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

Surface-Water and Ground-Water Hydrology and Contaminant Detections in Ground Water for a Natural Resource Damage Assessment of the Indiana Harbor Canal and Nearshore Lake Michigan Watersheds, Northwestern Indiana

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Administrative Report

Prepared for the
U.S. Department of the Interior,
U.S. Fish and Wildlife Service, Region 3

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U.S. Geological Survey

Surface-Water and Ground-Water Hydrology and Contaminant Detections in Ground Water for a Natural Resource Damage Assessment of the Indiana Harbor Canal and Nearshore Lake Michigan Watersheds, Northwestern Indiana

By David A. Cohen, Theodore K. Greeman and Paul M. Buszka

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Indianapolis, Indiana
June 2002

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

U.S. GEOLOGICAL SURVEY
CHARLES G. GROAT, Director

<u>Administrative Report</u>

for use by the U.S. Department of the Interior,
U.S. Fish and Wildlife Service

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CONVERSION FACTORS, VERTICAL DATUM AND ABBREVIATIONS

Multiply	By	To obtain
acres	0.404687	hectares
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square foot (ft^2)	0.09290	square meter
square mile (mi^2)	2.590	square kilometer
cubic foot per second (ft^3/s or cfs)	0.02832	cubic meter per second
foot per second (ft/s)	0.3048	meter per second
feet per foot (ft/ft)	0.3048	meter per meters
foot per day (ft/d)	0.3048	meter per day

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Altitude, as used in this report, refers to distance above or below sea level.

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L). Abbreviated water-quality units used in this report: Chemical concentrations are given in metric units. Chemical concentrations of chemical constituents in water are given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million.

Other abbreviations used in this report:

EB-GCR - east branch of the Grand Calumet River

FWS - U.S. Fish and Wildlife Service

GCR - Grand Calumet River

GIS - geographic information system

GRITS/STAT - Ground Water Information Tracking System with Statistics Module

IDEM - Indiana Department of Environmental Management

IDNR - Indiana Department of Natural Resources

IHC - Indiana Harbor Ship Canal

NRDA - natural resource damage assessment

PRP - primary responsible party

USEPA - U.S. Environmental Protection Agency

USGS - U.S. Geological Survey

WB-GCR - west branch of the Grand Calumet River

Surface-Water and Ground-Water Hydrology and Contaminant Detections in Ground Water for a Natural Resource Damage Assessment of the Indiana Harbor Canal and Nearshore Lake Michigan Watersheds, Northwestern Indiana

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EXECUTIVE SUMMARY

In 1998, the U.S. Fish and Wildlife Service (FWS) requested that the U.S. Geological Survey (USGS) prepare a report to aid in documenting the potential discharge of contaminated ground water to surface waters in the watersheds of the Indiana Harbor Canal and nearshore Lake Michigan in Lake County, northwestern Indiana. The FWS was acting as the representative of various Federal and State agencies that were designated as trustees of the natural resources of the State of Indiana (the “Trustees”) under the Natural Resource Damage Assessment and Restoration Program.

The study area of approximately 80 square miles (mi) occupies that part of Lake County, Indiana that is north of the Little Calumet River, and includes all or parts of the cities of East Chicago, Gary, Hammond, and Whiting. The Natural Resource Damage Assessment (NRDA) focuses on an area of approximately 54 square mi that occupies the northern two-thirds of the study area, and is the area that typically drains into the Indiana Harbor Canal, its tributaries, or directly into Lake Michigan. The NRDA area is one of the most highly industrialized regions in the United States. Industries in this region include large steel mills, petrochemical refining and storage facilities, scrap-metal processing, metal-parts fabrication for trucks, automobiles, and major appliances, and railcar and chemical manufacturing.

Surface drainage in the study area is to the Grand Calumet River, the Indiana Harbor Canal, and Lake Michigan in the north and to the Little Calumet River in the south. The drainage divide separating these areas of surface-water discharge approximately coincides with the Tolleston Beach Ridge, an arcuate upland in the southern part of the study area.

The Grand Calumet River consists of the two east-west oriented branches that meet at the southern end of the Indiana Harbor Canal. The east branch of the Grand Calumet River headwaters in the Marquette Park Lagoons and flows westward about 10 mi to its confluence with the Indiana Harbor Canal. The west branch of the Grand Calumet River is about 6 mi long with a surface-water flow divide approximately 1 mile west of its confluence with the Indiana Harbor Canal. Water in the west branch of the Grand Calumet River typically flows westward from this divide approximately 5 mi to its confluence with the Little Calumet River in Illinois, and eastward from this divide to its confluence with the Indiana Harbor Canal. Over 90 percent of the flow in the east and west branches of the Grand Calumet River is effluent discharge from industries and municipal wastewater-treatment plants.

The position of the flow divide on the west branch of the Grand Calumet River is variable and affected by numerous factors including water levels in Lake Michigan, the amount of effluent flow into the east and west branches and the Indiana Harbor Canal, and the wind speed and direction. During periods of extremely high water levels in Lake Michigan, this divide is absent—water from Lake Michigan flows southward through the Indiana Harbor Canal and then along with flow from the east branch of the Grand Calumet River, westward through the west branch of the Grand Calumet River to the Little Calumet River in Illinois. This occurence generally is rare and only has been observed during 8 months of the last 85 years, most recently in 1986.

The study area is underlain by approximately 40 to more than 225 feet (ft) of unconsolidated glacial, eolian, lacustrine, and paludal sediments of Pleistocene and Holocene age that were deposited on a bedrock surface modified by pre-Pleistocene erosion. These sediments form a surficial aquifer and an underlying confining unit that overlie a carbonate bedrock aquifer.

Eolian and lacustrine sands, and localized areas of man-made fill form a surficial aquifer in the study area commonly known as the Calumet aquifer. Substantial areas of the uppermost parts of the Calumet aquifer, primarily within the NRDA portion of the study area, are made or modified land composed of fill deposits. The Calumet aquifer generally is not used for municipal or industrial water supply because most major users obtain their water either directly from Lake Michigan or from the underlying bedrock aquifer.

Underlying the Calumet aquifer and above the bedrock is a confining unit that is composed primarily of clay till, and may contain thin discontinuous sand deposits. This confining unit generally varies in thickness from slightly less than 50 ft to more than 150 ft.

A carbonate bedrock aquifer is at the bedrock surface throughout the study area. The bedrock aquifer is composed of Devonian and Silurian carbonates, with a combined thickness of about 400 ft in the study area. Most of the ground-water withdrawals in the study area are from the bedrock aquifer.

Reported hydraulic properties for the three hydrologic units of interest—the Calumet aquifer, the confining unit, and the bedrock aquifer—from within and near the study area indicate the following.

A. Hydraulic conductivities in the Calumet aquifer generally are from 2 to 4 orders of magnitude greater than conductivities in the underlying clay confining unit. The high contrast in hydraulic conductivities between the Calumet aquifer and the underlying confining unit, combined with generally small (less than 0.2 ft/ft) vertical gradients between these two units indicate that net exchange of ground water between the confining unit and the Calumet aquifer is minor compared to the total amount of ground-water flow within the Calumet aquifer;

B. Ground-water flow in the underlying confining unit is mostly vertical with relatively minor amounts of horizontal flow; and;

C. Although the net ground-water exchange between the Calumet aquifer and the confining unit is relatively small compared with the total amount of ground-water flow in the Calumet aquifer, the vertical gradients indicate that more ground water flows downward from the Calumet aquifer into the confining unit than flows upward from the confining unit into the Calumet aquifer.

The Calumet aquifer is in good hydraulic connection with the surface-water bodies in the study area. Rises in surface-water levels in Lake Michigan, the Grand Calumet River, and the Indiana Harbor Canal typically result in a decrease in the slope of the adjacent water table—conversely, a fall in surface-water levels typically results in an increase in the slope of the adjacent water table. Transient reversals in the near-stream water-table slope, resulting in surface water infiltrating into the streambank, are caused by a lowering of the water table, due mostly to evapotranspiration and/or lack of precipitation—concurrent rises in surface-water levels enhance these reversals. These reversals typically are of hours to days in duration—reversals of 2 or more weeks probably only occur during periods of extremely high lake levels. The typical pattern of ground-water discharge from the Calumet aquifer to the Grand Calumet River and the Indiana Harbor Canal is not changed, however, because of the usual short duration and localized extent of these gradient reversals.

Five factors contribute toward stabilizing the flow regimes for ground- and surface-water resources in the study area:

1. The sandy texture of the soils in the area generally results in smaller contributions to streamflow from surface runoff;

2. Most of the flow in the east and west branches of the Grand Calumet River is industrial or municipal effluent, discharged at a generally constant rate;

3. Total topographic relief in the study area is low, generally less than 45 ft;

4. Surface- and ground-water levels fluctuate within a generally narrow range (less than 5 ft);

5. Leaky sewers at fixed depths below the ground surface tend to stabilize ground-water levels in their vicinity.

Pumping from the Calumet aquifer to dewater specific sites is common in the study area. Pumping lowers ground-water levels, creates a depression in the water table surrounding the pumpage, and locally alters ground-water-flow directions.

Wetlands in the study area generally are less than 50 acres, are situated mostly along or near streams, lakes, ponds, and ditches, and typically are among the more densely vegetated areas. Because of generally high rates of evapotranspiration during the growing season, wetlands may affect appreciably the development and duration of transient near-stream reversals in ground-water-flow directions along parts of the east and west branches of the Grand Calumet River and the Indiana Harbor Canal.

The ground-water-flow system in the Calumet aquifer is typified by broad flat water-table mounds that function as ground-water divides that commonly underlay topographically higher areas of land. Ground water in the Calumet aquifer generally flows laterally away from these divides and discharges to streams and wetlands in adjacent low-lying areas and to Lake Michigan.

A major east-west trending ground-water divide is located beneath the topographic high associated with the Tolleston Beach Ridge. North of this divide, ground water flows northward to the east and west branches of the Grand Calumet River. South of this divide, ground water flows southward to the Little Calumet River. Another major east-west trending divide is between the east branch of the Grand Calumet River and Lake Michigan east of the Indiana Harbor Canal—ground water generally flows northward from this divide to Lake Michigan, and southward from this divide to the east branch of the Grand Calumet River. Two smaller northeast-southwest trending divides are present on either side of the Indiana Harbor Canal downstream of the confluence with the Lake George Branch—ground water generally flows from these divides to the Indiana Harbor Canal, Indiana Harbor, and Lake Michigan.

All ground-water divides and associated flow patterns and discharge areas described above generally are very stable features of the ground-water-flow system in the study area. Dissolved contaminants transported by ground-water flow along any flow path will most likely also discharge to the same areas as does ground water.

Some water-table depressions represent areas where discharge to leaky sewers or pumpage have locally altered typical ground-water-flow patterns. Ground water in these areas generally flows radially into these water-table depressions and discharges to the leaky sewers or pumping center—dissolved contaminants transported by ground-water flow will most likely also discharge to the same points as the ground water. The size, vertical extent, and shape of these depressions typically vary with time, and patterns of ground-water flow are subject to more temporal and spatial changes in these areas where water-table depressions form.

The Trustees have identified 146 organic compounds, trace elements, and trace species that they consider contaminants of concern for the NRDA. Detections of these contaminants of concern in ground water from the study area were compiled for this report from three sources: (1) the U.S. Environmental Protection Agency Groundwater Information Tracking System with Statistics Module, (2) the USGS National Water Information System, and (3) paper reports submitted by private sources as part of environmental compliance activities.

One hundred eleven of the 146 NRDA contaminants of concern, including polychlorinated biphenyls, oil-related organic compounds, and trace metals, were detected in more than 9,400 water samples from 485 monitoring wells in the area. Most detections of contaminants of concern were in samples from areas where ground water commonly discharges to the Grand Calumet River, the Indiana Harbor Canal, or Lake Michigan. Limited available data collected between 1992 and 1996 also indicate the presence of light-nonaqueous phase liquids (LNAPLs) floating on ground water under large areas between the Lake George Branch and Lake Michigan, with LNAPL thicknesses ranging from a film to more than 10 ft.

Advection is the primary mechanism by which contaminants dissolved in ground water move at the rate of ground-water flow through an aquifer. Other physical and chemical processes that can affect contaminant concentrations in ground water include dispersion, precipitation-dissolution reactions, ion-exchange reactions, oxidation-reduction (redox) reactions, volatilization, biodegradation, and hydrolysis.

Some of the most frequently detected contaminants of concern also have potential natural sources, or may originate from sampling or analytical related interferences. These potential sources include mineral dissolution (arsenic), leaching of well construction materials (nickel), inadvertent contact during sampling with plasticizing materials (di-n-butylphthalate and bis(2-ethylhexyl) phthalate) and laboratory use of a common solvent (methylene chloride). Additional analysis of available data, new sampling of water from wells where these contaminants of concern were detected, and analysis of those data may be necessary to resolve whether the contaminant occurrences were environmental in nature or were affected by sampling procedures or sample handling.

INTRODUCTION

Section 311(f)(5) of the Clean Water Act of 1972 authorized the State and Federal governments to act on behalf of the public as trustees for natural resources with the goal of restoring natural resources that have been degraded by contamination (U.S. Environmental Protection Agency, 2002a). In 1980, the Comprehensive Resource, Compensation and Liability Act (CERCLA) expanded the responsibilities of the State and Federal trustee agencies (U.S. Department of Interior, 1999). These responsibilities are carried out by the Natural Resource Damage Assessment and Restoration Program of the U.S. Fish and Wildlife Service (FWS). In 1997, the FWS, the National Park Service (NPS), the Indiana Department of Natural Resources (IDNR), and the Indiana Department of Environmental Management (IDEM), acting as trustees of the natural resources in the State of Indiana (hereafter referred to as "Trustees"), initiated a Natural Resource Damage Assessment (NRDA) of the Indiana Harbor and the watersheds of the Indiana Harbor Ship Canal (IHC), portions of the Grand Calumet River (GCR) that are tributary to the IHC, and adjacent nearshore Lake Michigan (fig. 1).

The purpose of the NRDA is to determine and quantify damage to the natural resource resulting from the release of hazardous substances and oil, and to calculate the cost associated with that damage (Weiss and others, 1997). Natural resources in the NRDA include “land, fish, wildlife, biota, air, water, ground water, drinking-water supplies and other such resources belonging to, managed by, held in trust by, appertaining to, or otherwise controlled by the United States, any state government, any foreign government, any Indian Tribe, or if resources are subject to a trust restriction on alienation, any member of an Indian Tribe” (U.S. Department of Interior, 2001). The Trustees then attempt to "negotiate a settlement with the responsible parties for the cost of the restoration, the loss of the use of the land or natural resources to the general public, and the money spent by the Trustees to assess the damages" (U.S. Department of Interior, 1999, p. 1).

One element of the Trustees’ approach to injury determination is to identify and characterize ground water containing oil or other hazardous substances that discharges to surface water in the NRDA area (Weiss and others, 1997, p.14). The NRDA acceptance criteria for injury to ground-water resources includes identification of measured concentrations of oil or other hazardous substances in that water resource (United States Code of Federal Regulations 43 Part 11.62 (c)(2)). Such ground water is considered by the Trustees to represent a potential continuing source of contaminants that may degrade the surface-water resources, and, therefore, constitutes an “injury pathway” (Weiss and others, 1997, p. 24).

In 1998, the FWS, representing the Trustees, requested that the U.S. Geological Survey (USGS) prepare a report to aid in evaluating the potential discharge of contaminated ground water to surface water. The primary focus of the report involved areas in the IHC and adjacent nearshore Lake Michigan watersheds; these areas include 21 industrial facilities for which primary responsible parties (PRPs) had been identified. In keeping with DOI regulations that emphasize the performance of cost-effective NRDA’s, the FWS requested that the report use available data. The FWS also requested that the report include recommendations for additional data collection and analyses needed to more clearly identify contaminated ground water and its discharge areas.

Purpose and Scope

This report summarizes relevant water-quality and hydrogeologic information to aid the Trustees in performing a Natural Resource Damage Assessment in northwestern Indiana. The report summarizes hydrogeologic information for the NRDA and surrounding areas (the study area) with an emphasis on directions of ground-water flow and factors affecting ground-water discharge to the IHC and adjacent Lake Michigan watersheds. The report contains a compilation of more than 10,000 detections of contaminants of concern in water samples collected from approximately 500 wells in the study area between 1954 and 1998. Tables of the frequency of detections of contaminants of concern and figures showing typical areas of ground-water discharge are included. Processes that may affect the transport in ground water of some of the most frequently detected potential contaminants are discussed. The report also presents data on the thickness of light-nonaqueous phase liquids (LNAPLs) on ground water near the IHC, and discusses additional work needed to investigate the fate of contaminated ground water in the IHC and adjacent Lake Michigan watersheds.

Fig. 1

Description of Study Area

The study area occupies approximately 80 mi^2 in northwestern Indiana. This section describes the geographic extent of the study area and defines that portion of the study area that is included in the NRDA. Also included is a brief description of the physiography, surficial geology, climate, and land use in the study area.

Location and Extent of Study Area and Natural Resources Damage Assessment Area

The study area occupies approximately 80 mi^2 in northwestern Indiana. The study area is located along the southernmost tip of Lake Michigan, and includes all of Lake County, Indiana north of the Little Calumet River, and large parts of the city of Gary and all of the cities of East Chicago, Hammond, and Whiting (fig. 1). The NRDA focuses on that portion of the study area that typically drains into the IHC or directly into Lake Michigan. The NRDA area occupies approximately 54 mi^2 in the northern two-thirds of the study area, and is composed of all the land north and east of the drainage-basin boundary for the IHC, its tributaries, and Lake Michigan in Lake County, Indiana (fig. 1). Although the Trustees' primary focus was the NRDA area, they requested that hydrologic and water-quality data in the study area be included in the data compilation and analysis for this report. The Marquette Park Lagoons and surrounding lands in the northeastern part of Lake County are included in the both the study and NRDA areas—much of this land is part of the Indiana Dunes National Lakeshore, a unit of the National Park Service (fig. 1).

Physiography, Surficial Geology, and Land Use

The study area is located completely within the Calumet Lacustrine Plain section of the Northern Moraine and Lake Region physiographic province (Malott, 1922, p. 112). This area is an abandoned glacial and postglacial lake bottom. Landward of Lake Michigan land surface is made up of parallel sand ridges with intervening swales. These remnants of ancient shorelines mark a steady decrease in the size of Lake Michigan. These small dune ridges, with intervening swampy swales, diminish in size from east to west. Thompson, 1992 (p. 308) reports dune ridges generally ranging from 12 to 20 ft high at the eastern edge of the study area and small dune ridges from 5 to 8 ft high near the center. In many areas, small dune ridges were pushed into the intervening swales as part of the land-leveling process associated with urbanization.

The surficial geology in the study area (fig. 2) is mostly glacial and lacustrine sand, silt, and clay deposits of Wisconsinan and Recent age. Large areas with artificial fill and substantially modified land are present along the Lake Michigan shoreline and surrounding Lake George.

Wetlands are present in a variety of geomorphic settings (fig. 3). Interdunal wetlands occupy the swales between the numerous parallel beach ridges. Other wetlands are associated with the meanders of the GCR and Little Calumet River (LCR), and with lakes and ponds within the study area.

Land use in the area is primarily industrial and residential (fig. 4). The NRDA area is one of the most industrialized regions in the United States. Large steel mills are located along the shore of Lake Michigan, Indiana Harbor, and the IHC. Land along the IHC and Lake Michigan also is used for the refining and storage of petrochemicals. Other major industries in the NRDA area include scrap-metal processing, parts fabrication for trucks, automobiles, and major appliances, and railcar and chemical manufacturing.

The GCR is commonly the dividing line between heavy industrial and other land uses. Heavy industrial facilities are located mostly north of the GCR with most residential, commercial, recreational, and some light industrial areas located south of the river (fig. 4). A large part of the NRDA area has been used for the disposal of waste materials (Kay and others, 1997, p. 25).

Fig. 2

Fig. 3

Fig. 4

METHODS OF STUDY

This section describes methods used to compile location data, hydrologic data, and water-quality data for the study area. These data include: (1) locations of facility boundaries and monitoring wells with water-quality data, (2) hydrologic data for ground water and major surface-water bodies, and (3) ground-water-quality data.

