity of the underlying aquifer was specified in the model.

Values for specific yield vary due to sediment composition and generally range from 0.03 for clay to 0.44 for peat (Zheng and Bennett, 2002). Specific-yield values assigned to each hydrogeologic unit in the model ranged from 0.03 to 0.25. For this study, permafrost was considered to have a similar specific-yield value as clay because the storage capacity significantly decreases as interstitial pore-ice forms (Woo and others, 1983).

A required input parameter for the particle-tracking package MODPATH (Pollock, 1994) is effective porosity. Total porosity was used as a proxy for effective porosity owing to lack of data and is a characteristic of the soil or rock matrix (primary porosity) and (or) a characteristic such as fracturing of a formation (secondary porosity). Total porosity defines the ratio of the volume of void spaces (pores) to the volume of sediment. Porosity values range between 0.24 and 0.60 for unconsolidated materials and between 0 and 0.45 for bedrock (Zheng and Bennett, 2002). For the John River ground-water-flow model, porosity values were assigned at 0.06 for permafrost to 0.55, a value higher than fine sand but slightly lower than silt or clay (Zheng and Bennett, 2002). For this study, permafrost was considered to have low porosity with values close to bedrock due to the presence of interstitial pore ice.

The Stream Package (Prudic, 1989) for MODFLOW-2000 requires values for streambed thickness, width, and depth, whereas the Lake Package (Merritt and Konikow, 2000) requires only a value for lakebed thickness. Modeled streambed thickness varied from 1 m at the reworked section below Main Street to 10 m in the natural channels. The thicknesses of the lakebeds and the beds of the streams exiting the lakes were set at 10 m. The values used for stream depth and width were held constant throughout the simulation and were based on values obtained during the largest discharge measurements made at each location.

## Results of the Simulations

On the basis of observed and simulated stream discharge and ground-water heads (fig. 15 and 16, table 6) and the selected distribution of hydraulic-parameter values (fig. 12), the model reasonably represents ground-water-flow conditions for the John River aquifer. Simulations were produced to represent ground-water-flow conditions from low-winter to high-summer ground-water heads and during the two contrasting but somewhat steady-states in mid winter and mid summer (fig. 17). At low-winter heads (fig. 18), ground-water flow follows the general slope of the flood plain and parallels the streams. In areas where streamflow is lost to the aquifer and as ground-water heads rise owing to increasing amounts of stream-water seepage into the aquifer, ground-water flows away from the streams and toward the boundary of the flood plain (fig. 19 and 20). The simulation suggests that as ground-water heads rise during the spring owing to stream-flow recharge, the changes in flow from winter (fig. 18) to summer (fig 19) are most noticeable in the northeastern part of the flood plain and the upper reach of Contact Creek. As simulated ground-water heads reach summer levels (fig. 20), the hydraulic gradient steepens,

