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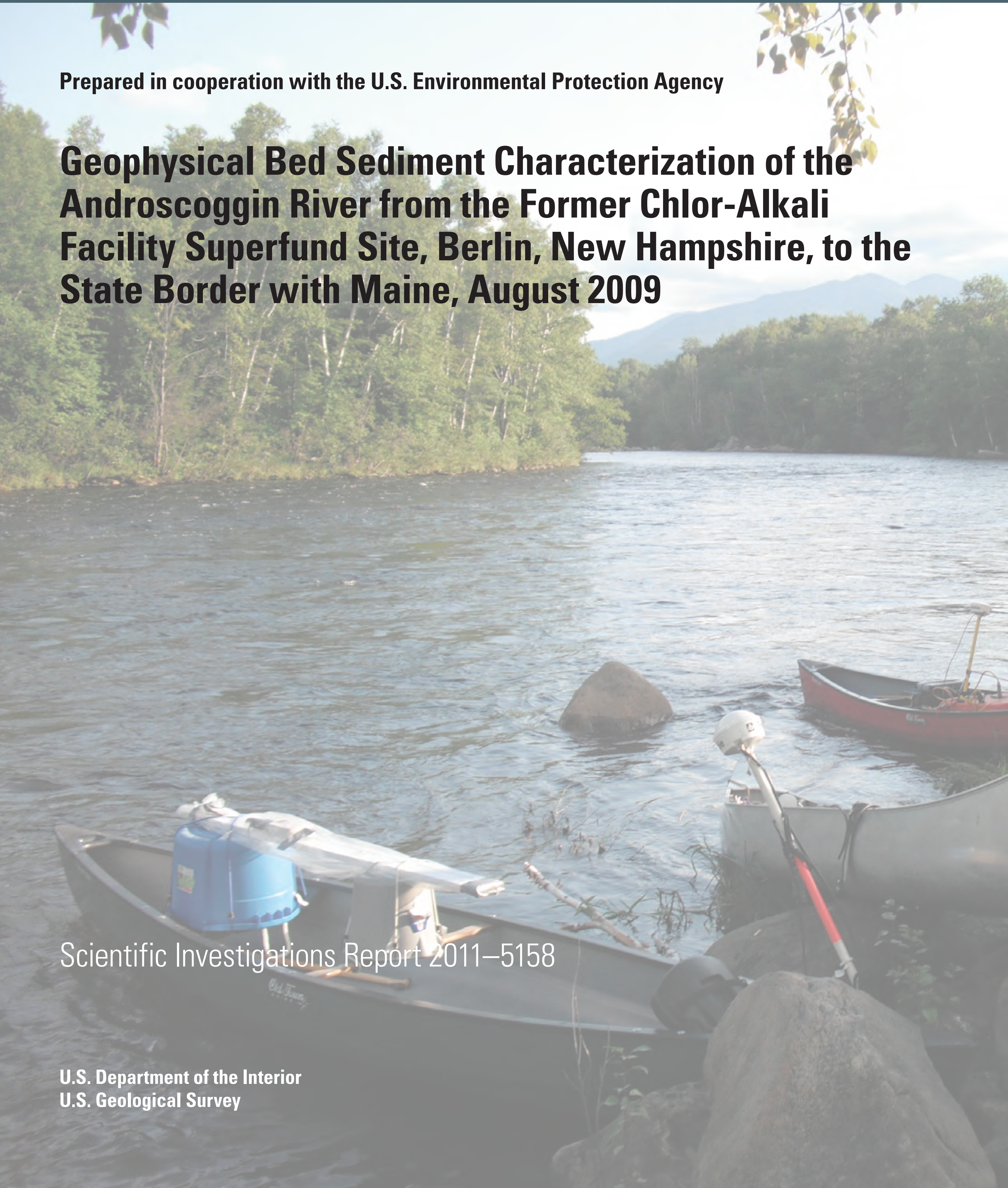
Geophysical Bed Sediment Characterization of the Androscoggin River from the Former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire, to the State Border with Maine, August 2009



Scientific Investigations Report 2011–5158

U.S. Department of the Interior
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Cover. Front: Geophysical equipment loaded in canoes. View looking downstream to the south from the right bank of the Androscoggin River downstream of the Cascade Dam, Gorham, N.H.
Back: View looking upstream on the Androscoggin River, upstream of the Shelburne Dam, Shelburne, N.H.