Locations of Industrial Facilities

Relevant information concerning industrial facilities in the study area is shown in table 1. The Trustees have identified PRPs for 21 facilities in the NRDA portion of the study area. The boundaries for these and other facilities in the study area (plate 1) are from four types of sources including:

1. Geographic information system (GIS) electronic datasets from the U.S. Environmental Protection Agency (USEPA), Region 5, Office of Strategic Environmental Analysis. Reported facility boundary accuracies are approximately 56 ft or 17 meters (Milo Anderson, U.S. Environmental Protection Agency, Region 5, Office of Strategic Environmental Analysis, oral commun., 1998).

2. GIS electronic datasets from IDEM. Facility boundaries were reported to have average accuracies of about 59 ft or 18 meters (Murray and others, 1997).

3. Hand-digitized facility boundaries from photocopies of Lake County plat maps. Facility boundaries were highlighted by FWS personnel (Dan Sparks, U.S. Fish and Wildlife Service, written commun., 1999) and digitized by hand into a GIS cover by USGS personnel. An image of the appropriate 1:24,000-scale topographic map was viewed in the background as a guide for digitizing the facility boundary lines. Facility boundary accuracies were estimated by USGS personnel to average about 197 ft or 60 meters.

4. Hand-digitized facility boundaries from a photocopy of an illustration in a report by Fluor Daniel Environmental Services Division (written commun., 1991). An image of the appropriate 1:24,000-scale topographic map was viewed in the background as a guide for digitizing the facility boundary lines. USGS personnel estimate the facility boundary accuracy to be about 197 ft or 60 meters.

Hydrologic Data

Surface-water and ground-water data and hydrologic interpretations were compiled from the USGS National Water Information System (NWIS) database and from previously published reports and other sources. These sources are cited in the text at their point of reference.

Ground-Water-Quality Data

The Trustees are concerned with natural-resource damages associated with the occurrence of polychlorinated biphenyls (PCB's), organic compounds, oil and oil-related compounds, and trace elements in ground water (Weiss and others, 1997, p. 11-13; Daniel Sparks, U.S. Fish and Wildlife Service, written commun., 1998). This section lists the contaminants of concern, sources of the ground-water-quality data, and characteristics of the ground-water-quality dataset, and includes a brief discussion of some limitations on the use of these data. Sources and characteristics of data on the occurrence of light-nonaqueous phase liquids in the Calumet aquifer also are included.

Table 1. Selected industrial and other facilities in the study area, northwestern Indiana

[PRP, Primary responsible party; IDEM, Indiana Department of Environmental Management; USEPA, U.S. Environmental Protection Agency; FDES, Fluor Daniel Environmental Services Division]

Facility designation	Boundary source	Approximate boundary accuracy (meters)	PRP identified by Trustees
AMG RESOURCES/VULCAN MATERIALS	plat maps	60	yes
AMOCO OIL COMPANY	IDEM	18	yes
CALUMET CONTAINER	IDEM	18	no
CITGO PETROLEUM COMPANY	plat maps	60	yes
CONSERVATION CHEMICAL COMPANY	IDEM	18	yes
DU PONT E.I. DE NEMOURS AND COMPANY	IDEM	18	yes
ENERGY COOPERATIVE, INC.	IDEM	18	yes
EXPLORER PIPELINE	plat maps	60	yes
GARY CITY LANDFILL	IDEM	18	no
GARY DEVELOPMENT COMPANY, INC.	IDEM	18	yes
GARY LAGOONS—LAIDLAW—JUSTAK	plat maps	60	no
GENERAL AMERICAN TRANSPORTATON COMPANY	IDEM	18	yes
GEORGIA PACIFIC	plat maps	60	yes
HAMMOND VALVE CORPORATION	IDEM	18	no
HECKETT PLANT 11	IDEM	18	no
HOUSES JUNKYARD	plat maps	60	yes
INLAND STEEL	IDEM	18	yes
LAKE SANDY JO—M & M LANDFILL	IDEM	18	no
LTV STEEL COMPANY, INC.	IDEM	18	yes
MIDCO I	IDEM	18	no
MIDCO II	IDEM	18	no
MOBIL OIL CORPORATION	USEPA	17	yes
NINTH AVENUE DUMP SUPERFUND SITE	IDEM	18	no
NIPSCO-MITCHELL GEN STATION D.H.	IDEM	18	no
PHILLIPS PIPE LINE, EAST CHICAGO TERMINAL	IDEM	18	yes
PRAXAIR, INC	IDEM	18	yes
RALSTON STREET LAGOON	FDES	60	yes
RUBBER, CLARK MATERIALS—PRIME GROUP	plat maps	60	no
SAFETY-KLEEN OIL RECOVERY COMPANY	IDEM	18	yes
SAXON METALS COMPANY	IDEM	18	no
SHELL OIL COMPANY	plat maps	60	yes
US STEEL—GARY WORKS	IDEM	18	yes
USS LEAD REFINERY, INC.	IDEM	18	yes

Contaminants of Concern

The contaminants of concern identified by the Trustees (Daniel Sparks, U.S. Fish and Wildlife Service, written commun., 1998) are listed in table 2. About 110 of these contaminants are included in the USEPA's list of priority pollutants (Douglas Yeskis, U.S. Environmental Protection Agency, written commun., 2002). Also included in table 2, where available, is the Chemical Abstract Service (CAS) registry number that provides a standard numeric identifier for a chemical compound or group of compounds (Howard and Neal, 1992).

Sources of Ground-Water-Quality Data

The ground-water-quality data in this report were obtained from the following three sources: (1) the USEPA Groundwater Information Tracking System with Statistics Module (GRITS/STAT; U.S. Environmental Protection Agency, 2001), (2) the USGS National Water Information System (NWIS), and (3) paper reports submitted by private sources as part of environmental compliance activities. Details of these data sources follow.

1. Groundwater Information Tracking System with Statistics Module (GRITS/STAT)—GRITS/STAT began as a database developed by USEPA Region 7 to provide a standardized electronic format for the storage of ground-water monitoring data that were collected to meet federal regulatory requirements. USEPA Headquarters later added a statistics module and the software became known as GRITS/STAT (U.S. Environmental Protection Agency, 2001). Water-quality analyses in GRITS/STAT for the NRDA and surrounding area had been previously retrieved and compiled by IDEM staff into an INFO table using the ARC-INFO GIS software (Environmental Systems Research Institute Inc., 1991).

The geographic coordinates for wells in GRITS/STAT with water-quality data had been determined by IDEM and were included in the INFO table. The locational accuracy of the geographic coordinates for this dataset was reported as approximately 59 ft or 18 meters (Murray and others, 1997). This locational accuracy was based on the average difference from confirmed locations of 10 percent of the wells in the dataset (Murray and others, 1997, p. 4). Some of these wells are mislocated by substantially larger distances than 59 ft, as indicated by the monitoring wells with noted location inaccuracies on Plate 1. For this study, these data were converted into a GIS electronic dataset and only analyses of contaminants of concern from water samples collected within the study area were retained.

2. National Water Information System (NWIS)—NWIS is the electronic storage and retrieval system used by the USGS for water-resources and related data. Water-quality analyses of contaminants of concern in the study area were retrieved and converted into a GIS electronic dataset. Locational accuracy for the wells associated with these analyses is reported in NWIS as approximately 101 ft or 31 meters.

3. Paper reports—Much ground-water-monitoring data collected by industrial facilities to meet Federal and State regulatory requirements only were compiled in paper reports (table 3). Photocopies of these paper reports were forwarded from IDEM and FWS to USGS staff (Jim Smith, Indiana Department of Environmental Management, and Daniel Sparks, U.S. Fish and Wildlife Service, written commun., 1999). All reports were reviewed and relevant water-quality and associated data that were not already in sources (1) or (2) above were entered into a spreadsheet. One or more of the photocopied report illustrations depicting the sampled wells and other geographic features were used to digitize well locations into a GIS electronic dataset. An image of the appropriate 7.5-minute topographic map was displayed in the background as an aid for the correct placement of wells. The locational accuracies of the features depicted in the source materials are variable and undetermined. The water-quality data entered in the spreadsheet then were merged with the appropriate well in the GIS electronic dataset.

The GIS datasets from the above sources were merged to form the ground-water-quality dataset presented in this report. The location and designation of all monitoring wells (plate 1) from which analyses of samples are compiled in appendix 1 at the back of this report. Relevant information regarding the three sources of water-quality data compiled for this report are summarized in Table 4.

Table 2. Contaminants of concern for the Natural Resource Damage Assessment, northwestern Indiana

[CAS, Chemical Abstract Services; NA, not available]

Constituent name	CAS Registry number	Constituent name	CAS Registry number
Trace elements and species			
Antimony	7440-36-0	Mercury	7439-97-6
Arsenic	7440-38-2	Molybdenum	7439-98-7
Beryllium	7440-41-7	Nickel	7440-02-0
Cadmium	7440-43-9	Selenium	7782-49-2
Chromium	7440-47-3	Silver	7440-22-4
Chromium, hexavalent ion	18540-29-9	Strontium	7440-24-6
Cobalt	7440-48-4	Thallium	7440-28-0
Copper	7440-50-8	Titanium	7440-32-6
Cyanide	57-12-5	Vanadium	7440-62-2
Lead	7439-92-1	Zinc	7440-66-6
Organic compounds			
Carbon disulfide	75-15-0	2,3,4,5,6-Pentachloroanisole	1825-21-4
1-Methylnaphthalene	90-12-0	2,4,5-Trichlorophenol	95-95-4
1,1,1-Trichloroethane	71-55-6	2,4,6-Trichlorophenol	88-06-2
1,1,2,2-Tetrachloroethane	79-34-5	2,4-Dichlorophenol	120-83-2
1,1,2-Trichloroethane	79-00-5	2,4-Dimethylphenol	105-67-9
Dibenzo(a,h)anthracene	53-70-3	2,4-Dinitrophenol	51-28-5
1,1-Dichloroethane	75-34-3	2,4-Dinitrotoluene	121-14-2
1,1-Dichloroethene	75-35-4	2,6-Dinitrotoluene	606-20-2
Total Dichloroethene	NA	Methyl ethyl ketone	78-93-3
1,2,3,4,5-Tetrachlorobenzene	95-94-3	2-Chloroethyl vinyl ether	110-75-8
1,2,4-Trichlorobenzene	120-82-1	2-Chloronaphthalene	91-58-7
1,2-Dichlorobenzene	95-50-1	1,2-Dichloroethene	540-59-0
1,2-Dichloroethane	107-06-2	1,2-Dichloropropane	78-87-5
trans-1,2-Dichloroethene	156-60-5	2-Chlorophenol	95-57-8
1,2-Diphenylhydrazine	122-66-7	2-Hexanone	591-78-6
1,3-Dichlorobenzene	541-73-1	2-Methyl-4,6-dinitrophenol	534-52-1
1,4-Dichlorobenzene	106-46-7	2-Methylnaphthalene	91-57-6

Table 2. Contaminants of concern for the Natural Resource Damage Assessment, northwestern Indiana—Continued

Constituent name	CAS Registry number	Constituent name	CAS Registry number
Organic compounds—Continued			
2-Methylphenol	95-48-7	Nitrobenzene	98-95-3
2-Nitroaniline	88-74-4	Pentachlorobenzene	608-93-5
2-Nitrophenol	88-75-5	Benzidine	92-87-5
3-Chlorophenol	108-43-0	Benzo(a)pyrene	50-32-8
3,3-Dichlorobenzidine	91-94-1	Benzo(b)fluoranthene	205-99-2
3-Nitroaniline	99-09-2	Benzo(k)fluoranthene	207-08-9
4-Bromophenyl phenyl ether	101-55-3	Benzo(g,h,i)perylene	191-24-2
4-Chloro-3-methylphenol	59-50-7	Benzoic-acid	65-85-0
4-Chlorophenyl phenyl ether	7005-72-3	Bis(2-chloroethoxy)-methane	111-91-1
4-Methyl-2-pentanone (MIBK)	108-10-1	Bis(2-chloroethyl) ether	111-44-4
4-Methylphenol	106-44-5	Bis(2-ethylhexyl) phthalate	117-81-7
4-Nitroaniline	100-01-6	Bis(chloromethyl) ether	542-88-1
4-Nitrophenol	100-02-7	Bis(2-chloroisopropyl) ether	108-60-1
Acenaphthene	83-32-9	Bromodichloromethane	75-27-4
Acenaphthylene	208-96-8	Bromoform	75-25-2
Vinyl acetate	108-05-4	Bromomethane	74-83-9
Acetone	67-64-1	Carbazole	86-74-8
4-Chloroaniline	106-47-8	Carbon tetrachloride	56-23-5
Aniline	62-53-3	Chlorobenzene	108-90-7
Anthracene	120-12-7	Dibromochloromethane	124-48-1
Benzo(a)anthracene	56-55-3	Chloroethane	75-00-3
Aroclor 1016	12674-11-2	Chloroform	67-66-3
Aroclor 1221	11104-28-2	Chloromethane	74-87-3
Aroclor 1232	11141-16-5	Chrysene	218-01-9
Aroclor 1242	53469-21-9	cis-1,3-Dichloropropene	10061-01-5
Aroclor 1248	12672-29-6	Dibenzofuran	132-64-9
Aroclor 1254	11097-69-1	Dichlorodifluoromethane	75-71-8
Aroclor 1260	11096-82-5	Diethyl phthalate	84-66-2
Aroclor 1268	11100-14-4	Dimethyl phthalate	131-11-3
Benzene	71-43-2	Dibutyl phthalate	84-74-2

Table 2. Contaminants of concern for the Natural Resource Damage Assessment, northwestern Indiana—Continued

Constituent name	CAS Registry number	Constituent name	CAS Registry number
Organic compounds—Continued			
Di-n-octyl phthalate	117-84-0	N-Nitrosodi-n-propylamine	621-64-7
Hexachloroethane	67-72-1	N-Nitrosodiphenylamine	86-30-6
Ethyl benzene	100-41-4	N-Nitrosopyrrolidine	930-55-2
Fluoranthene	206-44-0	Xylene	1330-20-7
Fluorene	86-73-7	Polychlorinated-biphenyls (PCB’s)	1336-36-3
Hexachlorobenzene	118-74-1	Pentachlorophenol	87-86-5
Hexachlorobutadiene	87-68-3	Phenanthrene	85-01-8
Indeno(1,2,3-cd)pyrene	193-39-5	Phenol	108-95-2
Isophorone	78-59-1	Pyrene	129-00-0
Methylene chloride	75-09-2	Styrene	100-42-5
Naphthalene	91-20-3	Tetrachloroethene	127-18-4
Butyl benzyl phthalate	85-68-7	Toluene	108-88-3
N-Nitrosodibutylamine	924-16-3	trans-1,3-Dichloropropene	10061-02-6
Hexachlorocyclopentadiene	77-47-4	Trichloroethene	79-01-6
N-Nitrosodiethylamine	55-18-5	Trichlorofluoromethane	75-69-4
N-Nitrosodimethylamine	62-75-9	Vinyl chloride	75-01-4

Ground-Water-Quality Dataset

Only analyses of ground-water samples in which one or more contaminants of concern were detected are included in the water-quality compilation for this report. This compilation of detections provides the Trustees with data that can be used in determining if the acceptance criteria for injury to ground-water resources have been met. The location and identification number for all monitoring wells with at least one detection of a contaminant of concern are shown in plate 1.

The water-quality dataset includes 9,405 detections of contaminants of concern in water samples obtained from 485 wells, and are compiled in tables A (trace elements and species) and B (organic compounds) in appendix A on the attached compact disc. These data are ordered first by the monitoring well from which the sample was obtained, then by the constituent analyzed, and then by the date of sample collection. Only the month and year of data collection were available for 111 analyses obtained from paper reports.

The dataset also includes 126 analyses for organic data in which the constituent was identified both in the sample and in the laboratory blank. These analyses represent a potential environmental detection in ground water because the constituents were identified in the samples. Additional sampling and analysis is needed to validate the presence of these constituents exclusive of the identified laboratory interference. All concentrations were recorded as raw numbers to 5 decimal places—they do not contain information regarding the precision of the analytical results.

Table 3. Written communication references for ground-water-quality data from private reports and letters compiled by the U.S. Geological Survey Natural Resources Damage Assessment activity, northwestern Indiana

Written communication references and general identification of paper reports
Conservation Chemical Corporation
Richard Prober, Havens and Emerson, Inc., Hazardous waste assessment at Conservation Chemical Company, Final Report Oct. 1983, 30 p., written commun., October 1983
David G. Pyles, Environmental Restoration System Inc., Project no. 90-109, written commun., 1990
Dupont East Chicago Plant, East Chicago, Indiana
Pixie A. B. Newman, CHM2 HILL, Inc., Groundwater Assessment Phase I, written commun., February 22, 1990
Energy Cooperative, Inc.
Craig Carlson, Ecology and Environment, Inc., Expanded site inspection report for Energy Cooperative, Inc. East Chicago, Indiana, U.S. Environmental Protection Agency ID: IND 082547803, SS ID: None, TDD: F05-9009-005, PAN: FIN0078XA, written commun., February 27, 1991
Environmental Resources Management-North Central, Inc., for Jay A. Steinburg, Trustee in the matter of Energy Cooperative, Inc., No. 81 B 05811, written commun., September 5, 1984
Environmental Resources Management-North Central, Inc., 1984, Final Report: Environmental Hazards at the ECI East Chicago Refinery (Proposed), 24 p.
Timothy B. Jones, ARCADIS Geraghty & Miller, Inc., Quarterly sampling and analysis of co-produced groundwater from the main refinery system, Energy Cooperative, Inc. (ECI) refinery site, East Chicago, Indiana, Project no. NP0003950001, written commun., August 21, 1998
Partial report, no cover letter, maps note ERM as possible consultants, Project: 911103B, no date
Steven P. Sittler, Geraghty & Miller, Inc., Phase V-A Investigation Report, ECI Refinery, East Chicago, Indiana, written commun., October 19, 1993
Greg Skannal, Burns & McDonnell, Boring, monitoring well, and testing data for the area along Indianapolis Blvd., Project no. 89-49-4-001-02, written commun., 1991
Steven J. Vevang, Geraghty & Miller, Inc., Quarterly sampling and analysis of co-produced groundwater from the main refinery system, Energy Cooperative, Inc. (ECI) refinery site, East Chicago, Indiana, written commun., 1994
General American Transportation Company (GATX)
John Fleissner, CH2M HILL, Results of 2nd semi-annual ground-water sampling at East Chicago Plant No. 2, written commun., 1989
John Fleissner, CH2M HILL, Results of first semi-annual June 29, 1988 ground-water sampling at East Chicago Plant No. 2, written commun., September 6, 1988
John Fleissner, CH2M HILL, Results of water sampling including May 14, 1987 samples, written commun., July 22, 1987
John Fleissner, CH2M HILL, Results of priority pollutant inorganic and organic analysis of May 13, 1986 ground-water samples from the East Chicago Plant No. 2, written commun., June 23, 1986
John Fleissner, CH2M HILL, Results of the statistical analysis of 1985 East Chicago Plant No. 2 ground-water analysis, written commun., 1986
John Fleissner, CH2M HILL, written commun., November 27, 1985.