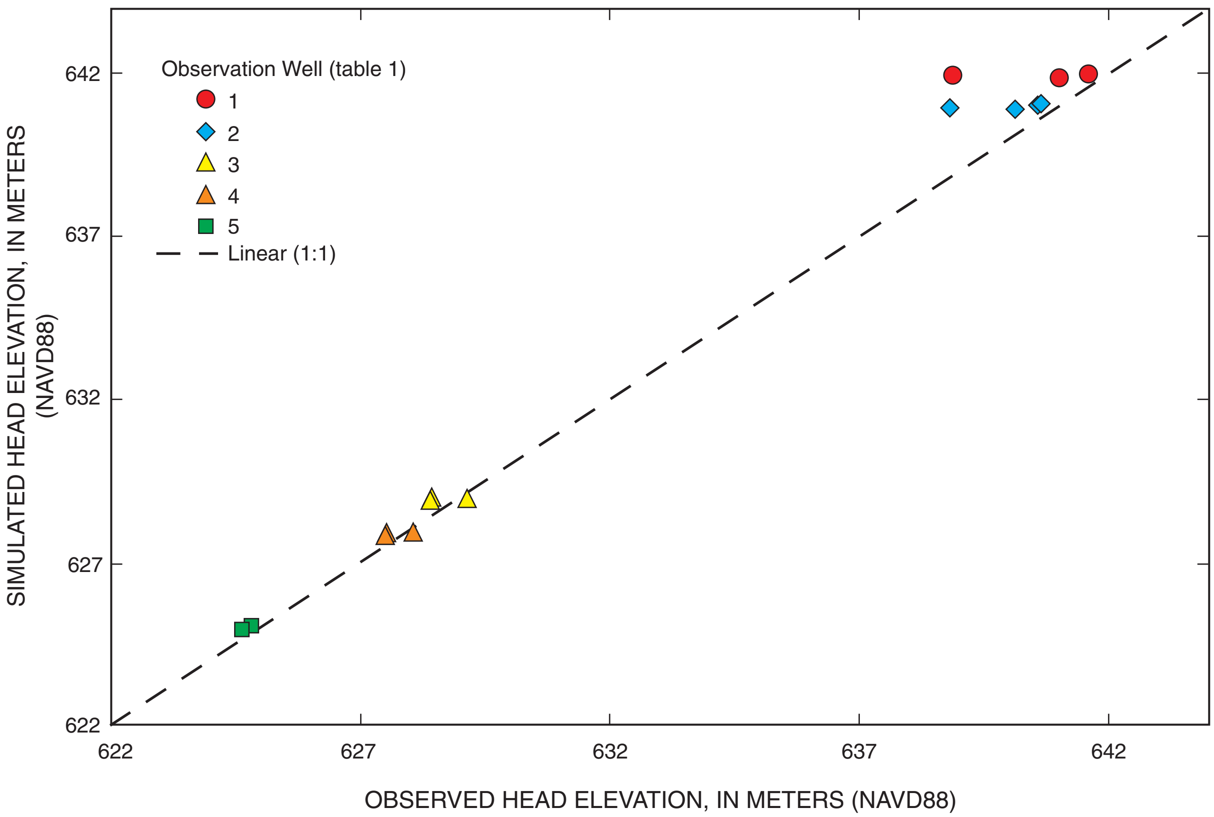



**Figure 15.** Comparison between observed and simulated ground-water heads.

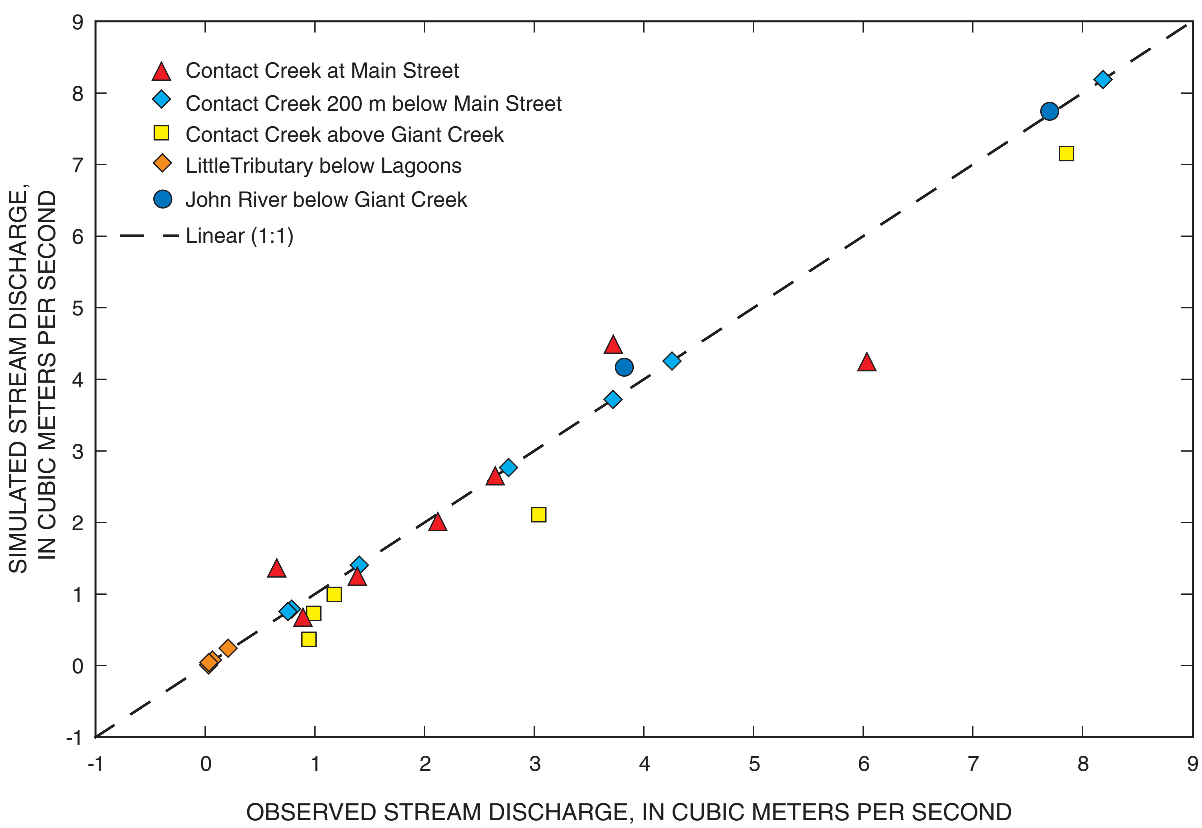



**Figure 16.** Comparison between observed and simulated stream discharge.

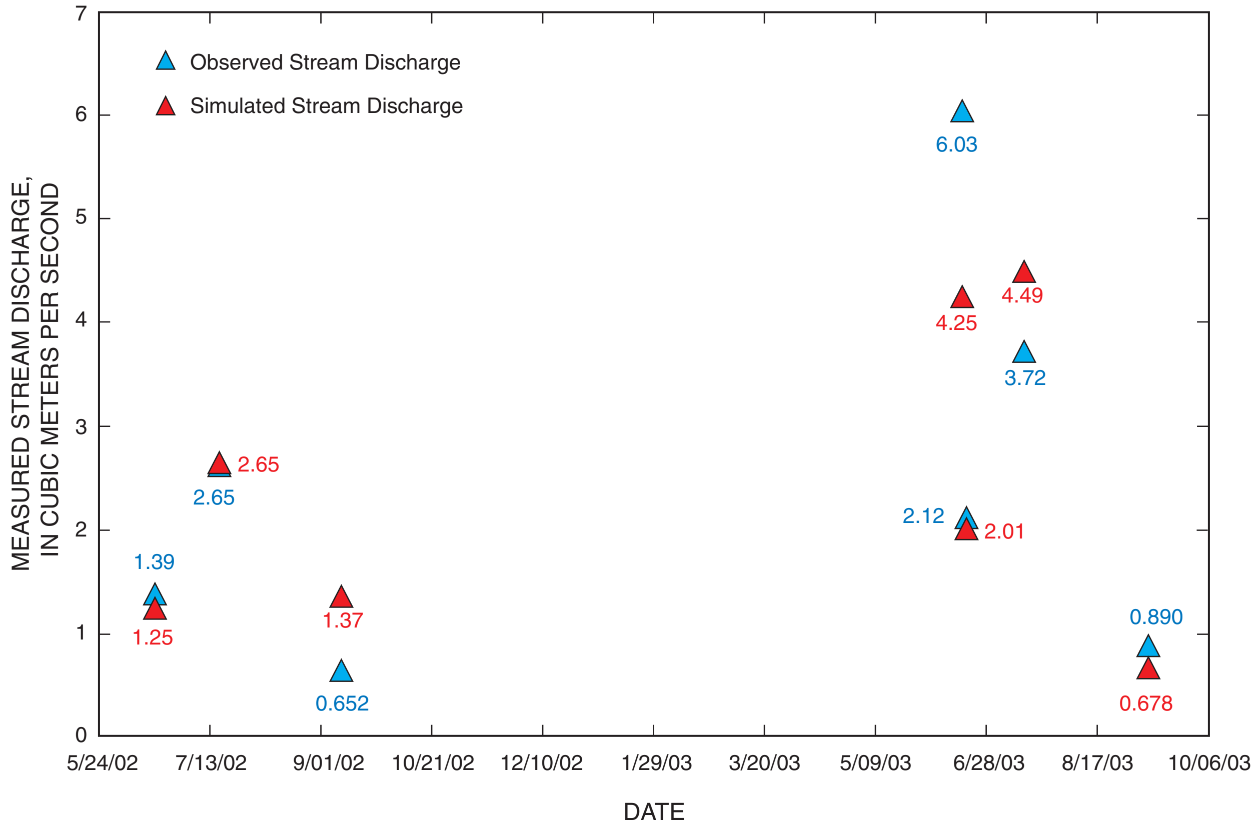



**Figure 17.** Time series of observed and simulated stream discharge for Contact Creek at Main Street.

as shown by comparing late-spring (fig. 19) to mid-summer (fig. 20) ground-water contours in the mid-Contact Creek reach area.

## Assessments of Results

### Comparison of Observed and Simulated Heads and Surface-Water Discharge

The cumulative mass-balance errors of the simulations averaged -0.01 percent and ranged from -0.08 to 0.06 percent for all stress periods in the transient simulation, indicating numerical stability of the flow-equation solutions. Simulated ground-water heads averaged 0.64 m higher than observed, ranging from 3.03 m higher than observed at observation-well 1 for the June 2003 field visit to 0.21 m lower than observed at observation-well 4 for the August 2003 field visit (table 6). Twelve of the 16 simulated ground-water heads were within 0.5 m of the observed values. All nine of the observed ground-water heads simulated for the July and August 2003 field visits were within 0.5 m of measured values.

Simulated discharge values averaged 12 percent less than observed, ranging from 111 percent more flow at Contact Creek at Main Street for the September 2002 field visit to 94 percent less flow at Contact Creek 200 m below Main Street for the September 2003 field visit. Nine of the 25 discharge values simulated were within 10 percent of the observed values and 14 of the 25 simulated discharge values were within 20 percent of the observed values. Simulated discharge for all eight of the observed discharge measurements for the July and August 2002 field visit averaged 3 percent more flow than observed and all were within 20 percent of the observed values (table 6).

Simulated discharge values were 21 percent less for the June 2003 field visit and 63 percent less for the September 2003 field visit than was observed. For the June and September 2003 field visits, the simulated ground-water heads for observation-wells 1 and 2 averaged 2.57 m and 0.78 m higher, respectively, than observed (table 6). The differences between these simulated and observed discharges and ground-water heads suggest that the simulated streamflow lost to the aquifer for Contact Creek during this period was much more than observed. However, the data did not allow for simulating the effects of significantly and rapidly changing stage and discharge, which often varied daily (fig. 17, table 6). These errors indicate the need for continuous ground-water levels and streamflow data to accurately model ground- and surface-water interactions