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By James R. Degnan, Andrew P. Teeple, Craig M. Johnston,
Mark C. Marvin-DiPasquale and Darryl Luce[1]

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Technical advice from Brian Jones, Geophysical Survey Systems Incorporated, was helpful for georeferencing ground-penetrating radar data on the water. Private land owner access provided by Richard Demers made data collection possible in a reach with no public access.

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
yard (yd)	0.9144	meter (m)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

In this report, the words "right" and "left" refer to directions that would be reported by an observer facing downstream.

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

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

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

Specific conductance (SC) is given in millisiemens per meter (mS/m) at 25 degrees Celsius (mS/m at 25°C).

List of Acronyms

CEP	continuous electromagnetic profiling
DC	Direct current
FDEM	multifrequency electromagnetic
GIS	geographical information system
GPR	ground-penetrating radar
GPS	global positioning system
NHD	National Hydrography Dataset
NAIP	National Agriculture Imagery Program
PAH	polynuclear aromatic hydrocarbons
PPS	push-point sampler
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey

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Geophysical Bed Sediment Characterization of the Androscoggin River from the Former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire, to the State Border with Maine, August 2009

By James R. Degnan, Andrew P. Teeple, Craig M. Johnston, Mark C. Marvin-DiPasquale and Darryl Luce[1]

Abstract

The former Chlor-Alkali Facility in Berlin, New Hampshire, was listed on the U.S. Environmental Protection Agency National Priorities List in 2005 as a Superfund site. The Chlor-Alkali Facility lies on the east bank of the Androscoggin River. Elemental mercury currently discharges from that bank into the Androscoggin River. The nature, extent, and the speciation of mercury and the production of methyl mercury contamination in the adjacent Androscoggin River is the subject of continuing investigations. The U.S. Geological Survey, in cooperation with Region I of the U.S. Environmental Protection Agency, used geophysical methods to determine the distribution, thickness, and physical properties of sediments in the Androscoggin River channel at a small area of an upstream reference reach and downstream from the site to the New Hampshire–Maine State border.

Separate reaches of the Androscoggin River in the study area were surveyed with surface geophysical methods including ground-penetrating radar and step-frequency electromagnetics. Results were processed to assess sediment characteristics including grain size, electrical conductivity, and pore-water specific conductance. Specific conductance measured during surface- and pore-water sampling was used to help interpret the results of the geophysical surveys. The electrical resistivity of sediment samples was measured in the laboratory with intact pore water for comparison with survey results. In some instances, anthropogenic features and land uses, such as roads and power lines affected the detection of riverbed properties using geophysical methods; when this occurred, the data were removed. Through combining results, detailed riverbed sediment characterizations were made.

Results from ground-penetrating radar surveys were used to image and measure the depth to the riverbed, depth to buried riverbeds, riverbed thickness and to interpret material-type variations in terms of relative grain size. Fifty two percent of the riverbed in the study area was covered with gravel and finer sediments. The electrically resistive river water and sediment in this study area were conducive to the penetration of the ground-penetrating radar and step-frequency electromagnetic signals and allowed for effective sediment characterization by geophysical methods.

The reach between the former Chlor-Alkali Facility and the Riverside Dam, had small areas of fine sediment (estimated 11 percent of riverbed area), found on the upstream left bank and the downstream right bank, with an electromagnetic conductivity (31.4 millisiemens per meter (mS/m) maximum) that was higher than the upstream reference reach. The greatest electromagnetic conductivity (195 mS/m), pore-water specific conductance (324 mS/m) and lab measured sediment conductivity of (76.8 mS/m, measured with a direct-current resistivity test box) in the study were measured approximately 1 mile (mi) downstream of the site from a sandbar on the left bank. Reaches adjacent to and within 2 mi downstream from the site, reaches had elevated electromagnetic conductivity despite having lower estimated percentages of riverbed area covered in sediment (11, 25, and 61 percent, respectively) than the reference reach (97), typically finer grained sediment will be more conductive. The Shelburne Reservoir is approximately 8 mi downstream from the site had the second greatest pore-water specific conductance measured, 45.8 mS/m. Many of the locations with the largest step-frequency electromagnetic values have not been sampled for pore water and sediment.