Table 3. Written communication references for ground-water-quality data from private reports and letters compiled by the U.S. Geological Survey Natural Resources Damage Assessment activity, northwestern Indiana—Continued

Written communication references and general identification of paper reports
General American Transportation Company (GATX)—Continued
John Fleisner, CH2M HILL, Ground water analyses for East Chicago Plant No. 2, Summary tables for November 1980 and November 1984 data, written commun., June 6, 1985
John Fleissner, CH2M HILL, Letter with results of first and second semiannual RCRA ground-water sampling for East Chicago Plant, sampled May 16, Oct. 18, 1984, written commun., January 22, 1985
John Fleissner, CH2M HILL, Cover letter no. L17035.AO, Results of RCRA ground-water sampling, May 6, 1983, written commun., February 23, 1984
John Fleissner, CH2M HILL, Water samples from July 6, 1983 collected at East Chicago Plant, written commun., August 16, 1983
John Fleissner, CH2M HILL, Letter to summarize ground-water monitoring, November 1980 and September 1982, East Chicago Plant, written commun., December 28, 1982
John Fleissner, CH2M HILL, Report attached describing study of subsurface conditions at East Chicago Plant No. 2, written commun., March 19, 1981
Michael Harris, CH2M HILL, Ground Water Hydrology Study for GATX East Chicago, Ind., Plant, written commun., July 28, 1980
Brian Hegge, Warzyn Engineering Inc., Summary of analytical results for ground-water samples received from the East Chicago, Ind., GATX facility for 1989 (July 20, 1989 and Dec. 28, 1989), written commun., February 22, 1990).
Indiana Department of Environmental Management, Office of Solid and Hazardous Waste Management, written commun., 1986 and Environmental Consultants, Laboratory Report, written commun., July 3, 1986
Paul McNally, NUS Corp., Sampling trip report, GATX Plant #2, sampling date November 12, 1984, EPA Case No. 3553, written commun., 1984
Karyl Schmidt, Indiana Department of Environmental Management, RCRA split samples, sampling date May 14, 1987, written commun., 1987
Karyl Schmidt, Indiana State Board of Health, Results of split sampling with GATX, sample date October 18, 1984, written commun., March 13, 1985.
Unknown author, CH2M HILL, Letter to report results of first quarter 1981 ground-water monitoring for East Chicago Plant, sampling dates April 21-22, 1981, written commun., May 27, 1981.
Randolph Videkovich, CH2M HILL, Water sample results from November 12 and 15, 1979, written commun., January 17, 1980
Craig Vinson, CH2M HILL, Letter with fourth quarter analytical results for East Chicago Plant, sampled November 16, 1981, written commun., January 27, 1982
Craig Vinson, CH2M HILL, Letter with results of samples received August 18, 1981, written commun., September 25, 1981
Ralston Street Lagoons (Gary Sanitary District)
Fluor Daniel Environmental Services Division, Report on Ralston Street Lagoon, Gary Sanitary District, Gary, Indiana, including results from sampling dates August 10 and September 20, 1983, December 27, 1984, and June 22, 1989
Gary Sanitary District, Appendixes for the Ralston Street lagoons remediation project: Final Report, written commun., 1989.

Table 4. Sources of data for the ground-water-quality dataset, Natural Resource Damage Assessment, northwestern Indiana

[GRITS/STAT, Ground Water Information Tracking System with Statistics Module; NWIS, National Water Information System]

Data Source	Approximate well-location accuracy (meters)	Number of different contaminants	Total number of analyses	Date range
GRITS/STAT	18	90	7,142	7/1/1981-6/9/1994
NWIS	31	51	728	11/6/1959-8/15/1996
Paper reports	Undetermined	91	1,535	11/12/1979-7/16/1998

Approximately 30 percent of the analyses have one or more codes for various quality-assurance categories including the following:

1. Replicates—All constituents that were analyzed two or more times from the same sample were considered replicates and were assigned a replicate code of “A“, “B”, “C”, and so on. For example, if one sample was analyzed three times for titanium, one analytical result would have a replicate code of “A”, a second analytical result would have a replicate code of “B”, and a third analytical result would have a replicate code of “C”.

2. Duplicates—Additional samples obtained sequentially from the same well during a single sampling event were considered duplicates and were assigned a duplicate code of “A”, “B”, “C”, and so on. Only the analytical results of the duplicate sample(s) were assigned a code. For example, if three sequential samples had been obtained from a well, the analytical results from the first sample would not be assigned any duplicate code, the analytical results from the second sample would be assigned a duplicate code of “A”, and the analytical results from the third sample would be assigned a duplicate code of “B”.

3. Splits—Samples from a well that were divided in half by volume and each half then analyzed for the same constituent(s) were referred to as “splits”. Splits were considered a type of duplicate. The analytical result from the first half of the split was not assigned any duplicate code and the analytical result of the second half was assigned a duplicate code of “W”. On occasion, a single duplicate sample was split. The analytical result from the first half of the split duplicate sample was assigned a duplicate code of “A” and the analytical results from the second half of the split duplicate sample was assigned a duplicate code of “X”.

4. Data Qualifiers—Up to two data-qualification codes conveying information regarding data validity or uncertainty could be associated with an analysis. There are nine different data-qualification codes—these codes and their meanings are summarized in table 5.

Table 5. Data qualifier codes for analyses in the ground-water-quality dataset for the Natural Resources Damage Assessment, northwestern Indiana.

[GC/MS, gas chromatography/mass spectrophotometer; GC/EC, gas chromotography with an electron capture detector]

Data qualifier code	Description
B	For organic data: The analyte was identified both in the sample and in the blank. All or part of the reported concentration may be because of laboratory contamination. For statistical analysis, professional judgment must be used in interpreting this data.
C	The analyte is determined to be present. The presence of the analyte was “confirmed by GC/MS”. Confirmed by GC/MS-pesticides are analyzed routinely by gas chromatography with an electron capture detector (GC/EC). When identified by GC/EC analysis in sufficient concentrations, pesticide identities are confirmed on the mass spectrometer by comparing the spectra of the analyte with the spectra of a particular pesticide. If a good spectral match is obtained, the pesticide identification is considered to be confirmed. The concentration is quantitated by GC/EC.
F	Measurements are from a field kit; results may be of limited accuracy.
G	Concentration reported is the higher of the environmental and duplicate samples analyzed.
J	The identification of the analyte is acceptable, but the quantitative value is an estimate. Estimated Value—Every sample analysis has quality-control criteria associated with the quantitative data that have been established based on similar analyses. When these criteria are exceeded, the value for that analyte or similar analytes is reported as an estimated value.
K	The analyte is determined to be present. The actual value is known to be ‘less than’ the recorded value. Less Than Values—The analyte is present, but the amount of the analyte is determined to be below an acceptable level for quantitation. The concentration can not be calculated but is determined to be less than the value given.
M	(Inorganics) Duplicate injection precision not met.
N	There is presumptive evidence that the analyte is present, but it has not been confirmed. The analyte is “tentatively identified”. (Tentative identification—There is an analytical indication that the analyte reported is present.) The quality-control requirements necessary for confirmation were not met.
05	Extra samples taken at composite stations.

Light-Nonaqueous Phase Liquids

Few data were readily available concerning the thickness of LNAPLs on top of ground water in the study area. Kay and others (1996) identified LNAPLs in 12 of approximately 250 measured monitoring wells in the study area during a synoptic survey in June 1992. Potential sources of inaccuracies in LNAPL thickness measurements are described in that report.

Additional LNAPL thickness data were compiled for measurements made during June, September, and December 1995 and November 1996. These data were obtained from files of various sources including IDEM, a water-quality database formerly maintained by the now closed Clean Sites, Inc., and the Amoco Corporation. A contour map showing the thickness of LNAPLs interpreted from these data (plate 2) was compiled for the NRDA area by Duwelius in 1997 and is included in this report (Richard Duwelius, U.S. Geological Survey, written commun., 2000). No data were available regarding the methods and associated accuracies of LNAPLmeasurements used to prepare this map.

Limitations on Use of the Ground-Water-Quality Dataset

Water-quality data obtained from GRITS/STAT and paper reports are recorded in the attached appendices on compact disc as originally reported from those sources. Some of the GRITS/STAT analyses, approximately 17 percent, had a blank in the “units” field and are reported as such. No attempts have been made to check or validate these data.

As previously noted, all concentrations are recorded as raw numbers to five decimal places. No inferences regarding analytical precision should, therefore, be made from the number of significant digits for any given concentration.

The dataset consists only of water samples with detections of the contaminants of concern. All analytical results for contaminants of concern that were reported as less than a reporting limit were considered nondetections, and were not included in the dataset. Only the wells with a sample with a contaminant detection were plotted in the figures for this report. Although present in the study area, wells from which water samples were obtained and a contaminant was not detected are not plotted on any figures in this report. Because the dataset represents only detections, the computation of distribution-based statistics from these data can be inappropriate or at least must be qualified as representing only detected concentrations. Caution must be exercised if quantitative statistical methods are applied to interpret the data.

SURFACE-WATER AND GROUND-WATER HYDROLOGY

The following section provides an overview of the surface-water and ground-water hydrology for the study area. This topic has been the subject of numerous studies, and in many instances the reader will be referred to the appropriate published material for additional detail.

Surface-Water Hydrology

Surface drainage in the study area generally is to the GCR, the IHC, and Lake Michigan in the north and to the LCR in the south. The drainage divide separating these areas of surface-water dischage approximately coincides with the Tolleston Beach Ridge, an arcuate upland in the southern part of the study area (fig. 2).

Surface-water flow in the NRDA portion of the study area has been altered greatly by human activity. Before about the early 1800's, the Little Calumet and Grand Calumet Rivers were sections of the same stream (Crawford and Wangsness, 1987, p. 6). The ancestral Calumet River originated to the south of the study area and flowed westward through the current LCR valley into Illinois. The channel made a hairpin turn in Illinois and flowed eastward back into Indiana through the current GCR valley and discharged into Lake Michigan near the Marquette Park Lagoons (fig. 1) (Shedlock and others, 1994, p. 16; Crawford and Wangsness, 1987, p. 6).

The development of portages, ditches, and canals connecting to Lake Michigan in northeastern Illinois through the 1800's slowed and eventually reversed the eastward flow in the ancestral Calumet River. The ancestral river mouth in Indiana eventually was closed by littoral drift of sand along the shoreline (Shedlock and others, 1994, p. 16). The opening of the IHC in 1909 divided the GCR into the east branch of the Grand Calumet River (EB-GCR) and the west branch of the Grand Calumet River (WB-GCR) (fig. 1). Additional details regarding pre-development drainage in the study area can be found in Cook and Jackson (1978) and Crawford and Wangsness (1987).

The GCR in the study area now consists of the two east-west oriented branches, the EB-GCR and the WB-GCR, that meet at the southern end of the IHC (fig. 1). The Marquette Park Lagoons are the headwaters for the EB-GCR—water from these lagoons flows westward through an underground culvert that discharges to the upstream end of the main channel at the eastern end of the U.S. Steel—Gary Works property (plate 1). Water in the main channel then flows westward approximately 10 mi to its confluence with the IHC. The EB-GCR ranges in depth from 3-4 ft in the upstream reaches and about 8-10 ft at the downstream end, and has an average velocity of approximately 1 ft/s (Crawford and Wangsness, 1987, p.3).

The WB-GCR is about 6 mi long and has a depth of about 2 ft. Stream velocity in the WB-GCR ranges from 0.2 to 1 ft/s (Crawford and Wangsness, 1987, p. 3). The WB-CGR has a surface-water divide that typically is near where I-90 (the Indiana Toll Road) crosses over the WB-GCR (fig. 1). Water in the WB-GCR flows eastward from this divide towards its confluence with the IHC and westward from this divide towards its confluence with the Little Calumet River in Illinois. The position of the divide is variable and influenced by numerous factors including water levels in Lake Michigan, the amount of effluent flow into the two branches of the GCR and the IHC, and the speed and direction of the wind (Crawford and Wangsness, 1987, p. 3).

In 1986, when record-high water levels in Lake Michigan were greater than 582 ft above sea level, Fenelon and Watson (1993) and Greeman (1995) reported that the drainage divide in the WB-GCR was absent. During this time, Lake Michigan drained southward through the IHC and then, along with flow from the EB-GCR, westward through the WB-GCR into Illinois (Greeman, 1995, p. 27). Historical water-level data for the period 1917 to 2000 (U.S. Army Corps of Engineers, 2002) indicate that average monthly water levels for Lake Michigan equaled or exceeded 582 ft above sea level only during June and July 1973, July 1974, and June through November 1986.

The main channel of the IHC extends northward approximately 3 mi from its confluence with the east and west branches of the GCR and then turns northeast for an additional 3 mi to its mouth at the Indiana Harbor and Lake Michigan. The east-west oriented Lake George Branch, approximately 2 mi in length, enters the IHC at the point where the main channel bends from heading north to heading northeast (fig. 1).

The drainage area for the IHC, which includes areas draining to the Lake George Branch, the EB-GCR, and the WB-GCR east of the flow divide, is less than 45 mi^2—it cannot be determined exactly because of the shifting location of the flow divide in the WB-GCR. The sandy texture of the soils in the area generally results in small contributions to streamflow from surface runoff.

Three USGS streamflow-gaging stations are located on the GCR/IHC in the study area. The mean annual discharge for the IHC at East Chicago (station number 04092750 in fig. 1) was 647 ft^3/s for the period of record 1994-99 (Stewart and others, 2000, p. 186). Backwater from Lake Michigan affects streamflow in the IHC and to a progressively lesser extent upstream into the EB-GCR and WB-GCR. Instantaneous measurements of streamflow indicate flow reversals for periods of minutes because of localized flow from Lake Michigan into the IHC (Renn, 2000, p. 8-9).

The EB-GCR at Industrial Highway gaging station (station number 04092677 in fig. 1) had a mean annual discharge of 484 ft^3/s for water years 1995-99 (Stewart and others, 2000, p. 185). The WB-GCR at the Hohman Avenue at Hammond gaging station (station number 05536357 in fig. 1) had a mean annual discharge of 44.9 ft^3/s for water years 1991-99 with occasional flow reversals (Stewart and others, 2000, p. 234).

Discharge of ground water to the GCR contributes less than 10 percent of the total streamflow (Crawford and Wangsness, 1987, p. 123). Discharge of industrial process water and discharge from municipal wastewater-treatment plants compose more than 90 percent of the streamflow in the EB-GCR and WB-GCR (Crawford and Wangsness, 1987, p. 123). Surface water generally flows from the EB-GCR and the WB-GCR (east of the flow divide) into the IHC and discharges to the Indiana Harbor and Lake Michigan.

Ground-Water Hydrology

The study area is underlain by approximately 40 ft to more than 225 ft of unconsolidated glacial, eolian, lacustrine, and paludal sediments of Pleistocene and Holocene age. These sediments were deposited on a bedrock surface modified by pre-Pleistocene erosion. This section describes the surficial aquifer, an underlying confining unit in the unconsolidated sediments, and a bedrock aquifer below the confining unit. The section also describes ground-water-flow directions and sources of recharge to and areas of discharge from ground water.

Calumet Aquifer

Surficial sands in the study area are known as the Lake Michigan sequence from the Quaternary Period (Brown and Thompson, 1995, plate 1). These eolian and lacustrine sands, along with localized made or modified land, form a surficial aquifer in the study area commonly referred to as the Calumet aquifer.

Substantial areas of the uppermost parts of the Calumet aquifer, primarily within the NRDA portion of the study area, are made or modified land composed of fill deposits. Thousands of acres of made land cover the original lake-bed sands along the Lake Michigan shoreline (fig. 2; Indiana Department of Natural Resources, 1979) with from 10 to 40 ft of slag, and more than 80 ft of slag in limited areas (Kay and others, 1997). Materials such as steel mill slag and coal ash and to a lesser extent municipal wastes, industrial wastes (excluding slag), construction debris, dredging spoil, ash and cinders, and biological sludges have been used to cover and fill low swampy land (Kay and others, 1997, p. 24 and plate 2). A large part of the NRDA area has been used for the disposal of an estimated $5x10^9$ ft^3 of principally steel and blast furnace slag. This estimate is based on areas previously mapped as containing steel-industry waste (Kay and others, 1997, plate 2), and multiplied by the average thickness of fill mapped in that area (Kay and others, 1997, plate 1).

The Calumet aquifer is unconfined throughout its extent with the exception of small areas where discontinuous layers of peat, muck, and organic deposits confine the sands (Duwelius and others, 1996, p. 5). The thickness of the Calumet aquifer (fig. 5) generally increases from west to east in the study area, and ranges from 0 ft in the extreme southwestern part of the study area to more than 100 ft in the northeast (Kay and others, 1996, p. 22). Well-driller records on file with the IDNR show approximately 55 wells open to the Calumet aquifer were drilled since 1959 for commercial, industrial, and domestic water supplies. It is likely that many of these wells still may be in use. However, the Calumet aquifer generally is not used for municipal or industrial water supply because most major users obtain their water supplies either directly from Lake Michigan or from the underlying bedrock aquifer.

Confining Unit

Throughout the study area, two unconsolidated units, the Quaternary Lake Border and Wheeler Till sequences (Brown and Thompson, 1995, plate 2), combine to form a confining unit between the underlying bedrock and the Calumet aquifer. These clay-rich unconsolidated units are glacially derived, composed primarily of eroded Mississippian-Devonian shale bedrock, and may contain thin discontinuous sand deposits (Kay and others, 1996, p. 24). The thickness of the confining unit (fig. 6) generally varies from slightly less than 50 ft to more than 150 ft.

Bedrock Aquifer

A carbonate bedrock aquifer (the ”bedrock aquifer”) is at the bedrock surface throughout the study area (fig. 7). This aquifer is composed of Devonian and Silurian carbonates, with a combined thickness of about 400 ft in the study area. The subcrop of the bedrock has about 75 ft of relief, and ranges in elevation from slightly less than 425 ft above sea level to slightly more than 500 ft above sea level within the study area. The most prominent feature of the bedrock surface is a north-trending valley just to the east of the IHC.

Generally, production wells only penetrate the upper 100 ft of the bedrock aquifer, as most supply needs are available within this interval (Fenelon, 1994, p. 23). Preglacial dissolution of the carbonate has increased permeability in the upper 100 ft of the bedrock aquifer. Whereas land-surface features indicative of karst topography have not been mapped on the buried bedrock surface, well drillers have reported cavern openings within the upper 100 ft of bedrock.

Ground-Water Hydraulic Properties

Hydraulic conductivity, in general terms, is a measure of the capacity for a porous medium to transmit water—the higher the hydraulic conductivity, the more readily water will move through the medium. The hydraulic gradient, in general terms, is a measure of the force pushing water in a given direction—a higher hydraulic gradient will result in more water moving in the direction of the gradient. These hydraulic properties along with the porosity, a measure of the open pore space in a medium, can be used to calculate a ground-water velocity. Following is a brief summary of findings from previous studies regarding these hydraulic properties in the study area.

Fig. 5

Fig. 6

Fig. 7

Horizontal and Vertical Hydraulic Conductivity

Within the study area, the Calumet aquifer, confining unit, and bedrock aquifer show demonstrably different ranges of horizontal and vertical hydraulic conductivities. Reported values for horizontal and vertical hydraulic conductivities in and near the study area are summarized in table 6.

Within the Calumet aquifer, Kay and others (1996, p. 32) noted a general trend of lower horizontal hydraulic conductivity from east to west. Geosciences Research Associates, Inc., (1988) indicate that the minor east-west variation in hydraulic conductivity coincides with a general westward thinning of the aquifer. They also observed a decrease in horizontal hydraulic conductivity with depth at one site in the study area that may coincide with a decrease in sand-grain size with depth. A 15:1 ratio of horizontal to vertical hydraulic conductivity was estimated for one aquifer test of the Calumet aquifer at the Midco I (plate 1) site (Geosciences Research Associates, Inc., 1987).

Horizontal hydraulic conductivities for the Calumet aquifer in Lake County were estimated from specific-capacity test data to range from 10 to 130 ft/d and averaged 60 ft/d (Rosenshein and Hunn, 1968). Kay and others (1996) measured horizontal hydraulic conductivities of the Calumet aquifer using slug-test methods that average rising and falling heads (Bouwer, 1989). Horizontal hydraulic conductivities in 10 wells screened in the Calumet aquifer in the study area ranged from 4.8 to 30 ft/d with an average of 17.9 ft/d (Kay and others, 1996, table 1). They also note that areas of the Calumet aquifer composed of fill deposits have more variable horizontal hydraulic conductivities. The highest horizontal hydraulic conductivity measured by Kay and others (1996, p. 32) for the Calumet aquifer was 360 ft/d in a well in northeastern Illinois that was screened in fill.