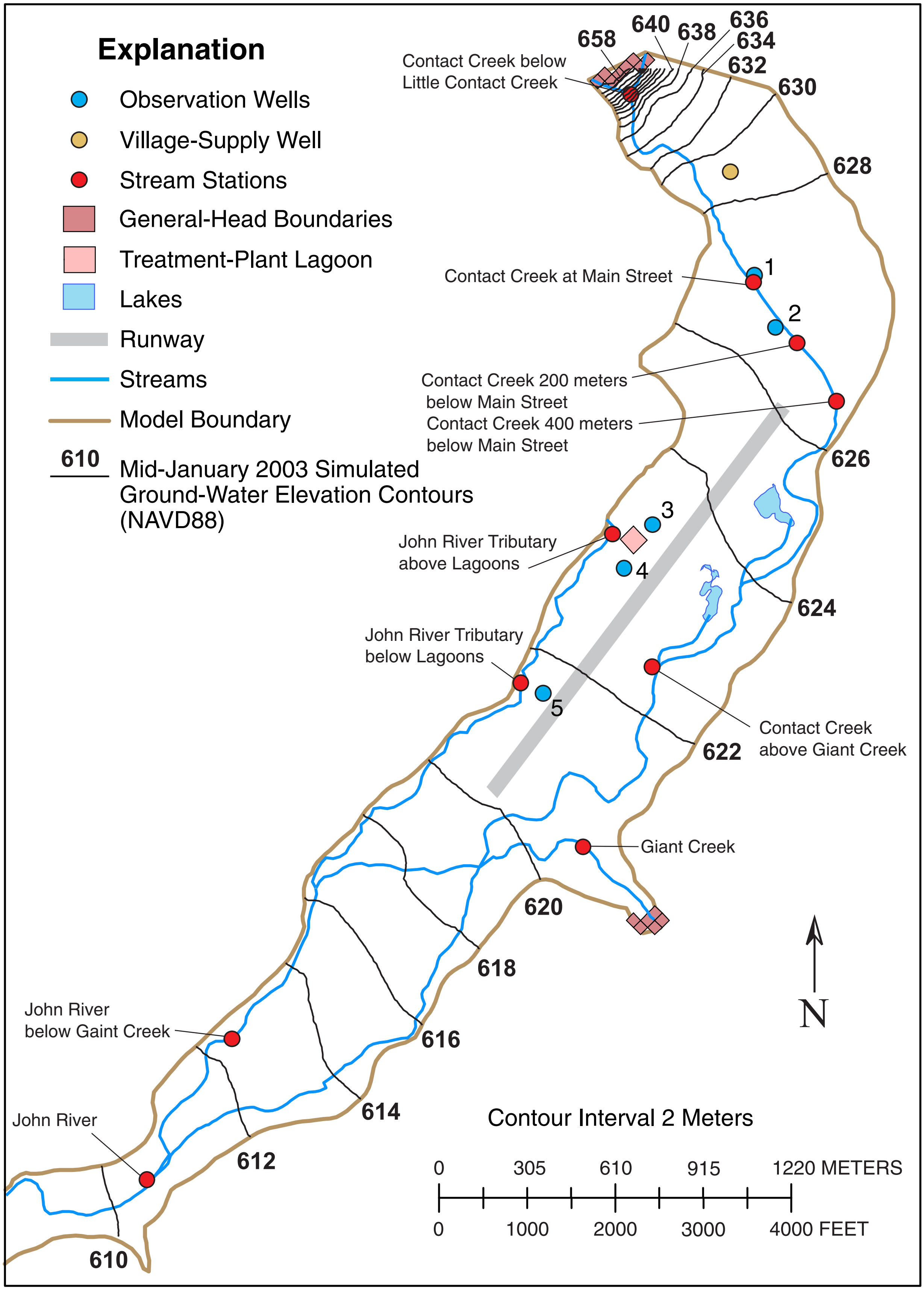
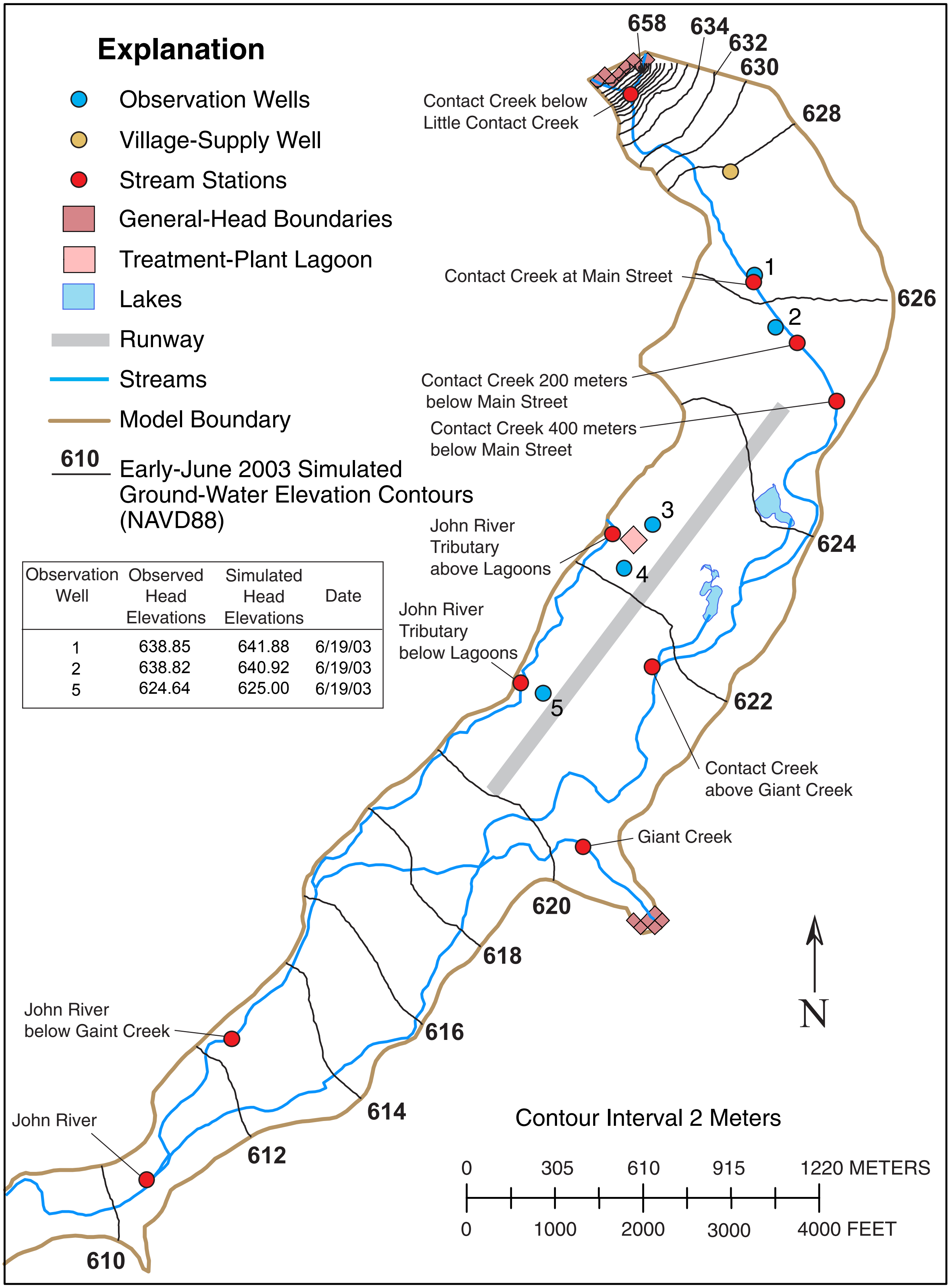