Introduction

This study was conducted by the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), to further understand the riverbed sediment and potential contaminant distribution downstream from the former Chlor-Alkali Facility Superfund Site (site) in Berlin, New Hampshire. The results of the study will be used for remedial activities and for development of an investigation and feasibility study plan for this site. The site was associated with a pulp and paper mill on the bank

[1]U.S. Environmental Protection Agency, Region 1.

of the Androscoggin River (fig. 1). The Chlor-Alkali Facility used electrolytic cells for chlorine gas production for the papermaking industry. Mercury was released and seeped into the soil, till and underlying fractured bedrock as a result of site activities (U.S. Environmental Protection Agency, 2011) and may represent a risk to human health and the environment.

An understanding of the extent of fine sediment and mercury contamination in the Androscoggin River is needed to determine the potential effects on the environment and to provide information for efficient remediation activities in the future. Currently (2011), the extent of mercury contamination in the Androscoggin River is unknown.

Eggleston (2009) indicated that resuspension of mercury-contaminated sediment can account for a large percentage of the annual downstream mercury load in a point-source, mercury-impaired watershed of the Shenandoah River in Virginia. An understanding of sediment distribution in the Androscoggin River downstream from the site would identify potential zones of contaminant deposition. Elemental mercury, such as that emanating from the site, can be transported with fine-grained, organic carbon-rich, riverbed sediments. Deposition of these sediments pose a concern because they provide an optimal environment for mercury methylation (Marvin-DiPasquale, Lutz, and others, 2009, Marvin-DiPasquale, Agee, and others, 2011). Methylation is the conversion of elemental mercury to the organic form (methyl mercury) through microbial activity. Methylmercury is the toxic form of mercury and more mobile within the food chain. This conversion enables the bioaccumulation of methyl mercury in fish.

Surface geophysical surveys such as ground-penetrating radar (GPR) and multifrequency electromagnetic (FDEM) surveys are effective techniques for determining the extent and nature of riverbed sediments. Sheets and Dumouchelle (2009) indicated the FDEM surveys (also known as continuous electromagnetic profiling (CEP)) were effective in mapping riverbed sediments in a 27 kilometer (km) reach of the Great Miami River in Ohio. Geophysical surveys in freshwater lakes and rivers have been used in New England to assess sediment characteristics for contaminant mapping (Ayotte and others, 1999), dam removal investigations (Dudley, 1999), aquatic habitat studies (Argue and others, 2007), and bridge scour assessments (Olimpio, 2000).

Site Background

From 1899 to 1965, a chlor-alkali facility located on the east bank of the Androscoggin River, was used to produce chlorine gas for the papermaking industry in Berlin, N.H. (fig. 1). The site was associated with a pulp and paper mill, and a sawmill. Chlorine was produced at the site using electrolytic diaphragm and potentially mercury cells. Chlorine was primarily produced to supply the papermaking industry for paper beaching. Mercuric chloride may also have been produced on site. The sawmill included a wood preserving operation from 1888 to 1930, which used mercuric chloride in a process known as "Kyanization" to preserve the wood (Gove, 1986).

In the 1990s, elemental mercury in the forms of a silver-colored liquid and vapor was observed in and near bedrock fractures along the left riverbank, immediately adjacent to the site and in river sediment. This prompted the New Hampshire Department of Environmental Services to initiate site investigations. Since the late 1990s, efforts have been made to contain mercury at the site and eliminate the seepage of contaminated groundwater to the river (Margaret A. Bastien, New Hampshire Department of Environmental Services, written commun., 2003). The former Chlor-Alkali Facility Superfund Site was placed on the USEPA National Priorities List in 2005 (U.S. Environmental Protection Agency, 2011).

Remedial efforts at the site included: (1) removal and demolition of buildings associated with the chlor-alkali facility, (2) installation of a subsurface bentonite-soil slurry (barrier) wall on the site perimeter that is connected to the bedrock surface, (3) installation of a synthetic cap over the site, to prevent precipitation infiltration, and (4) pressure grouting bedrock fractures along the riverbank. The intent of these remedial actions was to eliminate groundwater flow through the site's overburden and reduce this driving force for contaminant migration. Despite earlier actions to address the source of contamination, mercury continues to seep into the Androscoggin River at bedrock fractures at the edge of the site. Between 1999 and 2006, approximately 135 pounds (lbs) of elemental mercury and sediment containing mercury have been removed from the river and riverbank (U.S. Environmental Protection Agency, 2011).