Duwelius (1996) investigated the hydraulic connection between the EB-GCR and the Calumet aquifer. Using slug-test methods that average falling head and rising head measurements, Duwelius calculated horizontal hydraulic conductivities for the streambed ranging from 0.01 to 1,200 ft/d and vertical hydraulic conductivities ranging from 0.3 to 73 ft/d (see Duwelius, 1996, p. 4-11 for details regarding methods for calculating horizontal and vertical hydraulic conductivities). Duwelius (1996) calculated the largest values of streambed hydraulic conductivity for locations composed of fill materials such as concrete and asphalt rubble. He also calculated the smallest streambed hydraulic conductivity values were at locations with soft fine-grained sediments.

In general, hydraulic conductivity estimates for the confining unit are several orders of magnitude less than those of the Calumet aquifer. Kay and others (1996, p. 30) reported a range of horizontal hydraulic conductivity for the confining unit in Cook County, Illlinois, immediately west of the study area, from approximately 0.00087 to 0.054 ft/d—these include values for the weathered upper parts of the confining unit under water-table conditions. Horizontal hydraulic conductivities for unweathered deeper parts of the confining unit probably are more representative of conditions in the study area, and range from 0.00087 to 0.0056 ft/d (Robert Kay, U.S. Geological Survey, written commun., 2002). Geosciences Research Associates, Inc. (1987 and 1988) reported horizontal hydraulic conductivity values in the confining unit in at Midco I and Midco II (plate 1) as ranging from 0.0003 to 0.0006 ft/d and vertical hydraulic conductivities ranging from 0.0002 to 0.003 ft/d. In general, hydraulic conductivity estimates for the confining unit are about 2 to 4 orders of magnitude less than those of the Calumet aquifer (table 6).

The horizontal hydraulic conductivity of the bedrock aquifer is more variable than the unconsolidated sediments. Kay and others (1996, p. 30), measured horizontal hydraulic conductivity values for the bedrock aquifer in Illinois ranging from 0.033 to 0.44 ft/d. Rosenshein and Hunn (1968) and Geosciences Research Associates, Inc. (1987) reported horizontal hydraulic conductivities for the bedrock aquifer in and south of the study area that ranged from 0.02 to 70 ft/d, depending on fracture and dissolution characteristics.

Table 6. Estimates of hydraulic conductivity of the Calumet aquifer, the streambed in the Grand Calumet River, the confining unit below the Calumet aquifer, and the bedrock aquifer, northwestern Indiana (Modified from table 6 in Fenelon and Watson, 1993)

[<, less than]

Hydrologic unit	Location[1]	Aquifer test type	Hydraulic conductivity direction	Range of hydraulic conductivity (feet per day)
Calumet aquifer	Lake County, Indiana	Specific capacity	Horizontal	[2]10 - 130
	Near Midco I	Aquifer test	Horizontal	[3]47 - 63
	Near Midco I	Aquifer test	Vertical	[3]3 - 4
	Near Midco I	Slug test	Horizontal	[3]3 - 84
	Midco I	Slug test	Horizontal	[3]<1 - 21
	Ninth Avenue Dump	Slug test	Horizontal	[4]<1 - 180
	Midco II	Slug test	Horizontal	[5]2 - 26
	Near Lake Michigan	Slug test	Horizontal	[6]<1 - 3
	Lake County, Indiana	Slug test	Horizontal	[7]4.8 - 30
	Cook County, Illinois	Slug test	Horizontal	[7]2 - 360
	Illinois and Indiana	Not specified	Horizontal	[7]2.1 - 30
Streambed	East Branch Grand Calumet River	Slug test	Horizontal	[8]0.01 - 1,200
	East Branch Grand Calumet River	Slug test	Vertical	[8]0.3 - 73
Confining unit	Lake County, Indiana	Specific capacity	Vertical	[2]0.0004
	Midco I and II	Slug test	Horizontal	[3,5]0.0003 - 0.0006
	Midco I and II	Permeameter test	Vertical	[3,5]0.0002 - 0.003
	Cook County, Illinois	Slug test	Horizontal	[7]0.00087 - 0.054
Bedrock aquifer	Lake County, Indiana	Specific capacity	Horizontal	[2]0.1 - 70
	Midco I	Slug test	Horizontal	[3]0.02
	Cook County, Illinois	Slug test	Horizontal	[7]0.033 - 0.44

[1] Locations of Midco I, Midco II, and Ninth Avenue Dump are shown in Plate 1. [2] Rosenshein and Hunn (1968). [3] Geosciences Research Associates, Inc. (1987). [4] Warzyn Engineering, Inc. (1987). [5] Geosciences Research Associates, Inc. (1988). [6] Baker/TSA Division (1984). [7] Kay and others (1996). [8] Duwelius (1996).

Horizontal and Vertical Gradients

Horizontal ground-water gradients in the Calumet aquifer are affected by the relief of the land surface and the variable water levels of the ground water, the GCR/IHC, and Lake Michigan. In the NRDA area, the land-surface relief north of the GCR is low, with a total relief of about 20 ft in undisturbed areas. South of the GCR to the drainage-basin divide with the LCR the surface relief is only slightly higher at about 30 ft.

The water table in the Calumet aquifer normally slopes toward the GCR, other streams and ditches, sewers, the IHC, and Lake Michigan. The slope of the water table near the GCR is nearly flat in the summers and generally increases during the winters (Fenelon and Watson, 1993, p. 25; Greeman, 1995, p. 28).

Fenelon and Watson (1993, p. 23) indicate that average horizontal hydraulic gradients in the Calumet aquifer generally fall within a narrow range. Gradients measured (a) during the fall of 1986, a period of very high lake levels (583.23 ft) and seasonally low ground-water levels, and (b) during the spring of 1989, when Lake Michigan levels were about average (579.50 ft) and ground-water levels were seasonally high, remained between 0.0005 to 0.003 ft/ft. Horizontal hydraulic gradients within about 500 feet of a ground-water discharge area to surface water only were slightly steeper, and approached 0.005 ft/ft (Fenelon and Watson, 1993, p. 23). Similarly, Greeman (1995, p. 28) reports the steepest horizontal hydraulic gradient, calculated from periodic data collected between 1986 and 1992, was less than 0.0038 ft/ft. Horizontal hydraulic gradients in the study area, based on water-level measurements obtained along eight transects during June 23-25, 1992, ranged from 0.00094 to 0.0051 ft/ft (Kay and others, 1996, table 2).

Kay and others (1996, p. 48) calculated the horizontal hydraulic gradient of the potentiometric surface of the Silurian-Devonian bedrock aquifer along an 8-mile east-west transect in northern Indiana and Illinois. The gradient dips westward toward a pumping center in the bedrock aquifer north of the confluence of the GCR and LCR in Illinois. Because the western 2 mi of this transect were in Illinois nearest the pumping center, the horizontal hydraulic gradient along the eastern 6 mi of this transect in the study area probably is less than the reported value of 0.0088 ft/ft (Robert Kay, U.S. Geological Survey, written commun., 2002).

Areas with upward vertical hydraulic gradients in the Calumet aquifer usually occur where ground water is discharging to surface water or drains, and downward vertical hydraulic gradients usually occur in recharge areas. Kay and others (1996, p. 54) calculated vertical hydraulic gradients in wells screened in the Calumet aquifer and located in the study area and in northeastern Illinois. Of 30 sets of paired wells, 16 sets had upward gradients and 14 sets had downward gradients. Downward gradients ranged from 0.00097 to 0.13 ft/ft and upward gradients ranged from 0.0012 to 0.33 ft/ft. As expected in a local flow regime in an unconfined aquifer, vertical flow direction and magnitude is approximately distributed equally between upward and downward directions.

Kay and others (1996, table 4) measured vertical hydraulic gradients between the water table and the middle of the confining unit, the base of the Calumet aquifer and the middle of the confining unit, and the middle of the confining unit and the top of the bedrock aquifer. These measurements were made in 5 well nests in the study area and 23 well nests in adjacent northeastern Illinois—vertical hydraulic gradients were downward in 4 of the 5 well nests in the study area and 20 of the 23 well nests in northeastern Illinois. Over half of these 28 measured vertical gradients were less than 0.2 ft/ft, and only one was greater than 0.9 ft/ft.

Kay and others (1996, table 4) also measured a downward vertical hydraulic gradient in 35 of 36 sets of paired wells measuring gradients between the Calumet aquifer and the underlying bedrock aquifer in northwestern Indiana and northeastern Illinois. The preponderance of downward vertical gradients between the Calumet aquifer, the confining unit, and the bedrock aquifer indicate the likelihood of downward flow from the Calumet aquifer through the confining unit and into the bedrock aquifer throughout the study area.

Ground-Water-Flow Velocities

Kay and others (1996, table 2) calculated horizontal ground-water velocities through the Calumet aquifer along eight transects in the study area with velocities ranging from 0.027 to 0.34 ft/d (Kay and others, 1993, table 2). Fenelon and Watson (1993, p. 23) estimated an average horizontal ground-water velocity for the Calumet aquifer of 0.14 ft/d. They indicated that local, short-term (hours and days) velocities could be as great as from 0.55 to 0.82 ft/d, especially near discharge areas and particularly when Lake Michigan levels are low. Horizontal ground-water velocities for water-table conditions in a weathered portion of the confining unit in northeast Illinois were calculated by Kay and others (1996) to range from 0.00044 to 0.0010 ft/d. Confined flow conditions prevail for the confining unit in the study area. Horizontal ground-water velocities in the confining unit in the study area probably are substantially less than those calculated for Illinois (Robert Kay, U.S. Geological Survey, written commun., 2002).

Vertical ground-water velocities through the confining unit were about from 10 to 100 times less than horizontal ground-water velocities through the Calumet aquifer. Kay and others (1996) estimated a vertical ground-water velocity of 0.038 ft/d directed principally downward through the weathered upper part of the confining unit in northeast Illinois and a downward vertical ground-water velocity of 0.0015 ft/d for the unweathered lower part of the confining unit. This latter velocity probably is more representative of flow through the confining unit in the study area. They also calculated horizontal ground-water velocities through the bedrock aquifer ranging from 0.014 to 0.029 ft/d.

In general, the reported values for hydraulic conductivity, hydraulic gradients, and ground-water velocities indicate the following:

(1) Hydraulic conductivities in the Calumet aquifer generally are 2 to 4 orders of magnitude greater than conductivities in the underlying clay confining unit. The high contrast in hydraulic conductivities between the Calumet aquifer and the underlying confining unit, combined with generally small (less than 0.2 ft/ft) vertical gradients, indicate that net exchange of ground water between the confining unit and the Calumet aquifer is minor as compared to the total amount of ground-water flow within the Calumet aquifer;

(2) Ground-water flow in the underlying confining unit is mostly vertical with relatively minor amounts of horizontal flow; and

(3) Although the net ground-water exchange between the Calumet aquifer and the confining unit is relatively small compared with the total amount of ground-water flow in the Calumet aquifer, the vertical gradients indicate that more ground water flows downward from the Calumet aquifer into the confining unit than flows upward from the confining unit into the Calumet aquifer.

Water-Level Fluctuations

Ground-water levels in the study area commonly reach an annual maximum in June or July corresponding to periods of higher precipitation (National Oceanic and Atmospheric Administration, 1990) and moderate evapotranspiration. Annual minimum ground-water levels typically occur in September and October and often are followed by a rise during February or March because of recharge from the spring thaw.

Ground-water levels in the Calumet aquifer generally are stable and typically will vary less than 0.2 ft in a 4-day period (Greeman, 1995, p. 23), although larger fluctuations do occur, particularly in response to major precipitation events. Small diurnal fluctuations in ground-water levels because of evapotranspiration are common in wetlands and other vegetated areas. These small diurnal fluctuations can be seen in the hourly ground-water-level data (fig. 8) collected from well LK-13 (fig. 1) in a wetland area. During the day, water is absorbed by plant roots and transpired to the atmosphere from the leaves. The hydrograph in figure 8 shows how this activity lowers the water level several tenths of a foot each day. At night the plant activity decreases and water levels partially rebound (Greeman, 1995, p. 22), resulting in small daily declines of the water table. The almost 1-foot rise on May 11, 1991, indicates a water-level response to a precipitation event.

Greeman (1995) analyzed periodic water-level measurements collected in the study area between August 1985 and September 1992. Ground-water level changes, as the total difference between the highest and lowest measured water level in a well, generally ranged from 0.4 ft in a well near the upstream end of the EB-GCR to 5.01 ft at well LK-13 (fig. 1), with a mean change for the data-collection period of about 2.3 ft. Additional periodic measurements collected during 1992-2000 (Stewart and others, 2001) showed comparable fluctuations in ground-water levels.

The largest fluctuations observed in surface-water levels were in Lake Michigan and along the downstream reach of the IHC. From August 1985 to September 1992, Lake Michigan levels, measured at the southern end of Gary Harbor at site S14 (fig. 1), fluctuated 3.80 ft. During the same time, water levels on the IHC, approximately 0.4 mi south of US-12, fluctuated 3.71 ft—nearly an equivalent amount. Water-level changes on the IHC and the east and west branches of the GCR generally decrease in the upstream direction. Greeman (1995) reports water-level changes at six sites on the EB-GCR and two sites on the WB-GCR ranged from 2.19 to 2.45 ft from August 1985 to September 1992. Three circumstances contribute to this generally low magnitude of water-level changes in the GCR/IHC:

1. Most of the flow (approximately 90 percent according to Crawford and Wangsness, 1987) is industrial or municipal effluent, discharged at a generally constant rate;

2. Much precipitation infiltrates into the surficial sands, thereby reducing runoff; and

3. Total topographic relief in the study area is low, generally less than 45 ft.

Water-level changes of greater than 3 ft can occur in Lake Michigan because of the build up of lake water near the shoreline caused by winds blowing towards the south. This phenomenon is known as a seiche. A wind-induced rise in surface-water level in this area is short term and usually dissipates in a matter of hours (Greeman, 1995, p. 27; Fenelon and Watson, 1993, p. 24). Short-term, wind-induced changes in the water level in the GCR/IHC, although generally smaller in amplitude, have been observed as much as 7 mi upstream from Lake Michigan on the EB-GCR (Fenelon and Watson, 1993, p. 24). Fenelon and Watson (1993, p. 24) and Greeman (1995, p. 27) report that during the record-high Lake Michigan levels of 1985-1987, backwater effects were observed as much as 11 mi upstream on the EB-GCR and 7 mi upstream on the WB-GCR.

The generally small ranges of observed fluctuations in surface water (up to about 3.8 ft) and ground water (up to about 5 ft) contribute to generally stable flow regimes for both of these resources. Although directions of ground- and surface-water flow can change with time, these changes generally are localized and happen within hours to days.

Recharge and Discharge

Before urbanization and industrialization of the study area, recharge to the Calumet aquifer primarily was through direct infiltration of precipitation and upward ground-water flow from the bedrock. Discharge was primarily to rivers, streams, Lake Michigan, and through evapotranspiration (Fenelon and Watson, 1993, p. 15).

Urbanization and industrialization have greatly altered this natural recharge and discharge cycle. Once natural areas that are now covered with impervious buildings and pavement have reduced recharge from precipitation (Fenelon and Watson, 1993, p. 15; Kay and others, 1996, p. 29). Water withdrawals in the Chicago, Illinois area from the underlying bedrock aquifer and the deeper Cambrian-Ordovician aquifer have produced a cone of depression extending into Indiana. The water withdrawals have created downward vertical gradients, as discussed in the previous section, between the Calumet aquifer and the bedrock aquifer.

Other human activities also affect recharge and discharge. Leaky sanitary sewers, septic systems, and water-supply lines can lose water to the aquifer and function as local sources of recharge; leaky sanitary and storm sewers also can receive water from the aquifer and function as local discharge points; ditches and artificial water impoundments can function as both a source of recharge and as a discharge point.

Numerous finite-difference ground-water models in or near the study area have used a wide range of recharge rates, from 2 to 23 in/yr, depending on what parts of the aquifer were being simulated (Warzyn Engineering Inc., 1987, appendix V; Watson and others, 1989; Meyer and Tucci, 1979; Fenelon and Watson, 1993). Rosenshein and Hunn (1968) estimated recharge to the Calumet aquifer in Lake County to be less than 13 in/yr. The complexity of natural and artificial sources of recharge in the study area results in a wide range of, and increased uncertainty in, estimates for aquifer recharge rates.

Surface-Water / Ground-Water Interaction

Surface- and ground-water levels and directions of flow are closely related in the study area. This section describes the nature of the relation between surface and ground water, and discusses how various factors affect interactions between the two.

Ground and surface water in the study area are known to be in good hydraulic connection (Greeman, 1995, p. 23 and 27). Lake Michigan, the GCR/IHC, and other streams and ditches in the study area generally function as the base level for the water table in the Calumet aquifer. When the base level (surface water) rises, the water-table slope decreases, reducing ground-water velocities and discharge rates. Conversely, a lowering of the base level (surface water) results in an increase in the water-table slope, and increases ground-water velocities and discharge rates. If the level of Lake Michigan were to rise permanently, the ground water would most likely reestablish the previous slope at a higher elevation (Greeman, 1995, p. 27).

The ground-water/surface-water relation is illustrated by Fenelon and Watson (1993) along transects of wells and surface-water measuring points at four sites located adjacent to the IHC and the EB-GCR and WB-CGR (fig. 9). Water-level profiles along these transects for two time periods are shown in figure 10—August 1986 when Lake Michigan levels were seasonally high and ground-water levels were seasonally low, and March 1988 when Lake Michigan levels were seasonally low and ground-water levels were seasonally high. Note the higher water-table slope during the period with seasonally low surface-water levels and the lower water-table slope during the period with seasonally high surface-water levels.

During the period of seasonally high surface-water levels, there is a reversal in the water-table slope immediately adjacent to the stream bank at sites 1 and 3. Reversals usually are caused by a lowering of the water table through evapotranspiration and/or a lack of precipitation. A concurrent rise in surface-water levels will enhance these reversals. Hydrographs for the wells and surface water at sites 1 through 4 during a 30-day period in May and June of 1986 are shown in Figure 11. This was a period when Lake Michigan water levels were at a record high (Greeman, 1995, p. 24). The hydrographs at sites 2 and 4 show occasional reversals of short duration, whereas site 1 shows a reversal for most of the 30-day period.

The typical pattern of ground-water discharge from the Calumet aquifer to the IHC, the EB-GCR and the WB-GCR is not substantially changed because of the short duration and localized extent of gradient reversals between ground water and surface water. Periodic water-level measurements collected between 1985 and 2000 (Greeman, 1995; Stewart and others, 2001) indicate that gradient reversals at these sites typically are of short duration, on the order of hours to 3 to 4 days. Reversals of a duration greater than 3 to 4 days, as seen at site 1, probably only occur during periods of more extreme conditions, such as the record-high Lake Michigan levels during May and June of 1986.

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Effects of Municipal and Industrial Discharges

The predominance of industrial and municipal effluent in flow of the GCR contributes to minimizing surface-water level changes and stabilizing the typical gradient from ground water to surface water. Crawford and Wangsness (1987, p. 32) determined the dry-weather flow in the GCR is composed almost exclusively of industrial and municipal effluents. Based on streamflow measurements obtained during a diel study in October 1984, it was estimated that all but about 36 of the 500 ft^3/s average flow in the EB-GCR, and all of the approximately 17 ft^3/s average flow in the WB-GCR, is attributed to effluent. Because the effluent discharge constitutes approximately 90 percent of the flow in the GCR and the discharge rates of these effluents are generally constant through time, the steady discharge contributes to minimizing surface-water-level fluctuations and associated changes in the water-table slope in adjacent areas.

Effects of Sheet-Pile Barriers

Sheet-pile barriers have been used in the NRDA area along major parts of the Lake Michigan shoreline and parts of the IHC (plate 1). Sheet piles, composed of interlocking walls of sheet steel, usually are driven through the Calumet aquifer and anchored in the underlying confining unit. Most of the sheet piles have been emplaced to create stable vertical faces to the shoreline.