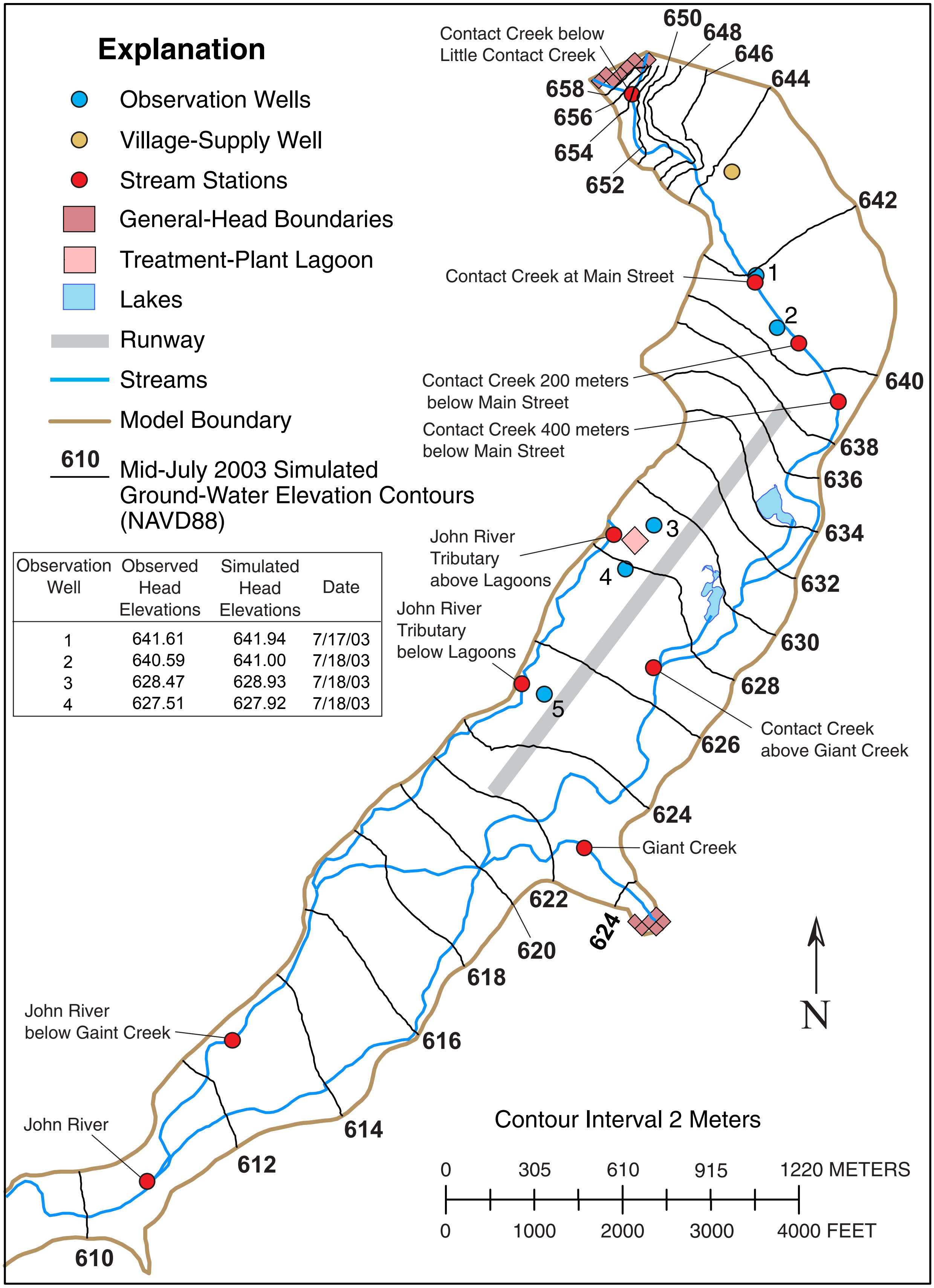