Previous Investigations

Investigations at the former Chlor-Alkali Facility Superfund Site have revealed elevated mercury, lead, arsenic, polynuclear aromatic hydrocarbons (PAHs), organo-chlorine chemicals (dioxin, dibenzofurans), and other toxic metals in groundwater and soils beneath the site. Mercury and lead, exceeding State regulations, were identified in soil and groundwater at overburden and bedrock borings, and wells installed at the site (Tighe and Bond, Inc., 2001). Sediments and surface water were sampled in the Androscoggin River upstream from the site and downstream to approximately the Maine State border (fig. 1) in the summers of 2006, 2007, 2009 and 2010 (U.S. Environmental Protection Agency, 2011).

Elevated specific conductance (SC) in groundwater has been found in wells and adjacent soil samples with dissolved phase and adsorbed mercury at the site. Despite containment and removal efforts, elemental mercury continued to appear in depressions at bedrock fractures along the riverbank at the site. Degnan and others (2005) assessed the preliminary hydrogeology of the site, which was followed up with additional targeted sampling and hydrogeologic analysis (Weston Solutions, 2005).

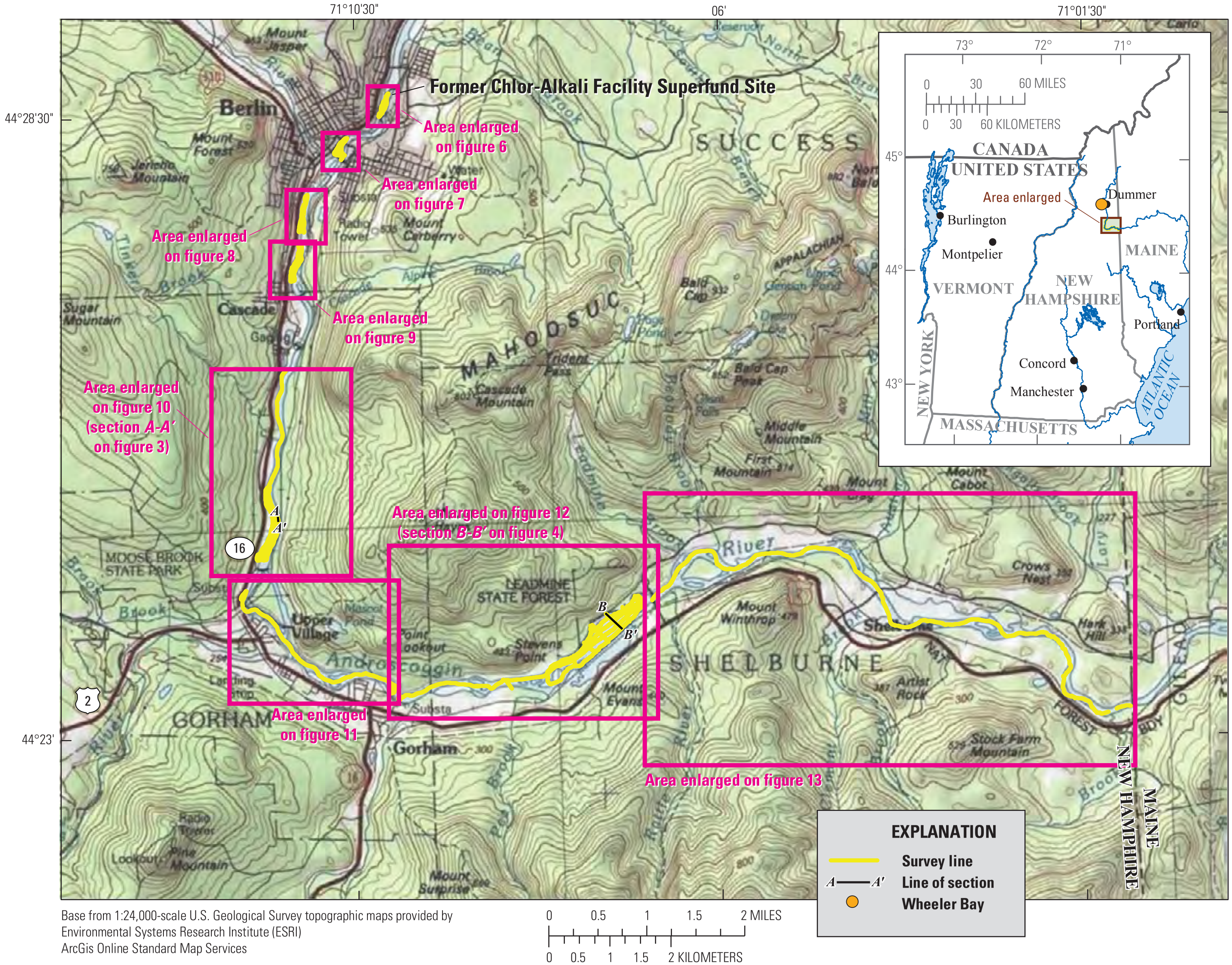


Figure 1. Location of the study area on the Androscoggin River in Berlin, Dummer, Gorham and Shelburne, New Hampshire, and locations of the surveyed reaches, and former Chlor-Alkali Facility Superfund Site on the Androscoggin River, New Hampshire.

Purpose and Scope

The purpose of this report is to describe riverbed sediment and pore-water conductivity distribution through the presentation of the results of geophysical surveys. Processed data from geophysical surveys were used to characterize and interpret properties of riverbed sediment presented in maps and cross sections. Surveys were conducted in navigable reaches along 18 miles (mi) of the Androscoggin River from the former Chlor-Alkali Facility Superfund Site downstream to the Maine State border and upstream at Wheeler Bay (fig. 1), during August 2009. Results of distribution, depth, relative grain size and electrical conductivity of streambed sediments are presented.

Study Area Description

The Androscoggin River at the Maine State border drains water from an approximately 1,500 square miles (mi^2) watershed. The drainage area is covered by 87 percent forest, 0.3 percent urban, 6.2 percent surface water, 3 percent wetlands, 2 percent barren, and 1 percent agriculture (U.S. Environmental Protection Agency, 2006). The drainage area upstream from the former Chlor-Alkali Facility Superfund Site is approximately 1,340 mi^2. In the town of Berlin, erosion-resistant bedrock forms a channel with near continuous cascades (Federal Emergency Management