More than half of U.S. Steel—Gary Works lake front is lined in sheetpiling, as is all but 500 ft of the mile-long Gary Harbor. From U.S. Steel—Gary Works west to the Inland Steel Corporation property, only a part of Buffington Harbor has a sheet-pile barrier. Almost all of the 6.8-mile perimeter of the Inland Steel Corporation property is lined in sheet pile, and there are sheet-pile barriers within the fill areas. Similarly, about 90 percent of the former LTV Steel Company's Lake Michigan perimeter has a sheet-pile barrier. Almost half of the remaining shoreline west of the former LTV Steel Company to the Illinois-Indiana State line has a sheet-pile barrier. Virtually all of Indiana Harbor, much of the northern half of the IHC, and lesser areas along the downstream parts of the southern half of the IHC and the Lake George Branch also have sheet-pile barriers (plate 1).

The hydraulic effects of sheet piles are to increase water levels behind the barriers and reduce ground-water flow across the barriers. Inland Steel built their entire facility on filled areas, using sheet piles to define the perimeter, and filled inside the perimeter with slag, calcium oxide, and other solid wastes from the steel manufacturing process. Although there are openings in the sheet-pile barrier at the south end of the Indiana Harbor and process-water outflows at several of the openings, water levels within the enclosure remain approximately 5 ft above Lake Michigan level. A similar situation has been described for much of U.S. Steel—Gary Works property (Greeman, 1995, figs. 8 through 13). These relatively high water levels may cause a localized increase in the rate of downward ground-water flow into the confining unit.

Although engineering technology would indicate that sheet piles are 100 percent effective in blocking horizontal ground-water flow, there is much visual evidence that sheet-pile barriers in the study area are leaky (Jim Smith, Indiana Department of Environmental Management; Dan Sparks, U.S. Fish and Wildlife Service; Scott Morlock, U.S. Geological Survey, oral commun., 2000). Metal sheet piles have been corroded extensively in many areas by slag runoff (Bayless and others, 1998).

Effects of Sewers

A substantial amount of ground water infiltrates into the sanitary sewers that underlie much of the study area (fig. 12) (Fenelon and Watson, 1993, p. 16). It is likely that most of this ground water, after being processed at a wastewater-treatment plant, eventually is discharged to the GCR, the IHC, or Lake Michigan. Fenelon and Watson (1993, p. 38) report the combined estimates of ground-water sewer infiltration from sanitary districts that include the cities of Gary, Hammond, Whiting, and East Chicago ranged from 15 to 50 ft^3/s. They attribute this wide variability to the difficulty in estimating and measuring domestic and industrial discharges to sewers, and total amounts of water being received at wastewater-treatment plants. Ground-water discharge to sewers is variable and is highly dependent on seasonal ground-water levels. More water infiltrates to sewers when ground-water levels are high than when ground-water levels are low, thereby complicating estimates of ground-water infiltration. A finite-difference model analysis performed by Fenelon and Watson (1993) indicates that the amount of ground-water discharge to sewers is most likely in excess of the amount of recharge from precipitation in the sewered areas.

Leakage to sewers tends to minimize ground-water-level fluctuations and contributes to stabilizing the ground-water-flow regime in affected areas. If the sewers are situated below the water table, they generally will continually receive ground water from the aquifer; this inflow to the sewer will persist until the water level in the aquifer falls to approximately the same elevation as the leaky sewer line. If they are situated above the water table, they generally will lose water to the aquifer; this loss to the aquifer will persist until the water level in the aquifer rises to approximately the same elevation as the leaky sewer line.

Effects of Pumping

Pumping from the Calumet aquifer to dewater specific sites is common in the study area. Construction companies often use pumping to dewater areas of earth-moving activities and underground construction sites, and pumping is used to maintain water levels below the bottom of sand- and gravel-mining excavations. Numerous manifold-type dewatering systems are in place to restrict contaminant movement across property boundaries and/or to recover soluble and insoluble contaminants from the aquifer (Greeman, 1995, p. 29).

Pumping lowers ground-water levels and creates a depression in the water table surrounding the pumpage. Ground-water gradients along most of the GCR/IHC usually are toward the river and canal (Fenelon and Watson, 1993, p. 25). If a depression in the water table because of pumpage extends outward from the pumping location to the GCR/IHC, a flow reversal can result and surface water can flow from the canal/river into the aquifer towards the pumping center. Periodic water-level data collected between 1986 and 1992 by Greeman (1995) indicated one occurrence of this nature that is discussed in greater detail in the section “Directions of ground-water flow”.

Effects of Wetlands

Wetlands in the study area may be important in decreasing ground-water gradients and the development and duration of transient reversals along parts of the GCR/IHC. Wetlands in the study area (fig. 3) are, with a few exceptions, less than 50 acres and are situated mostly along or near streams, lakes, ponds, and ditches. Wetlands typically are among the more densely vegetated areas in the highly urbanized and industrialized GCR/IHC watershed. Ground-water gradients near the stream bank tend to flatten out, and even occasionally reverse, during periods of seasonally low ground-water levels that typically accompany the summer growing season (figs. 9-11). Fenelon and Watson (1993, p. 29) report that transient gradient reversals along stream banks lasted relatively longer in areas that were vegetated (site 1 in figs. 9-11) than in areas with little or no vegetation (site 2 in figs. 9-11).

Fig. 12

Directions of Ground-Water Flow

The configuration of the water table, interpreted from synoptic water-level measurements in the Calumet aquifer for all or parts of the study area, has been mapped for various time periods by numerous investigators, including: Watson and others, 1989; Fenelon and Watson, 1993; Shedlock and others, 1994; Greeman, 1995; and Kay and others, 1996. Maps and information from these publications are used to describe ground-water flow in the Calumet aquifer, particularly in relation to the directions and discharge points for ground water and associated dissolved contaminants.

The ground-water-flow system in the Calumet aquifer is typified by broad flat water-table mounds that function as ground-water divides underlying topographically higher areas of land (figs. 13-15). Ground water in the Calumet aquifer generally flows laterally away from these divides and discharges to streams and wetlands in adjacent low-lying areas and to Lake Michigan. Dissolved contaminants transported by an advective process also will follow these general flow paths. Localized changes in this pattern occur where ground water discharges to sanitary sewers, small ditches, or areas of pumping at quarries, dewatering systems (containment systems) and sites of ground-water remediation, or where there are barriers to ground-water flow, such as sheet piles (Shedlock and others, 1994, p. 21; Kay and others, 1996, p. 29, Fenelon and Watson, 1993, p. 23; Greeman, 1995, p. 28).

Many of these typical ground-water-flow patterns can be seen in the water-table configuration for February 26-March 1, 1990, from Greeman (1995, p. 36) (fig. 13). Two major east-west trending ground-water divides are present in the study area. One divide (fig. 13) is beneath the topographic high associated with the Tolleston Beach Ridge (fig. 2). North of this divide, ground water flows northward toward and discharges to the GCR, or, at the extreme eastern end of the study area, ground water may discharge directly to Lake Michigan. South of this divide ground water flows southward towards and discharges to the LCR (Kay and others,1996, p. 44). This ground-water divide generally coincides with the surface-water divide (fig. 1) between drainage to the LCR to the south and drainage to the CGR to the north. Fenelon and Watson (1993, p. 23) point out that the crest of this divide shifted vertically by only 1 to 2 ft with minimal horizontal change between April 1986 and April 1989.

A second major east-west trending divide is between the EB-GCR and Lake Michigan east of the IHC. Ground water flows northward from this divide toward and discharges to Lake Michigan, and southward from this divide toward and discharges to the EB-GCR.

Another smaller east-west trending ground-water divide between Gary Harbor and the western Marquette Park lagoon (fig. 13) was indicated by Fenelon and Watson (1993, figs. 8-10) for March 1986, September 1986, and April 1989, and by Kay and others (1996, plate 1) for June 1992. This divide was not defined explicitly by the water-table contours for February-March 1990 (fig. 13), probably because fewer data points were used in this area to prepare the February-March 1990 water-table map than were used to prepare the other maps. The water-table contours in figure 13 do not in any way contradict or preclude this divide, and it is drawn in figure 13 with a dashed line (approximated), as are the associated directions of flow. Ground water generally flows radially off this divide toward and discharges to Lake Michigan, Gary Harbor, the very upstream reach of the EB-GCR, and the western Marquette Park Lagoon.

Two smaller northeast-southwest trending divides are present on either side of the IHC downstream of the confluence with the Lake George Branch (fig. 13). Ground water generally flows from these divides toward and discharges to the IHC, Indiana Harbor, and Lake Michigan.

All of the ground-water divides described above, with the possible exception of the small divide east of Gary Harbor, are stable features of the ground-water-flow system in the study area as these features do not change throughout time. These divides and associated flow patterns are present in all water-table configurations presented by numerous authors (Watson and others, 1989; Fenelon and Watson, 1993; Greeman, 1995; Kay and others, 1996).

There are several depressions in the water table on the east and west sides of the IHC (fig. 13). Other smaller water-table depressions also are present in other places at other times (fig. 14). In general, the size, vertical extent, and shape of these depressions vary with time, and form as a result of localized lowering of the water table. These depressions are most likely because of infiltration of ground water into sanitary sewers, drainage to small ditches, and discharge to dewatering systems or ground-water remediation pumpage. Patterns of ground-water flow are subject to more temporal and spatial changes in these areas where localized water-table depressions form. Typically, ground-water flow is radial from the surrounding areas toward the water-table depression.

Two small depressions in the water table are shown in the western part of figure 14. The southernmost of the two depressions probably was created by dewatering at a quarry that was discontinued sometime prior to February 26, 1990. No evidence of this depression is seen in water-level data from this area after March 1990 (Greeman, 1995, table 5; Kay and others, 1996, plate 1; Stewart and others, 2001). This depression extended to the EB-GCR and probably induced surface water from the river to flow into the aquifer toward the pumping.

The northernmost depression appears sporadically through time (Greeman, 1995, figs. 11-13; Fenelon and Watson, 1993, figs. 8-10) and probably results from local dewatering on the U.S. Steel—Gary Works property (plate 1). Both of these depressions produce relatively small local perturbations on ground-water-flow patterns in the area. Most ground water in this area still flows north and south from the east-west trending divide and discharges to Lake Michigan and the EB-GCR respectively.

Ground-water flow patterns in the area surrounding the IHC for the period February 26-March 1, 1990 (Greeman, 1995) indicate that five localized depressions in the water table have altered typical ground-water-flow patterns (fig. 15). The three southernmost depressions are a result of infiltration of ground water into leaky sewers (Greeman, 1995, p. 28; Fenelon and Watson, 1993, p. 16, 19, 23; Kay and others, 1996, p. 44; Watson and others, 1989, p. 30). These depressions produce divides between ground water flowing toward and discharging to the IHC and the Lake George Branch, and ground water flowing into the depressions and discharging into buried sewer lines. Ground-water discharge into the sewers tends to stabilize the ground-water-flow regime in these areas.

Another small depression in the water table is shown to the north of the Lake George Branch (fig. 15). This depression explicitly is indicated on water-table maps for April 1989 (Fenelon and Watson, 1993), November 1990 (Greeman, 1995), and June 1992 (Kay and others, 1996), and is shown as an area of lowered water levels on water-table maps for other periods. This water-table depression was caused by pumping by an oil refinery as part of a remediation effort (Fenelon and Watson, 1993, p. 19). It is most likely that much of the ground water draining to leaky sewers or pumped from the Calumet aquifer eventually is discharged to the GCR, IHC, or Lake Michigan.

Contaminants dissolved in ground water and transported by an advective process are most likely to discharge to the same areas as ground water. Most ground water from the NRDA area commonly discharges to the EB-GCR, the WB-GCR east of the flow divide, the IHC, or Lake Michigan (fig. 16). In smaller areas north and south of the Lake George Branch, immediately east of the IHC, and immediately north of the EB-GCR, ground water discharges to sewers or pumping wells. In parts of these areas, the ground-water discharge area is indeterminate from the available data. These discharge areas are based on the flow interpretations in this section and on surface- and ground-water-level data, water-table maps, and ground-water information in this and other reports (Watson and others, 1989; Fenelon and Watson, 1993; Shedlock and others, 1994; Greeman, 1995; Kay and others, 1996).

Fig. 13

Fig. 14

Fig. 15

Fig. 16

CONTAMINANT DETECTIONS IN GROUND WATER

The most frequently detected contaminants of concern in ground water from the study area are listed in Tables 7 and 8. The classification “most frequently detected in all samples” was made by assessing the number of times a contaminant was detected in all water samples (table 7). The classification “most frequently detected in two or more samples from a well” was made by assessing the number of wells in which a given contaminant was detected in at least two samples (table 8).

The 10 most frequently detected trace elements or species by both classifications were arsenic, lead, chromium, nickel, cyanide, zinc, selenium, cadmium, mercury and copper (tables 7 and 8). Most detections of the 10 most frequently detected trace elements or species were in samples from areas where ground water commonly discharges to the Grand Calumet River, the Indiana Harbor Canal or Lake Michigan (figs. 17-26).

The 15 organic compounds that were most frequently detected in all samples were phenol, benzene, toluene, bis (2-ethylhexyl) phthlate, methylene chloride, xylene, acetone, ethyl benzene, naphthalene, methyl-ethyl ketone, dibutyl phthalate, trichloroethene, 4-methylphenol, benzoic acid, and 2,4-dimethylphenol. The 15 organic compounds that were most frequently detected in two or more samples from each well, also included 4-methyl-2-pentanone (MIBK) but did not include acetone (table 8).

Based on this list and on compounds with specific toxicologic importance, as expressed by NRDA Trustee representatives, the locations of wells with at least one detection of the following organic compounds or groups of organic compounds are shown in figures 27-37: phenolic compounds (phenol, 2,4,6-trichlorophenol, 2,4-dichlorophenol, 2,4-dimethylphenol, 2-chlorophenol, 2-methylphenol, 2-nitrophenol, 4-chloro-3-methylphenol, 4-methylphenol, 4-nitrophenol, or pentachlorophenol), benzene, toluene, ethyl benzene, xylene, methylene chloride, acetone, naphthalene, polychlorinated biphenyl, bis(2-ethylhexyl) phthalate, and methyl ethyl ketone. Most detections of these organic compounds were in samples from areas where ground water commonly discharges to the Grand Calumet River, the Indiana Harbor Canal or Lake Michigan (figs. 27-37).

The other potential discharge areas all had smaller numbers of detections of contaminants of concern (tables 7 and 8). Because the ground-water-quality dataset was composed entirely of samples with detections of contaminants, it was not possible to evaluate whether the other areas have similar densities of sampled wells.

Interpretation of the above statistics is limited by various factors. All wells were not sampled the same number of times. The classification “most frequently detected in all samples” can overstate the areal extent of contaminant detections if several very frequently sampled wells in a contaminated part of the aquifer increase the absolute number of detections for a contaminant. The classification “most frequently detected in two or more samples from a well” does not imply that the detections were sequential in time and represented a continuous condition. Uncertainty of the location of some wells also may affect their classification relative to areas of the ground water that discharge to a common area.

Concentrations of three organic compounds that are among the most commonly detected in ground water also are suspected to be affected by sampling or laboratory procedures. For example, di-n-butylphthalate and bis(2-ethylhexyl) phthalate were detected in ground-water samples from northwestern Indiana and in similar concentrations in laboratory and field blank samples (Duwelius and others, 1996, page 47). Detections of methylene chloride (also known as dichloromethane) in laboratory blank samples from other studies by Mann (1990) and Brock and others (1994) have been attributed to its use as a laboratory solvent. Additional analysis of available data, new sampling of water from wells where these contaminants of concern were detected, and analysis of those data may be necessary to resolve whether the contaminant occurrences were environmental in nature or were affected by sampling procedures or sample handling.

Thicknesses of free-phase oil or organic compounds at the water table in the Calumet aquifer, measured as LNAPLs, ranged from a “film” to approximately 2.3 ft in 11 of the approximately 250 wells in the NRDA area that were surveyed by Kay and others (1996, table 5). The thickness was greater than 10.6 ft in a twelfth well in that survey (Kay and others, 1996, table 5). Additional data, collected in 1995 and 1996 and compiled by the USGS from private sources (Richard Duwelius, U.S. Geological Survey, written commun., 2000), indicated measurable thicknesses of LNAPLs in the Calumet aquifer under large parts of the area north of the Lake George Branch (plate 2). Smaller areas of LNAPLs were mapped south of the Lake George Branch on the east and west sides of the IHC. The areas of measurable LNAPL thickness presented in Plate 2 include areas where ground water commonly discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan and places where ground-water-discharge locations are variable or cannot be determined with available data.

Physical, Chemical, and Microbial Processes that Potentially Affect Contaminants in Ground Water

The purpose of this section is to describe processes that could affect the probable migration of some of the most frequently detected contaminants in ground water toward the potential major areas of ground-water discharge. If no processes affect the movement of a contaminant, it’s velocity and direction of migration is equal to that of ground-water flow (Freeze and Cherry, 1979, p. 389). Physical processes, such as hydrodynamic dispersion and dilution of ground-water discharge by mixing with surface water, can decrease contaminant concentrations. Chemical and microbial processes can slow the rate of transport of some contaminants relative to ground-water flow, or can contribute to dissolution or desorption of contaminants into ground water long after the original source has been mitigated or removed. The specific physical, chemical, and microbial processes that potentially affect contaminant concentrations and transport cannot be examined in detail using the available information. The processes also are described relative to how they may affect concentrations and transport of representative trace elements, species and organic compounds detected in the ground-water-quality dataset.

Physical Processes

Transport of dissolved contaminants by the motion of flowing ground water is defined as advection (Freeze and Cherry, 1979, p. 75). Non-reactive contaminants are transported at about the velocity of ground-water flow because of advection. Ground-water velocities in the Calumet aquifer and the confining unit that represent the velocity of advective transport of contaminants are discussed earlier in this report.

The mechanical mixing of ground water during advective flow through pores in an aquifer causes dissolved contaminants to “spread out” in the aquifer and decrease in concentration. The mechanical mixing is called hydrodynamic dispersion. The magnitude of dispersion relates to: microscopic velocity differences as ground water flows between and across pore surfaces, differences in pore sizes along flow paths through the aquifer, and the mixing related to the branching, interfingering, and the tortuous characteristics of pore spaces along the flow paths. Dispersion also includes diffusive transport—the migration of a contaminant in the direction of its concentration gradient. Diffusion is not an important factor in dispersive transport of a contaminant unless ground-water velocities are very small, such as in unfractured shale or clay deposits (Freeze and Cherry, 1979, p. 104).

At the ground-water and surface-water interface where a contaminant plume discharges to surface water, the complex patterns of flow can mix ground water and surface water. This mixing can decrease the apparent concentrations of a ground-water contaminant to some intermediate value between that in ground water and that in surface water. The flow of contaminants into surface water is affected by the permeability of the streambed sediments and the horizontal and vertical gradients between ground water and surface water (Conant, 2000). In high permeability zones, streambed sediments may allow direct contaminant transport into surface water without any chemical or microbial degradation or retardation. In low to moderate streambed permeability zones, contaminant transport can be slowed by chemical and microbial processes in the streambed sediment.

Table 7. Number of water samples in the ground-water-quality dataset in which trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study, northwestern Indiana.