**Figure 18.** Simulated ground-water contours for mid-January 2003.




| Observation Well | Observed Head Elevations | Simulated Head Elevations | Date |
|---|---|---|---|
| 1 | 638.85 | 641.88 | 6/19/03 |
| 2 | 638.82 | 640.92 | 6/19/03 |
| 5 | 624.64 | 625.00 | 6/19/03 |

**Figure 19.** Simulated ground-water contours for early-June 2003.




| Observation Well | Observed Head Elevations | Simulated Head Elevations | Date |
|---|---|---|---|
| 1 | 641.61 | 641.94 | 7/17/03 |
| 2 | 640.59 | 641.00 | 7/18/03 |
| 3 | 628.47 | 628.93 | 7/18/03 |
| 4 | 627.51 | 627.92 | 7/18/03 |

**Figure 20.** Simulated ground-water contours for mid-July 2003.

during break-up and freeze-up in areas where ground-water recharge is dominated by varying streamflow.

The simulation indicated that summer flow in Giant Creek has a minor effect on the ground-water system upstream of the confluence with Contact Creek. Giant Creek flow, however, does affect early-spring, late-fall, and winter ground-water levels in areas just upgradient and downstream of the headwaters.

## Variation and Uncertainty of Hydraulic Properties

Throughout the study area, hydraulic-conductivity values, as determined through calibration of the transient model, varied by three orders of magnitude. Lower hydraulic-conductivity values for the aquifer probably relate more to the interpreted geometry of the aquifer than to the actual properties of geologic material. At the Contact and Little Contact Creek confluence, bedrock likely is shallower than interpreted and possibly is an area occupied by offset faults. Additionally, surface features indicate the possibility that permafrost is present within this area. In the area where aufeis forms, Porter (1966) states that remnants of glacial-ice potentially exist just beneath the surface soils. Permafrost, nevertheless, likely occurs in this area with taliks (unfrozen sediments that occur beneath surface-water bodies in permafrost areas) occuring beneath the John River (Shiltec Alaska, Ltd., 1996; Porter, 1966).

Permafrost does occur in other areas of the flood plain (Shiltec Alaska, Ltd., 1996) and results in relatively low hydraulic-conductivity, specific-yield, and porosity values (Unit 1; fig. 12). Along the lower reach of Contact Creek and where the stream was diverted (Units 2 and 3; fig. 12), taliks probably occur (Shiltec Alaska, Ltd., 1996), although to an unknown depth, and permafrost likely wedges into the unconsolidated material along the edges of the flood plain.

Within the excavated area near the lakes (Unit 5; fig. 12), exposed sediments comprise cobbles and occasional boulders in a matrix of silt and sand. Along the north-eastern edge of the southwestern most lake, an upper 3-m thick horizon comprises clay-like materials with cobbles and occasional boulders, possibly explaining calibrated hydraulic-conductivity values, similar to that in permafrost areas, and low specific-yield values. During the 2003 field visits, springs were active in this area and within the lakebeds. Additionally, along the northern and eastern edges of both lakes, ground water seeps beneath this upper fine-grained layer.

Simulated hydraulic conductivity varied by three orders of magnitude along the abandoned Contact Creek channel. Compacted fill material used for construction of the runway, and possibly deeper penetration of frost, likely explains the low hydraulic-conductivity and specific-yield values. The runway occupies only part of the southwestern portion of the abandoned channel. The remaining channel is less modified and, generally, is still natural.

Along the middle reach of Contact Creek (Unit 2; fig. 12), village employees have repeatedly bulldozed the streambed and banks in attempts to prevent flooding of the village, thus lowering the streambed into coarser sediments and consequently resulting in higher hydraulic-conductivity values. Throughout the floodplain, the highest hydraulic-conductivity values (300 m/d) occur in this area. Although fine-grained streamflow-transported sediments settle into the coarse material and reduce hydraulic conductivity, repeated reworking of the streambed puts the fine-grained sediments back into the flowing stream water and these sediments are deposited farther downstream.

## Sensitivity Analysis and Model Limitations

Sensitivity analysis investigates variations in simulated outputs that result from changing the input variables used to simulate ground-water flow. Simulated ground-water heads and streamflow were subjected to sequential 10 percent increases (sensitivity simulation) in the values of hydraulic conductivity, aquifer thickness, specific yield, and streambed hydraulic conductivity. To evaluate and quantify the sensitivity of each parameter, the errors for each observed and simulated streamflow and head value from each sensitivity simulation were normalized to the best-fit simulation errors. The analysis proceeds by dividing the squared and summed errors (SSE) of the sensitivity simulations by the SSE from the best-fit simulation (fig. 21).

Hydraulic conductivity, aquifer thickness, and specific yield were the parameters that most affected ground-water heads and stream discharge SSE (fig. 21). A 10 percent increase in hydraulic conductivity and aquifer thickness decreased the best-fit simulation head SSE by 11 percent and 10 percent, respectively; whereas, discharge SSE were reduced by only 2 percent. Sensitivity simulation of specific yield decreased discharge SSE by 6 percent with only a 1 percent reduction in head SSE. Sensitivity simulation of streambed hydraulic conductivity caused an increase of 11 percent in the head SSE while causing only a 1 percent decrease in discharge SSE. Changes