Agency, 1981), whereas downstream from the site, in northern Gorham, the channel has a moderate gradient incised into glacial fluvial sediment. In the town of Shelburne the channel is slightly braided, anabranching (channel splitting, forming islands) with localized meandering sections (fig. 1). Flow, sediment transport, and channel migration are affected by the bedrock geology, glacial and fluvial sediments, and manmade channel controls in the Androscoggin River Valley.

Geologic Setting

Bedrock geology, including rock type and structure, serve to control channel locations, slope and fluvial characteristics. The Androscoggin River channel at the former Chlor-Alkali Facility Superfund Site and downstream for 2 mi in Berlin is underlain by metamorphosed biotite-quartz monzonite of the Oliverian Plutonic Suite (Ordovician) (Billings and Billings, 1975; Lyons and others, 1997). Degnan and others (2005) mapped the rock types on the river bank and river bed at the site as predominantly gneiss with lesser amounts of chlorite schist or pegmatite, with fracture patterns that were parallel to and were reflected in the trend of the river channel. Gneisses and amphibolites of the Ammonoosuc Volcanics (Ordovician) lie downstream from the site in the channel near the Cascade and Brown Dams (Billings and Billings, 1975; Lyons and others, 1997). The Ironbound Mountain Formation (Devonian) (grey phyllite and metasandstone) underlies the river between the Brown Dam and the Gorham Dam (Lyons and others, 1997). Downstream from the Gorham Dam, the river channel is in a deep sediment-filled valley where two-mica granite (Devonian) locally intrudes into the older metasedimentary rocks of the Littleton (Early Devonian) and Madrid Formations (Upper Silurian (?)) (Billings and Billings, 1975; Lyons and others, 1997). Schists of the Littleton, Rangeley, Madrid and Smalls Falls Formations (Lyons and others, 1997) have been eroded and filled with glacial outwash deep beneath the Androscoggin River from downstream of the Shelburne Dam to the Maine State border (fig. 2).

Overburden geologic materials just upstream from the former Chlor-Alkali Facility Superfund Site include stratified sand, gravel, and silt alluvium deposited by glacial outwash. Overburden in the vicinity of the site and downstream to the backwater of the Brown Dam (Cotton, 1975, Gerath, 1978, Olimpio and Mullaney, 1997) was generally less than 20 feet (ft) thick and consists of thin deposits of glacial till (an unsorted mixture of clay, silt, sand, cobbles, and boulders). Glacial till covers bedrock on the valley floor and walls where slopes are gentle, but is absent along the Androscoggin River at the site and for 2 mi downstream from the site (U.S. Environmental Protection Agency, 2011).