Trace element or trace species name	Number of samples in which trace elements or trace species were detected				
	Total number of samples with detections	From areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan	From areas where ground water discharges to sewers or pumping wells	From areas where the ground-water discharge area is indeterminate	From areas where ground water discharges to the Little Calumet River or south of the study area
Arsenic	952	829	1	114	8
Lead	596	437	2	136	21
Chromium	554	514	0	26	14
Nickel	462	421	1	29	11
Cyanide	418	397	0	11	10
Selenium	399	370	0	28	1
Zinc	399	309	0	62	28
Cadmium	370	291	0	73	6
Mercury	239	206	0	29	4
Copper	223	179	1	11	32
Silver	223	213	0	10	0
Vanadium	149	116	1	7	25
Antimony	119	113	0	6	0
Cobalt	101	95	0	1	5
Beryllium	94	93	0	1	0
Thallium	92	70	1	19	2
Strontium	65	59	0	3	3
Molybdenum	14	0	0	13	1
Titanium	4	4	0	0	0
Chromium, hexavalent ion	2	2	0	0	0

Table 7. Number of water samples in the ground-water-quality dataset in which trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study area, northwestern Indiana—Continued

	Number of samples with organic compound detected by analysis				
Organic compound name	Total number of samples with detections	Number of detections from areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan	Number of detections from areas where ground water discharges to sewers or pumping wells	Number of detections from areas where ground water discharges to neither of the two prior groups	Number of detections from areas where ground water discharges to the Little Calumet River
Phenol	687	631	0	54	2
Benzene	305	268	0	24	13
Toluene	283	268	0	14	1
Bis (2-ethylhexyl) phthalate	255	208	0	17	30
Methylene chloride	156	114	0	7	35
Xylene	152	141	0	9	2
Acetone	147	114	0	8	25
Ethyl benzene	140	131	0	9	0
Naphthalene	95	85	0	10	0
Methyl ethyl ketone	89	83	0	2	4
Dibutyl phthalate	83	69	1	2	11
Trichloroethene	80	75	0	5	0
4-Methylphenol	78	76	0	2	0
Benzoic acid	70	70	0	0	0
2,4-Dimethylphenol	70	70	0	0	0
2-Methylnaphthalene	66	56	0	10	0
4-Methyl-2-pentanone (MIBK)	63	61	0	0	2
Phenanthrene	59	50	0	9	0
1,1-Dichloroethane	58	57	0	0	1
1,1,1-Trichloroethane	55	54	0	1	0
Isophorone	50	48	0	1	1
trans-1,2-Dichloroethene	50	48	0	2	0
2-Methylphenol	48	48	0	0	0

Table 7. Number of water samples in the ground-water-quality dataset in which trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study area, northwestern Indiana—Continued

	Number of samples with organic compound detected by analysis				
Organic compound name	**Total number of samples with detections**	**Number of detections from areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan**	**Number of detections from areas where ground water discharges to sewers or pumping wells**	**Number of detections from areas where ground water discharges to neither of the two prior groups**	**Number of detections from areas where ground water discharges to the Little Calumet River**
Fluorene	41	32	0	9	0
Vinyl chloride	38	37	0	1	0
Chloroform	36	27	0	7	2
Tetrachloroethene	35	33	0	1	1
Carbon disulfide	35	23	0	12	0
Acenaphthene	34	27	0	7	0
Chloroethane	33	31	0	0	2
1,2-Dichloroethene	33	33	0	0	0
Chlorobenzene	32	30	0	2	0
Pyrene	29	21	0	8	0
Butyl benzyl phthalate	24	6	0	1	17
1,1-Dichloroethene	22	21	0	1	0
Anthracene	19	17	0	2	0
Pentachlorophenol	19	11	0	8	0
Diethyl phthalate	19	17	0	1	1
Di-n-octyl phthalate	17	9	0	3	5
Polychlorinated biphenyls (PCBs)	17	17	0	0	0
Acenaphthylene	16	15	0	1	0
Fluoranthene	15	14	0	1	0
2-Hexanone	15	15	0	0	0
4-Chloroaniline	14	14	0	0	0
Trichlorofluoromethane	14	9	0	4	1
Bromodichloromethane	14	11	0	3	0
Dibenzo(a,h)anthracene	13	12	0	1	0

Table 7. Number of water samples in the ground-water-quality dataset in which trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study area, northwestern Indiana—Continued

Organic compound name	Number of samples with organic compound detected by analysis				
	Total number of samples with detections	Number of detections from areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan	Number of detections from areas where ground water discharges to sewers or pumping wells	Number of detections from areas where ground water discharges to neither of the two prior groups	Number of detections from areas where ground water discharges to the Little Calumet River
Chrysene	12	11	0	1	0
1,2-Dichloropropane	12	12	0	0	0
Benzo(b)fluoranthene	11	11	0	0	0
Dibromochloromethane	11	9	0	2	0
Benzo(a)anthracene	10	9	0	1	0
Bis(2-chloroethyl) ether	9	9	0	0	0
1,1,2-Trichloroethane	9	9	0	0	0
Chloromethane	8	8	0	0	0
Bromoform	7	7	0	0	0
Bromomethane	7	7	0	0	0
1,1,2,2-Tetrachloroethane	7	7	0	0	0
N-Nitrosodiphenylamine	7	7	0	0	0
2-Chloroethyl vinyl ether	7	7	0	0	0
Carbon tetrachloride	7	7	0	0	0
2,4-Dichlorophenol	6	6	0	0	0
Dichlorodifluoromethane	6	6	0	0	0
2,4,6-Trichlorophenol	5	5	0	0	0
1,2-Dichloroethane	5	5	0	0	0
Styrene	5	3	0	0	2
Benzo(a)pyrene	5	5	0	0	0
Aroclor 1248	5	5	0	0	0
Aniline	4	4	0	0	0
Bis(2-chloroethoxy)-methane	4	4	0	0	0
Indeno(1,2,3-cd)pyrene	4	3	0	1	0
Total Dichloroethene	4	4	0	0	0

Table 7. Number of water samples in the ground-water-quality dataset in which trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study area, northwestern Indiana—Continued

	Number of samples with organic compound detected by analysis				
Organic compound name	**Total number of samples with detections**	**Number of detections from areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan**	**Number of detections from areas where ground water discharges to sewers or pumping wells**	**Number of detections from areas where ground water discharges to neither of the two prior groups**	**Number of detections from areas where ground water discharges to the Little Calumet River**
2,6-Dinitrotoluene	3	2	0	1	0
Benzo(g,h,i)perylene	3	3	0	0	0
2-Nitrophenol	3	3	0	0	0
Dimethyl phthalate	2	1	0	1	0
2,4-Dinitrotoluene	2	2	0	0	0
Benzo(k)fluoranthene	2	2	0	0	0
1,4-Dichlorobenzene	2	2	0	0	0
4-Nitrophenol	2	2	0	0	0
Bis (2-chloroisopropyl) ether	1	1	0	0	0
Aroclor 1260	1	1	0	0	0
4-Chloro-3-methylphenol	1	1	0	0	0
1,3-Dichlorobenzene	1	1	0	0	0
2-Chlorophenol	1	1	0	0	0
Nitrobenzene	1	1	0	0	0
4-Nitroaniline	1	1	0	0	0
Hexachloroethane	1	1	0	0	0
Carbazole	1	1	0	0	0
Aroclor 1242	1	1	0	0	0
1,2-Dichlorobenzene	1	1	0	0	0

Table 8. Number of wells in the ground-water-quality dataset in which two or more samples containing trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study area, northwestern Indiana

Trace element or trace species name	Number of wells with two or more detections of a trace element or trace species				
	Total number of wells with two or more detections	From areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan	From areas where ground water discharges to sewers or pumping wells	From areas where the ground-water discharge area is indeterminate	From areas where ground water discharges to the Little Calumet River or south of the study area
Arsenic	136	111	0	24	1
Zinc	111	88	0	13	10
Chromium	107	99	0	5	3
Lead	95	79	0	8	8
Nickel	88	82	0	4	2
Cyanide	87	82	0	3	2
Cadmium	64	56	0	6	2
Selenium	60	54	0	6	0
Copper	48	38	0	1	9
Mercury	48	39	0	9	0
Vanadium	38	28	0	1	9
Silver	33	31	0	2	0
Cobalt	21	20	0	0	1
Strontium	19	18	0	0	1
Antimony	17	16	0	1	0
Beryllium	17	17	0	0	0
Thallium	12	12	0	0	0

Table 8. Number of wells in the ground-water-quality dataset in which two or more samples containing trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study area, northwestern Indiana—Continued

	Number of wells with two or more detections of an organic compound				
Organic compound name	**Total number of wells with two or more detections**	**Number of wells from areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan**	**Number of wells from areas where ground water discharges to sewers or pumping wells**	**Number of wells from areas where ground water discharges to neither of the two prior groups**	**Number of wells from areas where ground water discharges to the Little Calumet River**
Phenol	96	85	0	11	0
Benzene	81	68	0	8	5
Toluene	72	68	0	4	0
Bis (2-ethylhexyl) phthalate	57	40	0	5	12
Methylene chloride	49	33	0	1	15
Acetone	48	33	0	3	12
Xylene	37	33	0	3	1
Ethyl benzene	31	29	0	2	0
Naphthalene	24	20	0	4	0
4-Methylphenol	24	23	0	1	0
4-Methyl-2-pentanone (MIBK)	22	21	0	0	1
Benzoic-acid	21	21	0	0	0
Dibutyl phthalate	19	14	0	0	5
Methyl ethyl ketone	19	18	0	0	1
2-Methylnaphthalene	18	15	0	3	0
Trichloroethene	18	18	0	0	0
Phenanthrene	16	13	0	3	0
2,4-Dimethylphenol	15	15	0	0	0
1,1,1-Trichloroethane	15	15	0	0	0
2-Methylphenol	12	12	0	0	0
1,1-Dichloroethane	12	12	0	0	0
Trans-1,2-dichloroethene	12	12	0	0	0
Isophorone	11	11	0	0	0

Table 8. Number of wells in the ground-water-quality dataset in which two or more samples containing trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study area, northwestern Indiana—Continued

	Number of wells with two or more detections of an organic compound				
Organic compound name	**Total number of wells with two or more detections**	**Number of wells from areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan**	**Number of wells from areas where ground water discharges to sewers or pumping wells**	**Number of wells from areas where ground water discharges to neither of the two prior groups**	**Number of wells from areas where ground water discharges to the Little Calumet River**
Carbon disulfide	10	6	0	4	0
Fluorene	10	7	0	3	0
Acenaphthene	8	6	0	2	0
Butyl benzyl phthalate	7	0	0	0	7
Tetrachloroethene	7	7	0	0	0
Di-n-octyl phthalate	6	3	0	1	2
Chloroethane	6	5	0	0	1
Pyrene	6	3	0	3	0
Benzo(b)fluoranthene	5	5	0	0	0
1,2-Dichloroethene	4	4	0	0	0
Diethyl phthalate	4	4	0	0	0
Chlorobenzene	4	4	0	0	0
Chloroform	4	4	0	0	0
Pentachlorophenol	4	2	0	2	0
1,2-Dichloropropane	3	3	0	0	0
Acenaphthylene	3	3	0	0	0
Dibenzo(a,h)anthracene	3	3	0	0	0
4-Chloroaniline	3	3	0	0	0
Bis (2-chloroethyl) ether	3	3	0	0	0
1,1-Dichloroethene	3	3	0	0	0
Trichlorofluoromethane	3	1	0	2	0
2-Hexanone	2	2	0	0	0
Chrysene	2	2	0	0	0
Vinyl chloride	2	2	0	0	0

Table 8. Number of wells in the ground-water-quality dataset in which two or more samples containing trace elements, trace species, or organic compounds were detected, as grouped by discharge area in the study area, northwestern Indiana—Continued

	Number of wells with two or more detections of an organic compound				
Organic compound name	**Total number of wells with two or more detections**	**Number of wells from areas where ground water discharges to the Grand Calumet River, Indiana Harbor Canal, or Lake Michigan**	**Number of wells from areas where ground water discharges to sewers or pumping wells**	**Number of wells from areas where ground water discharges to neither of the two prior groups**	**Number of wells from areas where ground water discharges to the Little Calumet River**
Total Dichloroethene	2	2	0	0	0
Benzo(a)anthracene	2	2	0	0	0
Anthracene	2	2	0	0	0
Aroclor 1248	2	2	0	0	0
Dichlorodifluoromethane	1	1	0	0	0
Fluoranthene	1	1	0	0	0
Polychlorinated biphenyls (PCBs)	1	1	0	0	0
Benzo(a)pyrene	1	1	0	0	0
Bis(2-chloroethoxy)-methane	1	1	0	0	0
1,2-Dichloroethane	1	1	0	0	0
Styrene	1	0	0	0	1
2,4,6-Trichlorophenol	1	1	0	0	0
Aniline	1	1	0	0	0
Benzo(k)fluoranthene	1	1	0	0	0
2,4-Dichlorophenol	1	1	0	0	0
1,4-Dichlorobenzene	1	1	0	0	0

Transient flow reversals between ground water and surface water, such as those documented in near-stream parts of the NRDA area (Greeman, 1995; Fenelon and Watson, 1993) can mix ground water and surface water in the aquifer to some intermediate composition. In addition, mixing of contaminated ground water with surface water in the zone of sediment immediately below the surface water-sediment interface in a stream also can create adverse ecological effects in the streambed sediment (Conant, 2000) and associated food chain.

Chemical Processes Affecting Trace Element or Trace Species Concentrations in Ground Water

Chemical processes that generally affect trace element or species concentrations in ground water include precipitation-dissolution reactions, ion-exchange reactions, and oxidation-reduction (redox) reactions. This section describes those processes, and outlines detection, potential sources, and potential processes affecting the concentrations of the more frequently detected trace elements and one species: arsenic, lead, chromium, nickel, and cyanide.

In adsorption, charged surfaces of geologic materials, such as clay minerals, iron and manganese oxyhydroxides, and organic matter, attract and remove unlike-charged elements or combinations of elements (complexes or species) from solution (Horowitz, 1991, p. 38). In reversible adsorption or exchange, the adsorption of a certain concentration of charged elements from solution is equaled by desorption of an equal charge-equivalent amount of other elements from the solid surface (Drever, 1982, p. 82-85). Adsorption onto geologic materials can, therefore, initially act to remove contaminants from solution when the materials are first exposed to the contaminant. If contaminant concentrations decrease, reversible sorption will act to release or desorb those same contaminants into solution from the geologic materials.

The amount of a trace element or species that can be adsorbed relates to the charge state and complexation of the contaminant, the composition of the geologic material (mineralogy and mineral surface coatings), and the hydrogeochemical environment. For example, the pH of 89 percent of all ground-water samples in the Calumet region ranged from 6.0 to 8.5 standard units (Duwelius and others, 1996, p. 17). At these pH values, trace elements that are in solution as cations typically are positively charged species and would be adsorbed onto negatively charged surfaces (cation exchange). Examples of these trace elements among the contaminants of concern include lead, nickel, zinc, cadmium, silver, and copper from the list of most frequently detected trace elements. Conversely, trace elements that typically are present in solution as negatively charged species at these pH values would be adsorbed by positively charged surfaces (anion exchange). Examples of these trace elements among the contaminants of concern include arsenic, chromium, cyanide, selenium, and vanadium. Changing redox conditions (indicated by Eh measurements in the field) also can change the oxidation state at which an ion may be present, which affects the solubility of that ion.

The solubility of trace elements and species in ground water and in the geologic material also affects their concentration and transport in ground water. Trace elements can precipitate from ground water as primary or trace components of minerals and thereby decrease their concentration in ground water. Similarly, geologic materials can dissolve into ground water and increase concentrations of many trace elements. The thermodynamic behavior of various species may be used to estimate the most stable phase that will form in the environment. The solubility of some trace elements often is affected by precipitation of hydroxide and carbonate solids that are stable at neutral to high pH values. For example, precipitation of iron oxides, hydroxides, and carbonates frequently affect iron (II) concentrations in ground water, as a function of pH and redox potential.

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Redox reactions may affect trace element solubility by affecting the valence of dissolved species, thereby rendering them either more or less soluble in ground water. Changes in redox are affected by reactions involving trace elements, the minerals they are precipitated within, and the minerals onto which they are adsorbed. Redox reactions are affected by the presence or absence of electron donating species such as oxygen, ferric iron, nitrate, carbon dioxide, and sulfate, and electron receptors such as ferrous iron, nitrite and ammonium, methane, hydrogen sulfide, and organic compounds.

Arsenic

Arsenic was the most frequently detected trace element or species in ground water for wells in the study area, both in its frequency of detection (953 samples) and by the number of wells with two or more detections (136 wells) (tables 7 and 8). By comparison, Duwelius and others (1996) detected arsenic in water from 48 of 90 wells they sampled in the Calumet aquifer in Indiana and Illinois in 1993.

The largest computed loads of arsenic (Willoughby and Siddeq, 2001) from ground-water discharge to surface water were from the reach of the EB-GCR that extends from it’s confluence with the IHC to about 3 mi east of that point. The largest computed loads of arsenic ranged from 0.075 kg/d to 0.079 kg/d when a horizontal hydraulic conductivity of 50 ft/d was assumed (Willoughby and Siddeq, 2001, fig. 2 and table 4). Their load estimates for arsenic and other contaminants of concern may however, be smaller than actual loads. For example, none of the wells used for the load estimates were installed in known areas of contaminated ground water. Additionally, the water-quality data used for their load estimates were from a relatively small number of wells (21). Use of a larger hydraulic conductivity for the load estimates, as in Willoughby and Siddeq (2001, table 5), also would produce larger computed loads of the contaminants of concern to surface water.

The following discussion of potential sources and processes affecting arsenic in ground water is summarized from Warner (2000) and references cited below. Arsenic enters the environment from pesticides, coal combustion, the smelting of nonferrous metal ores, embalming fluid, and the weathering of arsenic minerals. Arsenic minerals may locally be associated with disseminated shale in glaciofluvial sediments, as described for a part of Indiana by Yarling (1992). Arsenic release from iron oxide minerals appears to be the most common cause of widespread arsenic concentrations in ground water that exceed 10 g/L in the United States (Welch and others, 1999). The information from Yarling and from Welch and others indicate the potential for arsenic concentrations in ground water to originate from natural sources. The USEPA maximum contaminant level for arsenic is 10 µg/L for concentrations in drinking water (U.S. Environmental Protection Agency, 2002b).

Inorganic forms of arsenic predominate in most natural waters. Total (unfiltered) and dissolved arsenic in ground water usually is a combination of arsenite and arsenate. Arsenite is found mostly in reducing conditions, in the absence of hydrogen sulfide. Arsenite is the most toxic and mobile form of arsenic and is found in association with iron in the soluble ferrous state (Fetter, 1993). Arsenate constitutes the stable form of arsenic under oxidized redox conditions in water, whereas arsenite dominates under reduced conditions. Inorganic arsenic species may bind to dissolved, colloidal, and sedimentary organic matter where their concentrations are high. Arsenate tends to adsorb on or coprecipitate with hydrous iron oxides, aluminum hydroxide, and clay.

Release of arsenic into ground water can occur in response to a variety of geochemical conditions, including through reaction of iron oxide with organic carbon, reduction of iron oxides by contact with reduced (oxygen depleted) water, by dissolution of arsenic sulfide minerals, and by contact with alkaline ground water. For example, arsenic concentrations generally were greater in slag affected water (water from geologic materials beneath alkaline slag deposits) from northwestern Indiana and northeastern Illinois than in background ground water and in ground water that was in direct contact with slag (Bayless and others, 1998, table 6). The largest arsenic concentrations detected by Duwelius and others (1996, p. 37) in water from the Calumet aquifer were from shallow wells in an area of fill (mainly slag fill) and near waste-disposal areas.

Release of arsenic from aquifer minerals as induced by reducing conditions also is possible. Oxidation-reduction potential measurements indicated reducing conditions in 75 percent of the samples from the Calumet aquifer, with conditions becoming more reduced with depth (Duwelius and others, 1996).

Lead

Lead was the second most frequently detected trace element or species in individual samples (596 samples) and the fourth most frequently detected by the number of wells with at least two or more detections (95 wells). By comparison, Duwelius and others (1996) detected lead in water from 44 of 90 wells sampled in the Calumet aquifer in Indiana and Illinois in 1993.

The largest computed loads of lead (Willoughby and Siddeq, 2001) from ground-water discharge to surface water were computed to be from the reach of the EB-GCR that extends from its confluence with the IHC to about 3 mi east of that point. The largest computed loads of lead ranged from 0.277 kg/d to 0.283 kg/d when a horizontal hydraulic conductivity of 50 ft/d was assumed (Willoughby and Siddeq, 2001, fig. 2 and table 4).

The following general discussion of processes affecting lead in ground water is summarized from Warner (2000), Hem (1985), Xintaras (1992) and the references cited below. Lead may enter the environment naturally through the weathering of rock, particularly sulfide minerals. Human affected sources, which contribute more lead to water than weathering, include mining, milling, smelting, and refining operations; atmospheric deposition; street runoff; and industrial and municipal wastewater discharges (Canadian Council of Resource and Environment Ministers, 1992). Concentrations of lead in wet deposition at a monitoring station in Gary ranged from less than 1 μg/L to 24 μg/L for 1-week samples collected during 3 years of sampling between 1992 and 1998 (Willoughby, 2000, p. 35). The USEPA action level for lead is 15 μg/L for drinking water (U.S. Environmental Protection Agency, 2002c).