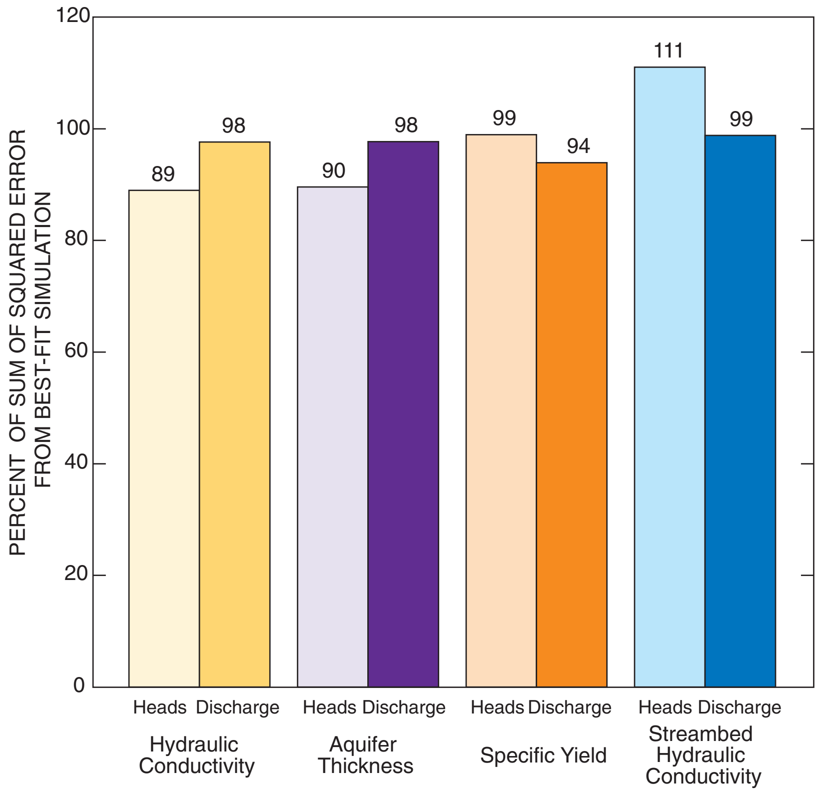



**Figure 21.** Results of sensitivity analysis from 10 percent changes in hydraulic-conductivity, aquifer-thickness, specific-yield, and streambed hydraulic-conductivity values.

in the amount of recharge from sources outside the study area primarily influence winter heads and because ground-water level data was not available for the winter of 2002–03, sensitivity of heads and discharge to changes in general-head boundaries were not evaluated.

The lack of specific hydrogeologic data, both in the spatial and temporal sense, limits the application and accuracy of the ground-water model of the John River aquifer near Anaktuvuk Pass. The hydraulic parameters assigned to each hydrogeologic unit in the Anaktuvuk Pass flow model are not based on methods commonly used to determine those values, such as appropriately designed aquifer tests, laboratory testing for sediment permeability, etc. The values of specific yield and porosity assigned to each unit are values suggested by Zheng and Bennett (2002) for sediments of the kind observed in these areas or reported in well logs. The values of hydraulic conductivity were assigned on the basis of trial-and-error changes to hydrogeologic-unit values to achieve the goals of calibration but were constrained to values suggested by Zheng and Bennett (2002) for sediments of the kind observed in these areas or reported in well logs. The processes that occur during spring break-up, such as thawing of both the active layer and the frost table (fig. 8), which result in changing storage coefficients of the aquifer, are difficult to simulate using MODFLOW-2000 (Harbaugh and others, 2000). During the open-water season, however, and on the basis of reasonable values of the hydraulic properties, the model provided satisfactory results but could be significantly improved with additional data such as continuous ground-water-level and streamflow data, aquifer tests, and coring of deeper sediments in the aquifer. These data would be of significant use for future studies designed to advance the knowledge gained from this ground-water and surface-water flow-field study.

## Simulation of Particle Movement

On the basis of results of the numerical model, it was felt the model was sufficient for use in conjunction with MODPATH (Pollock, 1994) to simulate the movement and possible extent of travel of conservative particles held within the water matrix. The 2-year average velocity of hypothetical particles injected into the aquifer near the treatment-plant lagoon and moving downgradient through the ground-water system was 0.89 m/d. After 4 years of travel, the average particle velocities increased to 1.2 m/d upon reaching the higher hydraulic-conductivity units at the headwater stream segments (fig. 22).

Although MODPATH (Pollack, 1994) does predict the direction and travel time of conservative-particle movement sufficiently, these predictions may be in error. Because of the limited data available during this study, particle-tracking calibration was not possible. Some of the additional data required for calibration of particle movement and, therefore, an adequate assessment of the modeling results, include: 1) measuring effective porosity, 2) determining the fate of conservative particles in cold-weather climates, and 3) continuous monitoring of injected and traceable particles at locations upgradient and downgradient of the injection point. This data would be necessary for constructing a predictive solute-transport model such as a Three-Dimensional Method-of-Characteristics Solute-Transport model (MOC3D) (Konikow and others, 1996) used in conjunction with MODFLOW-2000 (Harbaugh and others, 2000).