Alluvial fan deposits, consisting of sand, gravel, and silt are found on the left bank (east) of the river upstream from the Cascade and Brown Dams and on the right bank near the Gorham Dam and Shelburne Reservoir. Stratified sand, gravel, and silt alluvium is the dominant deposit beneath the river channel from the backwater behind the Brown Dam to the New Hampshire–Maine State border. Ice-contact deposits of sand and gravel are found downstream from the Shelburne Dam in the river channel in the form of eskers, channel fillings, kames, and kame terraces. Undifferentiated glacial drift, consisting mostly of till, was found along the left bank of the river in Gorham and Shelburne (Gerath, 1978; Gerath and others, 1985).

River Flow and Channel Features

Flow in the Androscoggin River is regulated by eight hydroelectric dams in the study area; flows are controlled to respond to power demands, floods, and structure maintenance. The mean annual flow measured at USGS gage 01054000 in Gorham, N.H., is 2,110 cubic feet per second (ft^3/s). The month of May has the highest average annual flow, 4,210 ft^3/s and August has the lowest, 1,960 ft^3/s.

Dams and lakes in the headwaters of the Androscoggin River provide storage for a substantial amount of runoff and reduce flood peaks (Federal Emergency Management Agency, 1994). Though hydroelectric dams in Berlin, Gorham, and Shelburne (fig. 2) control flow and sediment transport during normal flows, due to minimal storage volume they have little effect on controlling flood flows (Federal Emergency Management Agency, 1981). The average channel slope in the study area from the site to the Maine State line is 26.1 feet per mile (ft/mi). The slope is much greater (100 ft/mi, fig. 2) between the site and the Cascade Dam

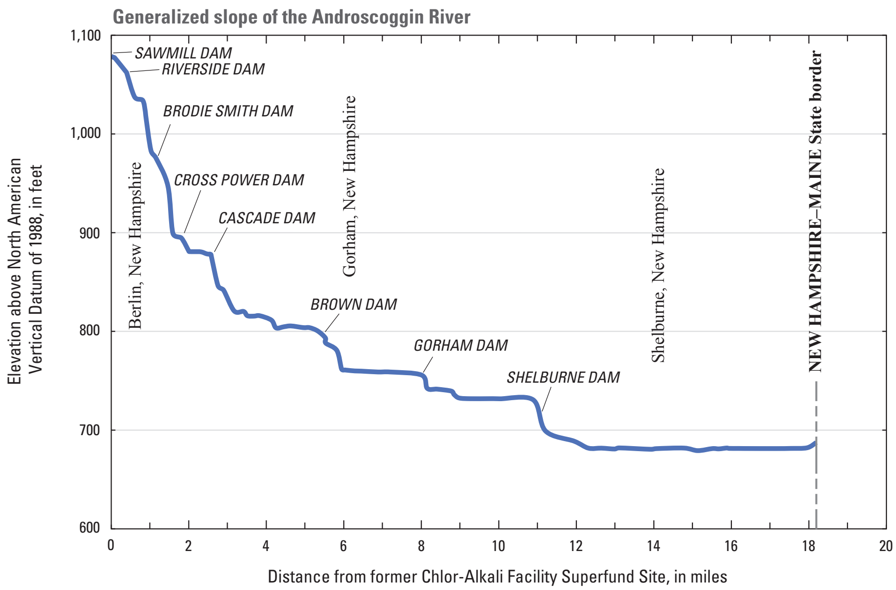


Figure 2. Generalized slope and location of dams on the Androscoggin River from the former Chlor-Alkali Facility to the New Hampshire–Maine State border.

(fig. 2) and greatly increases the river's capacity to produce hydroelectric power, and transport sediment and contaminants in this reach.