In the natural environment, the divalent form (Pb^{2+}) is the stable ionic species of lead. Lead also combines in solution as complexes with hydroxide and as ion pairs with carbonate and sulfate (Hem, 1985). Concentrations of dissolved lead generally are low in ground water because of the tendency of lead to sorb onto sediment surfaces and form insoluble compounds with carbonates, hydroxides, sulfides, sulfates, and various oxides (Canadian Council of Resource and Environment Ministers, 1992). The conditions that enhance leaching of lead from soils are: (1) lead concentrations that either approach or exceed the sorption capacity of the aquifer solids, (2) the presence in the soil of materials that are capable of forming soluble chelates with lead, and (3) an acidic pH of the leaching solution (National Science Foundation, 1977).

Chromium

Chromium was the third most frequently detected trace element or species in individual samples (554 samples) and the fourth most frequently detected by the number of wells with at least two or more detections (107 wells). By comparison, Duwelius and others (1996) detected chromium in water from 5 of 90 wells sampled in the Calumet aquifer in Indiana and Illinois in 1993.

The largest computed loads of chromium (Willoughby and Siddeq, 2001) from ground-water discharge to surface water were computed to be along contiguous reaches of the EB-GCR and of the IHC. The largest computed loads of chromium ranged from 13.3 kg/d to 20 kg/d when a horizontal hydraulic conductivity of 50 ft/d was assumed (Willoughby and Siddeq, 2001, fig. 2 and table 4). These detections and load estimates were reported for analyses of total chromium. Hexavalent chromium (Cr (VI)) was detected in only two samples in the ground-water-quality dataset.

The following general discussion of processes affecting chromium in ground water is summarized from Warner (2000), World Health Organization (1996), Hem (1985) and the references cited below. Chromium is present in water primarily in its trivalent (Cr (III)) and hexavalent (Cr (VI)) form. Chromium may enter the environment naturally through weathering of minerals that contain chromium. Human-affected sources of chromium include metal-plating operations; fossil fuel burning; tanning; and the manufacturing of ceramics, paints and dyes (Warner, 2000). The 1992 Canadian Water Quality Guidelines (Canadian Council of Resource and Environment Ministers, 1992) indicate chromium limits of 20 μg/L to protect fish and 2 μg/L to protect aquatic life, in general. The USEPA MCL for chromium is 100 μg/L (U.S. Environmental Protection Agency, 2002c).

In the environment, chromium (VI) occurs mostly as CrO_4^{2-} or $HCrO^{4-}$ and chromium (III) as $Cr(OH)_n^{(3-n)+}$ (World Health Organization, 1996). Under anaerobic conditions or in the presence of organic carbon, Cr(VI) will be reduced to Cr(III), which tends to sorb on particulate matter or precipitate out of solution (Canadian Council of Resource and Environment Ministers, 1992; McNeely, Neimanis and Dwyer, 1979). Hexavalent chromium is soluble and not generally sorbed by soils or particulate matter (Canadian Council of Resource and Environment Ministers, 1992). The distribution of compounds containing chromium (III) and chromium (VI) depends on the redox potential, the pH, the presence of oxidizing or reducing compounds, the kinetics of the redox reactions, the formation of chromium (III) complexes or insoluble chromium (III) salts, and the total chromium concentration. Dissolved chromium concentrations often are low in water, particularly in well aerated waters with little organic matter.

Nickel

Nickel was the fourth most frequently detected trace element or species in individual samples (462 samples) and the fifth most frequently detected by the number of wells with at least two or more detections (88 wells). By comparison, Duwelius and others (1996) detected nickel in water from 21 of 90 wells sampled in the Calumet aquifer in Indiana and Illinois in 1993.

The largest computed loads of nickel (Willoughby and Siddeq, 2001) from ground-water discharge to surface water were computed to be along contiguous reaches of the EB-GCR. The largest computed loads of chromium ranged from 0.0033 kg/d to 0.22 kg/d, assuming a horizontal hydraulic conductivity of 50 ft/d (Willoughby and Siddeq, 2001, fig. 2 and table 4).

The following general discussion of potential sources of nickel and processes affecting nickel in ground water is summarized from the World Health Organization (1996) and Hem (1985), and the references cited below. Nickel enters the environment naturally through weathering. Human-affected sources of nickel include production of stainless steels, production of metal alloys, in electroplating, as catalysts, in nickel-cadmium batteries, in coins, in welding products, and in certain pigments (World Health Organization, 1996). The USEPA has no standard for nickel concentrations in drinking water. The World Health Organization (1996) maintains a guideline concentration of 20 µg/L for nickel in drinking water.

Nickel has been identified as leaching from stainless steel and certain stainless-steel well materials (Hewitt, 1992; World Health Organization, 1996). Most wells sampled from the Calumet aquifer in northwestern Indiana by Duwelius and others (1996, table 1) contained some stainless steel. Well-construction details were not compiled for water samples in the ground-water-quality dataset. Therefore, it is not possible to determine with available data whether any association is present between nickel detections and stainless steel materials used in well construction.

In natural waters, nickel occurs predominantly as the ion Ni^{2+} or as the hydrated ion pair $Ni(H_2O)_6^{2+}$ in natural waters at pH values ranging from 5 to 9 standard units (World Health Organization, 1996); this pH range includes most ground water in northwestern Indiana except slag-affected waters. Cation exchange is, therefore, a likely process to affect nickel concentrations in ground water because of the positively charged valence of nickel in water. Complexes of nickel form in water with hydroxide, carbonate, sulfate, chloride and ammonia. Nickel coprecipitates with iron and manganese oxides (Hem, 1985).

Cyanide

Cyanide was the fifth most frequently detected trace element or species in individual samples (418 samples) and the sixth most frequently detected by the number of wells with at least two or more detections (87 wells). By comparison, cyanide was detected by Duwelius and others (1996) in water from 15 of 90 wells sampled in the Calumet aquifer in Indiana and Illinois in 1993. Fenelon and Watson (1993) indicated that cyanide in ground water discharging to the GCR probably is from small areas with highly contaminated ground water.

The largest computed loads of cyanide (Willoughby and Siddeq, 2001) from ground-water discharge to surface water were computed to be in the most upstream reaches of the EB-GCR and along the IHC near the Indiana Harbor. where it joins with Lake Michigan. The largest computed loads of cyanide ranged from 7.11 kg/d to 17.8 kg/d when a horizontal hydraulic conductivity of 50 ft/d was assumed (Willoughby and Siddeq, 2001, fig. 2 and table 4).

Much of the following general discussion of processes affecting cyanide in ground water is summarized from Warner (2000) and the references cited below. Cyanide is released to the environment primarily from industrial operations, such as electroplating, metal cleaning, steel plants, coking operations, and oil refineries (Warner, 2000, World Bank Group, 1998) and through its application to roads as an anticaking agent in halite deicing salt. Cyanide concentrations in industrial effluent can range from an average of 3 mg/L from electroplating and from 30 to 60 mg/L from steel mills (Warner, 2000). Cyanide concentrations generally are low in drinking water; a 1970 USEPA survey of 969 community water-supply systems throughout the Nation listed a maximum cyanide concentration of 0.008 mg/L (U.S. Department of Health, Education, and Welfare, 1970). The USEPA MCL for cyanide in drinking water is 0.2 mg/L (U.S. Environmental Protection Agency, 2002c).

Cyanide occurs in a variety of chemical forms, from the simple ion (CN^-) and undissociated form (HCN) to salts (for example, sodium cyanide and potassium cyanide) to organic and metal complexes. In waters with pH values greater than 8.0, the CN^- anion generally will be the predominant dissolved form. Reported pH values for water from the Calumet aquifer ranged from 5.3 to 12.1 with a median value of 7.2 (Duwelius and others, 1996). The largest pH values in the aquifer are found in association with slag fill (Bayless and others, 1996). Slag fill is most prevalent over the aquifer near steel-making operations where it is produced (Kay and others, 1997). Therefore, it is likely that cyanide will be most mobile near sites where slag fill is thickest, pH values are highest, and cyanide is in its most soluble anionic form (CN^-).

The cyanide ion has a strong affinity for many metal ions but is not strongly adsorbed or retained in soils because of its negative or neutral charge. Some metallocyanide complexes, such as iron-cyanide, may photolytically dissociate in sunlight when pH is less than 8.0 (Canadian Council of Resource and Environment Ministers, 1992). Because cyanide is biodegradable and readily forms metallocyanide complexes (such as with copper and iron), large-scale distribution of cyanide in water is unlikely (McNeely, Neimanis and Dwyer, 1979).

Chemical and Microbial Processes Affecting Organic-Compound Concentrations in Ground Water

Chemical and microbial processes that can affect organic-compound concentrations and transport in ground water typically decrease compound concentrations. These processes typically either (1) sorb the compound onto organic matter, (2) volatilize the compound across the water table, into the unsaturated zone and ultimately into the atmosphere, (3) transform and degrade the compound into other compounds or inorganic products by microbial metabolism (biodegradation), or (4) chemically transform the compound (hydrolysis or oxidation-reduction reactions). This section generally describes these processes and outlines detection and process information for two of the more frequently detected groups of organic compounds in ground water from the study area: Phenols, alkyl phenols, and chlorophenols and Benzene and alkyl benzenes. For a more complete discussion of processes affecting organic compound fate, the reader is referred to Smith and others (1988).

Sorption of organic compounds by sediments typically happens either by adsorption onto a surface or by partitioning into an organic substance (Smith and others, 1988). Adsorption forms a physical bond between a compound and a sediment particle’s surface (such as through van der Waal’s forces), or by formation of a chemical bond between the compound and the sediment. Partition related sorption distributes the organic compound through the sediment organic matter as if the sediment organic matter is an organic solvent such as octanol or a lipid. Most sorption of nonionic (neutrally charged) and acidic compounds (compounds with negatively charged functional groups) is thought to occur by partitioning (Smith and others, 1988).

Volatilization from the water table of organic contaminants that are generally lighter than water can reduce contaminant concentrations in ground water. Volatilization-related losses from ground water involves exchange of the compound from the water into the air in the unsaturated zone, and diffusion out of the unsaturated zone into the atmosphere. Volatilization is dependent on site factors including soil porosity, moisture content, unsaturated-zone permeability, and climatic conditions such as barometric pressure and temperature. Volatilization also depends on the vapor pressure of the organic compound as measured by its related property, the Henry's Law constant (Smith and others, 1988). The higher the Henry's Law constant, the more volatile the compound.

Biodegradation involves the decomposition of organic compounds through enzyme-related reactions. The rate of biodegradation depends on the size of the microbial population, the substrate used for microbial subsistence, the concentration of the organic contaminant, and physical factors of the site (such as the pH and temperature of ground water and the hydraulic conductivity of the aquifer). When an organic compound is biodegraded, the contaminant generally is transformed in the presence of an electron acceptor: oxygen in aerobic conditions, and nitrogen, iron, sulfate, or carbon dioxide in anaerobic environments.

Hydrolysis changes the chemical speciation of an organic compound (Smith and others, 1988). Hydrolysis involves the reaction of the compound with water to exchange some functional group from the organic compound with a hydroxyl (OH^-) group from the water. The rate of hydrolysis depends on the properties of the compound and characteristics of the water, such as pH, temperature, salinity, and the amount of other organic matter in solution (Smith and others, 1988).

The interpretation of which processes affect contaminant transport is complicated by the physical properties of the most concentrated contaminants. For example, some contaminants are lighter or denser than water and are present in sufficient concentration to be present as a separate phase from water (a nonaqueous phase liquid or NAPL). A NAPL can be a solvent for other organic compounds and can transport them in concentrations that exceed their solubility in water. Examples of NAPL would be the LNAPL as shown in plate 2.

Conant (2000) and Lorah and others (1997) note in their studies that the majority of chemical and microbial attenuation of volatile organic contaminants occurred in the last 10 ft of sediment before discharge to a stream or wetland. Removal of this sediment by dredging can disrupt the observed natural attenuation and increase the potential for direct discharge of contaminated ground water to the surface-water resource.

Phenol and Alkyl Phenols

Phenol was the most frequently detected organic compound in individual samples (687 samples) and by the number of wells with at least two or more detections (96 wells) (tables 7 and 8). The alkyl phenols (4-methylphenol, 2-methylphenol and 2,4-dimethylphenol) were less frequently detected and were detected in two or more samples in fewer wells than phenol. Duwelius and others (1996) also identified phenol and the alkyl phenols as among the most frequently detected semivolatile organic compounds in ground-water samples collected in 1993 from near industrial facilities, filled land, or waste-disposal sites in northwestern Indiana and northeastern Illinois. Fenelon and Watson (1993) indicated that less than 1 percent of the total load of phenol in the GCR is from ground-water discharge.

The largest computed loads of phenol, as total phenols (Willoughby and Siddeq, 2001), from ground-water discharge to surface water were computed to be along contiguous reaches of the EB-GCR and of the IHC. The largest computed loads of phenol ranged from 0.0015 kg/d to 0.009 kg/d, assuming a horizontal hydraulic conductivity of 50 ft/d (Willoughby and Siddeq, 2001, fig. 2 and table 4).

The following general discussion of processes affecting phenol and related alkyl phenols in ground water is summarized from Smith and others (1988) and the references cited below. Phenol is a monohydroxybenzene that behaves as a weak acid in water (Smith and others, 1988). Fenelon and Watson (1993) and Smith and others (1988) describe phenols as byproducts of coke making, petrochemical refining and in production of plastics, resins, explosives, fungicides and herbicides. Chronic toxicity to aquatic life occurs at a concentration of about 2.6 mg/L and a limit of 3.5 mg/L is set by the USEPA to ensure a lack of hazardous effects to humans (Smith and others, 1988). The USEPA MCL for pentachlorophenol in drinking water is 1 μg/L (U.S. Environmental Protection Agency, 2002c).

Most phenols (other than chlorinated phenols) do not strongly sorb to sediment or bioaccumulate (Smith and others, 1988). Volatilization, nonphotolytic oxidation, and hydrolysis are also not appreciable fate processes for phenols. Phenols can be biodegraded in water and sediment, however, high concentrations of phenols have been documented in organic sediments associated with industrial discharges. Therefore, it is likely that water soluble phenols could be transported by ground water in a similar manner to other soluble anions.

Benzene and Related Alkyl Benzene Compounds

Benzene and toluene were the second and third most frequently detected organic compounds, both in individual samples (305 and 283 samples, respectively) and in terms of the number of wells with at least two or more detections (81 and 72 wells, respectively) (tables 7 and 8). Xylene and ethyl benzene, two other alkyl benzene compounds were among the top 10 most frequently detected organic compounds in the above categories. By comparison, Fenelon and Watson (1993) reported that benzene was detected in water from 23 of 34 samples collected from the Calumet aquifer. Duwelius and others (1996) reported that benzene, toluene, and xylene also were among the most frequently detected volatile organic compounds detected in ground water. Benzene, toluene and xylene detections were associated with steel, petrochemical, and commercial land-use classifications used by Fenelon and Watson (1993). No estimates of benzene, toluene or xylene loading to surface water in the study area have been reported in the scientific literature to date (2002).

The following general discussion of processes affecting these compounds in ground water is summarized from Smith and others (1988) and the references cited below. Benzene and the named alkyl benzenes commonly are detected in association with petrochemical industry activities, including refining, petrochemical storage and coal coking (Burdick and Leffler, 1983). These compounds are used in a variety of processes to create a wide variety of organic chemicals (Smith and others, 1988). The USEPA MCL for benzene in drinking water is 5 μg/L (U.S. Environmental Protection Agency, 2002c). The USEPA MCL for toluene in drinking water is 1 mg/L (U.S. Environmental Protection Agency, 2002c). The USEPA MCL for total xylenes in drinking water is 10 mg/L (U.S. Environmental Protection Agency, 2002c).

Benzene and the named alkyl benzenes are characterized by relatively high water solubilities, high vapor pressures, and low negative-log octanol-water partition coefficients. This characterization indicates that the compounds tend to volatilize into the atmosphere and into unsaturated zone air. Rates of biotransformation of these compounds can be relatively rapid in aerobic ground water and slower in anaerobic ground water (Landmeyer and others, 1996).

ITEMS FOR ADDITIONAL STUDY

Following are items for additional study to more clearly define directions of ground-water flow and discharge areas for ground water and occurence of associated contaminants in the NRDA area.

There are large areas east and west of the IHC where available data are insufficient to make determinations regarding directions of flow and ultimate discharge points for ground water and associated contaminants (fig. 17). Although various data may be available for some parts of these areas, they were most likely collected at different times using a variety of methods. The most useful data are those collected in a synoptic fashion. A data-collection network composed of transects of wells and, where appropriate, surface-water sites, to obtain synoptic water-level and water-quality data will enable more detailed definition of flow directions, water-quality characteristics, and discharge points for ground water and associated contaminants in these areas.

Little information is available regarding the effects of sheet-pile barriers in the NRDA area on ground-water flow and quality. Two areas of investigation are needed to more clearly define whether sheet-pile barriers impede ground-water flow and discharge of associated contamination into surface water adjacent to the GCR, the IHC and Lake Michigan.

1. Inventory location and condition of sheet-pile barriers in the NRDA area using more precise surveys. Document in a GIS database the location, type, and characteristics of sheet piles, where sheet-pile barriers visibly leak between ground water and surface water. The GIS database would be useful to establish possible flow boundaries for future cumputer simulations of ground-water flow and ground-water/surface-water interaction.

2. Where leakage is observed across sheet-pile barriers, obtain samples for water-quality analyses and concurrently obtain a ground-water sample for analysis from the landward side nearby the leakage. The water-quality data can be used to determine the relation between surface water and ground water across sheet piles and determine if contaminated ground water is discharging into the IHC and/or Lake Michigan.

3. Monitor water levels and water quality along various representative transects of nested wells across sheet-pile barriers, with at least one transect near the middle of a visibly nonleaky section of shhet pile, one transect opposite a leaky section of sheet pile and one transect at each end of the sheetpiled reach. These data and interpretations of local ground-water flow will help determine the fate of contaminants dissolved in ground water that may become impounded behind sheet-pile barriers.

There is a need to define the relative contributions of ground water, bed sediments, and point discharges to contaminant loading in the GCR/IHC. Water-level and water-quality data obtained along transects perpendicular to the GCR/IHC that include data from surface water in the stream, interstitial water from the streambed materials, and ground water from various depths beneath the streambed would help determine if contaminated ground water is discharging directly into the stream. Also, these data will address the issue of what is the source of contaminants in the stream—ground water, bed sediments, or a contaminated water column from an upstream source. Age dating of the ground water and water in streambed sediment would help to further refine the distinction among these sources.

Available hydrogeologic data indicate a downward vertical gradient from the Calumet aquifer to the underlying bedrock aquifer. Few water-quality samples have been obtained from the bedrock aquifer and it is, therefore, unknown if downward flowing ground water from the Calumet aquifer may have introduced contamination to this water resource. Analysis of samples from the bedrock aquifer would provide a basis to evaluate water quality in the bedrock aquifer, indicate if this resource has sustained damage, and help determine the potential of the bedrock aquifer to receive discharge from the Calumet aquifer.

Transient reversals of ground-water flow have been observed in some areas adjacent to the GCR/IHC, resulting in water from the stream entering the Calumet aquifer along the stream banks. Eventually, this water in bank storage returns to the stream, but chemical interactions with the streambed and aquifer sediments and near-stream plant communities may transform dissolved contaminants in the water during these periods of bank storage. For example, plants commonly found in wetland areas along the GCR/IHC may take up and metabolize chemicals in ground water, and hazardous materials may remain with or be altered by the plants. Water-level and water-quality data obtained from transects of shallow wells in these areas would help establish residence times and document geochemical processing in these bank-storage areas.