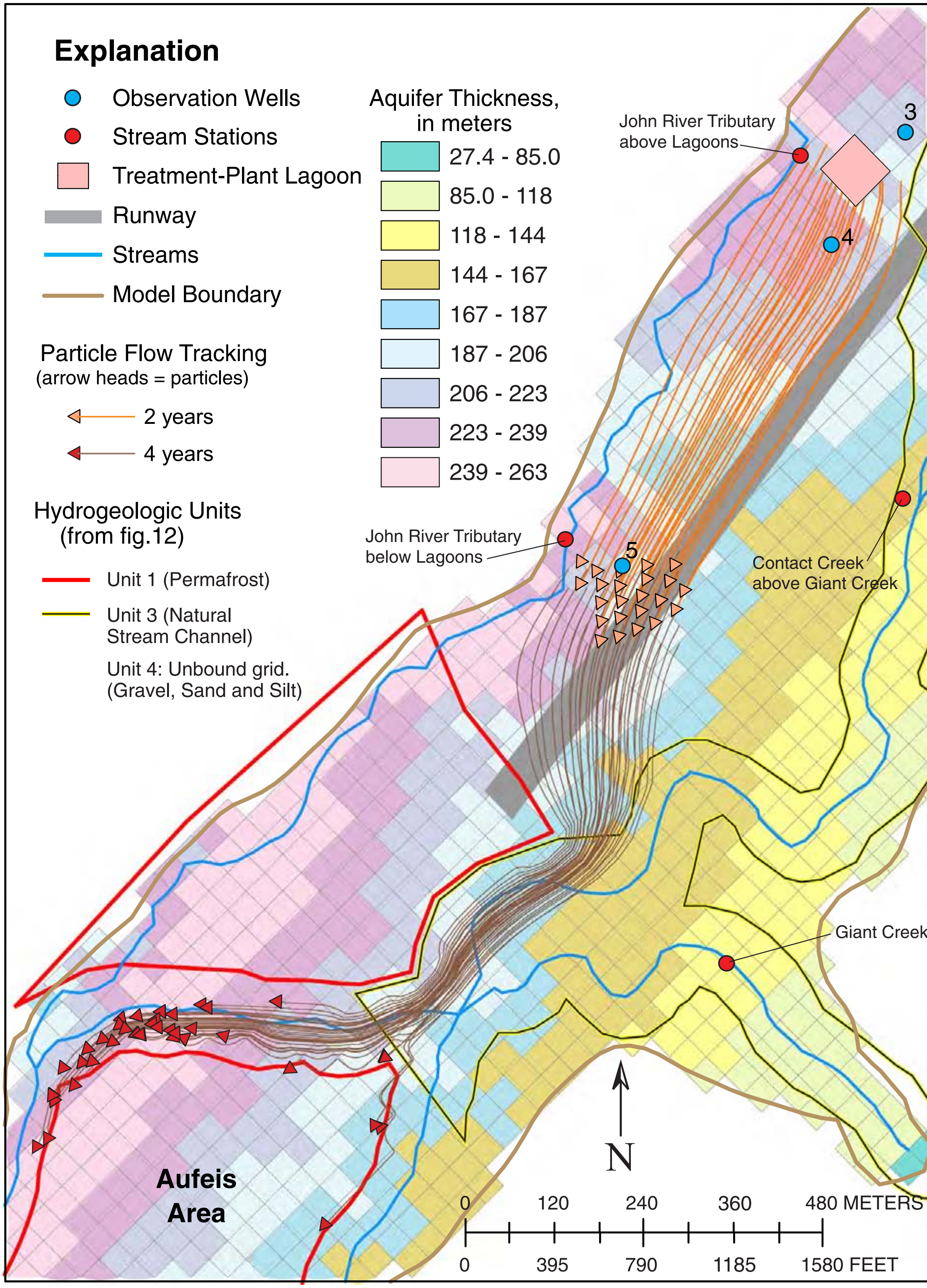



**Figure 22.** Particle tracking simulation results.

## Summary and Conclusions

The headwaters of the John River are located at the Continental Divide in the Brooks Range of Alaska near the village of Anaktuvuk Pass. A water-supply system and a wastewater-treatment plant recently have been constructed in the village. Because the headwaters of the John River are adjacent to Gates of the Arctic National Park and Preserve, the hydrology of the upper John River was studied from 2002–03 as part of a cooperative study between the U.S. Geological Survey and the National Park Service. The purpose of this study was to evaluate the current quality of the ground water and surface water in the headwaters area of the John River, to characterize the local ground- and surface-water system, and to investigate the interaction between the two systems. Major findings are:

- The water in the two principal streams that form the John River are Contact Creek (90.3 $km^2$) and Inukpasugruk Creek (commonly referred to as Giant Creek, 120 $km^2$). Contact Creek and Giant Creek are a calcium bicarbonate type water, but Giant Creek contributes a sulfate component to the John River.

- A small stream, referred to as the John River Tributary (4.6 $km^2$), also enters the John River near Anaktuvuk Pass. Lagoons that receive the effluent from the wastewater-treatment plant are in this small watershed. The water in this stream above and below the lagoon is also a calcium-bicarbonate type. Comparison of the water chemistry above and below the lagoon indicates water below the lagoon was higher in concentrations of dissolved ions, specifically bicarbonate, calcium, magnesium, sodium, sulfate, dissolved solids, and nitrate. Because the flow of the John River Tributary is only about 2 percent of the John River flow, there is no significant effect on the water quality of the John River.

- As water is lost from the channel of Contact Creek, as evidenced by discharge measurements, it recharges the underlying alluvial aquifer. At flows higher than 7 $m^3/s$, it appears the aquifer is fully recharged. Approximately 40 springs were located at the downstream end of Contact Creek and the John River.

- A numerical ground-water model of the John River near Anaktuvuk Pass was constructed. There are limitations of the model owing to the lack of spatial and temporal hydrogeologic data in the study area. Although the model did not simulate acceptable results in terms of streamflow and ground-water levels during spring break-up periods, it did simulate acceptable results during the mid-winter and open-water periods. Model results could be improved with additional continuous ground-water level and streamflow data.

- Results of MODPATH, a program to simulate the movement and possible extent of travel of a conservative particle, indicated that the velocities of particles injected into the alluvial aquifer beneath the treatment-plant lagoon averaged 0.89 m/d over a two-year period. After 4 years of travel, the average particle velocities increased to 1.2 m/d upon reaching the higher hydraulic-conductivity units at the headwater stream segments.

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