The sewers in the NRDA area are known to leak and act as receptors of ground-water discharge, and probably intercept ground water and associated dissolved contaminants that would otherwise discharge to the GCR/IHC. Currently (2002), available data are insufficient to establish the extent of the areas that are affected by leaky sewers. Water-level data obtained from transects of wells in areas underlain by sewers would better define the areas where leaky sewers capture ground water before it discharges to the GCR/IHC.

The ground-water-quality dataset lacks samples where contaminants of concern were not detected (“nondetects”). Compilation of nondetects would enable identification of wells where particular contaminants of concern were detected in consecutive samples, indicating a persistent contamination that would indicate the need for additional sampling or data analysis to evaluate the potential injury to the water resource. Compilation of nondetects would enable a clearer definition of areas where contaminated ground water was likely to discharge to the aquifer.

Additional sampling of ground-water quality adjacent to the stream and interstitial water in the streambed sediment may be necessary to verify contaminant discharge to surface water. Long-term average samples, such as those collected during 3-6 months by diffusion bag or solid-phase diffusion samplers, collected in concert with hydrologic measurements, could be used to indicate areas where ground-water discharge of contaminants was most prevalent and where restoration was best targeted.

The planned removal of contaminated streambed sediment from the GCR/IHC (U.S. Environmental Protection Agency, 2002d) is a mitigation strategy that may change the hydraulic connection and the associated microbial and chemical processes that inhibit contaminant migration from ground water into surface water. The chemistry of surface water, ground water, and interstitial water in streambed sediment and physical hydrologic characteristics of these locations should be monitored at selected locations after dredging to assess reestablishment of contamination in surface water and streambed sediment.

SUMMARY

In 1997, Federal and State agencies that were designated Trustees for the natural resources of the State of Indiana initiated a Natural Resource Damage Assessment of the water resources in the IHC and adjacent nearshore Lake Michigan watersheds. In 1998, the FWS, acting as a representative of the Trustees, requested that the USGS prepare a report to aid in documenting the potential discharge of contaminated ground water to surface waters in the IHC and adjacent nearshore Lake Michigan watersheds in northwestern Indiana.

The study area (approximately 80 mi^2)is located along the southernmost tip of Lake Michigan and is all of Lake County, Indiana north of the Little Calumet River. The NRDA portion of the study area is approximately 54 mi^2 and consists of all the land that drains to the IHC, its tributaries, and Lake Michigan in Lake County, Indiana.

The study area is an abandoned glacial and postglacial lake bottom completely located within the Calumet Lacustrine Plain section of the Northern Moraine and Lake Region physiographic province. Southward of the Lake Michigan shoreline the land surface is made up of parallel sand ridges with intervening swales—the swales may sometime contain interdunal wetlands. Other wetlands in the study area are associated with lakes, ponds, and meanders of the GCR and LCR. The Tolleston Beach Ridge forms an arcuate upland in the southern part of the study area that approximately coincides with the divide between the GCR and LCR drainage basins.

The surficial geology in the study area is mostly glacial and lacustrine sand, silt, and clay deposits of Wisconsinan and Recent age. Large areas with artificial fill and substantially modified land are present along the Lake Michigan shoreline and surrounding Lake George.

Land use in the area primarily is industrial and residential. The NRDA portion of the study area is one of the most industrialized areas in the United States. Large steel mills are located along the shore of Lake Michigan, Indiana Harbor, and the IHC. Land along the IHC and Lake Michigan also is used for the refining and storage of petrochemicals. Other major industries in the area include scrap-metal processing, parts fabrication for trucks, automobiles, and major appliances, and railcar and chemical manufacturing.

The GCR commonly is the dividing line between heavy industrial and other land uses. Heavy industrial facilities mostly are located north of the GCR with most residential, commercial, recreational, and some light industrial areas located south of the river. A large part of the NRDA area has been used for the disposal of waste materials.

Information regarding the boundaries of industrial facilities in the study area were obtained primarily from GIS electronic datasets from the USEPA, GIS electronic datasets from the Indiana Department of Environmental Management and Lake County plat maps. Additional sources for surface- and ground-water data and hydrogeologic interpretations included the USGS NWIS database and previously published reports.

The Trustees identified 146 contaminants of concern for the NRDA, of which approximately 110 are on the USEPA priority pollutant list. More than 9,400 detections of 111 of the contaminants of concern in water samples from 485 wells in the study area were compiled from three sources; the USEPA GRITS/STAT database; the USGS NWIS database; and numerous written communications from private sources submitted as part of environmental compliance activities. This compilation of detections provides the Trustees with data that can be used in determining if the acceptance criteria for injury to ground-water resources have been met.

Limited available data collected between 1992 and 1996 indicate the presence of LNAPLs floating on ground water under substantial areas between the Lake George Branch and Lake Michigan, and under smaller areas south of the Lake George Branch on the east and west sides of the IHC. Measured and reported thicknesses of LNAPLs ranged from a thin film to greater than 10.6 ft.

All concentrations in the water-quality compilation are recorded as raw numbers to 5 decimal places, and no inferences regarding analytical precision should be made from the number of significant digits for any given concentration. Although available for the study area, analyses in which contaminants of concern were not detected were omitted from the dataset. Because the dataset represents only detections, the computation of distribution-based statistics from these data is in many cases inappropriate or at least must be qualified as representing only detected concentrations.

Surface drainage in the study area generally is to the GCR, the IHC, and Lake Michigan in the north and to the LCR in the south. The drainage divide separating these areas of surface-water dischage approximately coincides with the Tolleston Beach Ridge, an arcuate upland in the southern part of the study area.

The GCR consists of the two east-west oriented branches that meet at the southern end of the IHC. Water in the EB-GCR flows westward from its headwaters in the Marquette Park Lagoons approximately 10 mi to its confluence with the IHC. Water depths in the EB-GCR range from 3-4 ft in the upstream reaches to 8-10 ft in the downstream reaches, with an average stream velocity of about 1 ft/s. The WB-GCR is about 6 mi long, has a depth of about 2 ft, and a stream velocity of less than 1 ft/s.

A surface-water divide in the WB-GCR is located near the I-90 Toll Road; water flows eastward from this divide toward the IHC and westward from this divide toward the LCR in Illinois. During periods of extreme high water levels in Lake Michigan, generally greater than 582 ft above sea level, this divide is absent. Water from Lake Michigan flows south through the Indiana Harbor Canal and then along with flow from the EB-GCR, westward to the LCR in Illinois. The drainage area for the IHC, which includes areas draining to the Lake George Branch, the EB-GCR, and the WB-GCR east of the flow divide, is less than 45 mi^2. The drainage area cannot be exactly determined because of the shifting location of the flow divide in the WB-GCR.

Mean annual discharge from the EB-GCR, WB-GCR, and Indiana Harbor Canal at USGS streamflow-gaging stations were reported as 647 ft^3/s, 484 ft^3/s, and 44.9 ft^3/s, respectively. The discharge measurements for the IHC and the WB-GCR were affected by backwater conditions and flow reversals at these stations. Surface water generally flows from the EB-GCR and the WB-GCR east of the flow divide into the IHC and discharges to the Indiana Harbor and Lake Michigan.

Eolian and lacustrine silica sands and localized areas of fill deposits form a mostly unconfined surficial aquifer in the study area commonly referred to as the Calumet aquifer. Substantial areas of the uppermost parts of the Calumet aquifer, primarily within the NRDA portion of the study area, are made or modified land composed of fill deposits that include thousands of acres of made land covering the original lake-bed sands along the Lake Michigan shoreline. The sands and fill deposits that form the Calumet aquifer in the study area range in thickness from 0 to more than 100 ft. The Calumet aquifer generally is not used for municipal or industrial water supply because most major users obtain their water supplies either directly from Lake Michigan or from the underlying bedrock aquifer.

A confining unit of from 50 to 150 ft thick separates the Calumet aquifer from the underlying bedrock. This clay-rich unit is derived glacially and composed primarily of eroded Mississippian-Devonian shale bedrock, and may contain thin, discontinuous sand deposits.

A carbonate aquifer composed of Devonian and Silurian carbonates, with a combined thickness of about 400 ft, is at the bedrock surface throughout the study area. Most production wells only penetrate the upper 100 ft of the bedrock aquifer, as most supply needs are available within this zone.

Reported horizontal hydraulic conductivities for the Calumet aquifer in and near the study area generally ranged from 2.1 to 130 ft/d. One value of 360 ft/d was reported from northeastern Illinois in a well that was screened in fill deposits. Reported horizontal hydraulic conductivities for the EB-GCR streambed ranged from 0.01 to 1,200 ft/d and vertical hydraulic conductivities ranged from 0.3 to 73 ft/d. The largest values of streambed hydraulic conductivity were measured in fill materials such as concrete and asphalt rubble.

Horizontal hydraulic conductivities for the confining unit in the study area generally are in the range of from 0.00087 to 0.0056 ft/d. Reported horizontal hydraulic conductivities for the bedrock are more variable than the unconsolidated sediments and generally ranged from 0.02 to 70 ft/d in and near the study area.

Reported horizontal hydraulic gradients in the Calumet aquifer generally fluctuate within one order of magnitude and ranged from 0.0005 ft/ft to.0051 ft/ft. One measurement indicated a value of less than 0.0008 ft/ft for the horizontal hydraulic gradient in the bedrock underlying the study area.

In 30 sets of paired wells located in the study area and in northeastern Illinois, 16 sets had upward vertical hydraulic gradients and 14 sets had downward vertical hydraulic gradients. Downward gradients ranged from 0.00097 to 0.13 ft/ft and upward gradients ranged from 0.0012 to 0.33 ft/ft. Predominantly downward vertical hydraulic gradients were measured in and near the study area between the Calumet aquifer and the confining unit, between the Calumet aquifer and the bedrock, and between the confining unit and the bedrock.

Horizontal ground-water velocities in the Calumet aquifer ranged from 0.027 ft/d to 0.82 ft/d, whereas horizontal ground-water velocities in the confining unit are most likely less than 0.0004 ft/d. Vertical ground-water velocities through the confining unit are about 10 to 100 times less that the horizontal ground-water velocities through the Calumet aquifer. Calculated horizontal ground-water velocities through the bedrock aquifer in and near the study area ranged from 0.014 to 0.029 ft/d.

The reported hydraulic properties indicate the following:

(1) Hydraulic conductivities in the Calumet aquifer generally are 2-4 orders of magnitude greater than conductivities in the underlying clay confining unit. The net exchange of ground water between the confining unit and the Calumet aquifer is minor as compared to the total amount of ground-water flow within the Calumet aquifer;

(2) Ground-water flow in the underlying confining unit is mostly vertical with relatively minor amounts of horizontal flow; and

(3) Although the net ground-water exchange between the Calumet aquifer and the confining unit is relatively small, the vertical gradients indicate that more ground water flows downward from the Calumet aquifer into the confining unit than flows upward from the confining unit into the Calumet aquifer.

Ground-water levels in the Calumet aquifer generally fluctuate within a generally narrow range, from 0.4 ft to 5.01 ft for the period 1985-1992. Diurnal water-level fluctuations because of evapotranspiration in wetland and other vegetated areas contribute to small daily declines in the water table. Surface-water levels in the IHC and GCR fluctuated no more than 3.71 ft for the period 1985-1992. Various factors contribute to this generally low magnitude of water-level fluctuations; more than 90 percent of the combined flow in the EB-GCR and WB-GCR is industrial or municipal effluent discharged at a generally constant rate; total topographic relief in the study area is low, generally less than 45 ft; and much precipitation infiltrates into the surficial sands, thereby reducing runoff. The generally small ranges of observed fluctuations in surface and ground water contribute to stable flow regimes for both of these resources.

Urbanization and industrialization in the study area have altered greatly the pre-development cycle of recharge from precipitation and upward flow from the bedrock, and discharge to surface-water bodies and through evapotranspiration. Buildings and pavement now cover previously natural areas and have reduced infiltration of precipitation. Water withdrawals to the west have reversed vertical hydraulic gradients between the Calumet aquifer and the underlying bedrock in the study area. Leaky sanitary sewers, septic systems, and water-supply lines can lose water to the aquifer and function as local sources of recharge; leaky sanitary and storm sewers also can receive water from the aquifer and function as local discharge points; ditches and artificial water impoundments can function as both a source of recharge and as a discharge point. The complexity of natural and artificial sources of recharge in the study area results in a wide range of, and increased uncertainty in, estimates for aquifer recharge rates.

Ground and surface water in the study area are in good hydraulic connection. A rise in surface-water levels in Lake Michigan, the Grand Calumet River, and the Indiana Harbor Canal typically results in a decrease in the slope of the adjacent water table—conversely, a fall in surface-water levels typically results in an increase in the slope of the adjacent water table. Transient reversals in the near-stream water-table slope, resulting in surface water infiltrating into the streambank, are caused by a lowering of the water table due mostly to evapotranspiration and/or lack of precipitation. Concurrent rises in surface-water levels enhance these reversals, which typically are of hours to days in duration—reversals of 2 or more weeks only were observed during periods of record-high lake levels in 1986.

Over 90 percent of the streamflow in the EB-GCR and the WB-GCR is industrial and municipal effluent. A generally constant rate of effluent discharge contributes to minimizing water-level fluctuations and associated changes in the water-table slope in adjacent areas. Effluent discharge to surface water is one of thecharacteristics of local hydrology that contributes to stabilizing the ground and surface-water flow regimes in the study area.

Sheet-pile barriers, usually driven through the sands and fill deposits of the Calumet aquifer and anchored in the underlying confining clay, are present along substantial parts of the Lake Michigan shoreline and parts of the Indiana Harbor Canal. The effects of the barriers on rates and directions of ground-water flow in the study area are largely unknown, although there is much visual evidence that sheet piles in the study area are leaky. Metal sheet piles in many areas have been corroded extensively by slag runoff. Higher ground-water levels behind sheet-pile barriers at Inland Steel and U.S. Steel—Gary Works may result in a localized increase in the rate of downward ground-water flow into the confining unit.

A substantial amount of ground water infiltrates into the sanitary sewers that underlie much of the study area. Finite-difference model analyses indicate that the amount of ground water discharging to sewers is most likely in excess of the amount of recharge from precipitation in the sewered areas. Leaky sewers situated below the water table will continually receive ground water from the aquifer until the water level in the aquifer falls to approximately the same elevation as the leaky sewer line. Leaky sewers situated above the water table generally will lose water to the aquifer until the water level in the aquifer rises to approximately the same elevation as the leaky sewer line. This process tends to minimize ground-water-level changes and contributes to stabilizing the ground-water-flow regime in the areas underlain by leaky sewer lines.

Pumping from the Calumet aquifer to dewater specific sites is common in the study area. Pumping lowers ground-water levels, creates a depression in the water table surrounding the pumpage, and locally alters ground-water-flow directions.

Wetlands in the study area generally are less than 50 acres, are situated mostly along or near streams, lakes, ponds, and ditches, and typically are among the more densely vegetated areas. Because of generally high rates of evapotranspiration during the growing season, wetlands may be important in the development and duration of transient near-stream reversals in ground-water-flow directions along parts of the east and west branches of the GCR and the IHC.

The local ground-water-flow system in the surficial aquifer is typified by broad flat water-table mounds that function as ground-water divides underlying topographically higher areas of land. Shallow ground water (near the water table) generally flows laterally away from these divides and discharges to streams in adjacent low-lying areas and to Lake Michigan. A major east-west trending divide is located beneath the topographic high associated with the Tolleston Beach Ridge. North of this divide ground water flows northward to the Grand Calumet River and south of this divide ground water flows southward to the Little Calumet River.

Another major east-west trending divide is between the east branch Grand Calumet River and Lake Michigan east of the Indiana Harbor Canal—ground water generally flows northward from this divide to Lake Michigan, and southward from this divide to the EB-GCR. Two smaller northeast-southwest trending divides are present on either side of the IHC downstream of the confluence with the Lake George Branch—ground water generally flows from these divides to the IHC, Indiana Harbor, and Lake Michigan.

All of these ground-water divides and associated flow patterns are stable features of the ground-water-flow system, and in most of the NRDA portion of the study area ground water flows towards and discharges to the EB-GCR, the WB-GCR east of the flow divide, the IHC, Indiana Harbor, and Lake Michigan. Dissolved contaminants that are transported by advection and not completely removed from solution by other processes also will discharge to the same points as the ground water in which they are dissolved.

Various depressions in the water table represent areas where discharge to leaky sewers or pumpage locally have altered typical ground-water-flow patterns. Three water-table depressions east and west of the IHC and south of the Lake George Branch are caused by infiltration of ground water into leaky sewers. Another water-table depression north of the Lake George Branch and other depressions between Buffington and Gary Harbors north of the EB-GCR are caused by pumpage for quarry dewatering, ground-water remediation, or other industrial pumpage.

One-hundred eleven contaminants of concern, including polychlorinated biphenyls, oil-related organic compounds, and trace metals, were detected in more than 9,400 water samples from 485 monitoring wells in the area. The most frequently detected trace elements and species by both criteria were arsenic, lead, chromium, nickel, cyanide, zinc, selenium, cadmium, mercury, silver, copper and vanadium. The most frequently detected organic compounds in all samples were phenol, benzene, toluene, bis (2-ethylhexyl) phthalate, methylene chloride, xylene, acetone, ethyl benzene, naphthalene, methyl-ethyl ketone, dibutyl phthalate, trichloroethene, 4-methylphenol, benzoic-acid, and 2,4-dimethylphenol. The most frequently detected organic compounds as measured by the number of wells that had at least two samples with a compound detection also included 4-methyl-2-pentanone (MIBK) but did not include acetone. Most detections of the 10 most frequently detected trace elements or species and the 15 most frequently detected organic compounds were in samples from areas where ground water commonly discharges to the Grand Calumet River, the Indiana Harbor Canal or Lake Michigan. Limited available data collected between 1992 and 1996 also indicate the presence of light-nonaqueous phase liquids floating on ground water under large areas between the Lake George Branch and Lake Michigan, with thicknesses ranging from less than 0.1 ft to more than 10.6 ft.

Physical processes that may affect ground-water concentrations and transport of contaminants of concern include physical processes (advection, dispersion and mixing of ground-water discharge with surface water). Flow reversals between ground water and surface water, such as those documented for the NRDA area, can mix ground water and surface water in the aquifer and change contaminant concentrations in both. Adverse ecological effects may result in the streambed sediment because of high contaminant concentrations in ground water discharging to surface water.

Advection is the primary mechanism by which contaminants dissolved in ground water move at the rate of ground-water flow through an aquifer. Chemical processes that generally affect trace element or species concentrations in ground water include precipitation-dissolution reactions, ion-exchange reactions, and oxidation-reduction (redox) reactions. Chemical and microbial processes that can affect organic compound transport in ground water typically either (1) concentrate the compounds in sediment by sorption onto organic matter, or (2) decrease compound concentrations. Processes that decrease contaminant concentrations do so by (a) volatilization into the unsaturated zone air, (b) transforming and degrading them into other compounds or inorganic products by microbial metabolism (biodegradation), or (c) chemically transforming the organic compound (hydrolysis or oxidation-reduction reactions).

Based on literature summaries that describe the above processes, adsorption may affect concentrations of lead, chromium, nickel, and phenol. Lead concentrations also can be affected by mineral precipitation. Arsenic and chromium valences and solubility are affected by oxidation-reduction reactions. Arsenic, cyanide, and the phenols are anions at the prevailing pH values of most ground water and may be the least affected by sorption and most likely to be transported with ground-water flow. Additional field and laboratory data are needed to establish whether these processes affect transport of these contaminants of concern in ground water.

Some of the most frequently detected contaminants of concern also have potential natural sources or may originate from sampling or analytical related interferences. These potential sources include mineral dissolution (arsenic), leaching of well construction materials (nickel), inadvertent contact during sampling with plasticizing materials (di-n-butylphthalate and bis(2-ethylhexyl) phthalate) and laboratory use of a common solvent (methylene chloride). Additional analysis of available data, new sampling of water from wells where these contaminants of concern were detected, and analysis of those data may be necessary to resolve whether the contaminant occurrences were environmental in nature or were affected by sampling procedures or sample handling.

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