Most of the dams in the study area make use of the head drop available at the dam site to generate power. The Riverside and Brodie Smith Dams in Berlin (fig. 2) divert water out of the river channel and into a penstock (in this case, a large pipe) to increase heads on the turbines that are located farther downstream. Steeper parts of the channel downstream from the Riverside and Brodie Smith Dams receive limited flow during average flows, because of the penstock diversion, but carry large flood flows. Sediment may accumulate in deeper pools in these sections of river; however, these areas are not navigable because of steep channel slopes and were not surveyed in this investigation. The arrangement of dams and penstocks, from the Saw Mill Dam at the former Chlor-Alkali Facility Superfund Site to the Berlin–Gorham town line, creates areas of backwater where sediment can accumulate upstream from the Riverside, Brodie Smith, Cross Power, and Cascade Dams (fig. 2).

The Androscoggin River is incised, boulder filled, and average flows form rapids downstream of the Cascade, Brown, and Gorham Dams in Gorham for about 2, 1.5, and 1.5 mi, respectively. Pooled reaches between these dams affect the gradient or the backwater from the next downstream dam. Downstream from the Brown Dam to the Shelburne Reservoir, the channel gradient decreases and grades into a slightly braided sediment-filled channel with anabranching sections. The river runs unobstructed downstream from the Shelburne Dam in Shelburne and has braided and meandering sections for approximately 6.5 mi to the New Hampshire–Maine State border. A significant feature that may alter sediment distribution is ice-scour during the winter. At Riverside Dam, approximately 1,000 ft south of the site, large amounts of ice have been observed abrading the bottom of the river and being transported over the dam.

Methods of Data Collection and Analysis

GPR and FDEM geophysical survey methods were used to investigate sediment that has been deposited on the bed of the Androscoggin River from Wheeler Bay downstream to the New Hampshire–Maine State border. Direct-current (DC) electrical resistivity (the inverse of conductivity) laboratory sediment sample tests, with samples from locations with known pore-water conductivity, were analyzed to understand variations in FDEM conductivity measured in the field with FDEM surveys. Thermoplastic canoes with minimal metal parts, were used for GPR and FDEM surveys in navigable sections of the river.

The study was conducted in two types of river environments–pooled backwater (areas behind dams) and riffle and rapids from the former Chlor-Alkali Facility Superfund Site in Berlin, N.H., downstream to the Shelburne Reservoir (fig. 1). The lower velocity pooled parts of reaches are more likely to contain finer-grained sediments that are more conducive to mercury methylation (Marvin-DiPasquale, Lutz, and others, 2009; Marvin-DiPasquale, Agee and others2011).

Flow velocity during the study period prevented collection of straight cross-section surveys perpendicular to flow in several of the narrow, steep gradient reaches. Survey techniques were modified to work with high flows: GPR and FDEM data were collected by survey crews traveling upstream, on the side of the river with lower flow velocity and downstream with the thalweg flow on the high velocity side and center. After processing, cross sections were extracted from the survey data. Geophysical data were georeferenced using a global positioning system (GPS) with submeter horizontal positioning accuracy (Trimble Navigation Limited, 1998).

Ground-Penetrating Radar

GPR methods have widely been used to map the extent and type of geologic material beneath water (Beres and Haeni, 1991; Haeni, 1996; Olimpio, 2000). GPR results provide an image of the riverbed, general sediment grain size, and depth of buried riverbed surfaces. GPR surveys in this study made use of a transmitting and receiving 300 MHz (megahertz) frequency antennas. Electromagnetic radar waves were generated to image the subsurface. The radar-wave propagation is affected by differences in electromagnetic properties of the bed sediment including dielectric permittivity, electrical conductivity, and magnetic susceptibility because of differences in river and sediment water conductance, and sediment type (Keary and Brooks, 1991). The penetration of GPR signals is limited where the radar-wave reflection is scattered because of diffractions from large cobbles and boulders on the riverbed.

At locations where conditions are conducive to continuous and successful data collection, GPR provides a rapid means of providing detailed insight into riverbed-sediment conditions. Concurrent and linked GPS data collection is necessary for georeferencing data surveyed from the water surface. GPR surveys were performed in a continuous data-collection mode, which required a relatively constant data collection speed. Display gain was adjusted by multiplying data by a constant to increase or decrease signal amplitude to provide an improved image. An example of data and interpretation from this method is shown in figure 3. Adjustments were made during the survey to ensure adequate data collection, and were applied later during processing in Radan software (Geophysical Survey Systems, Inc., 2008) during interpretation. Patterns in the GPR record were used to distinguish between fine and course material using the methods of Beres and Haeni (1991). Interpreted locations of bed material and depth were exported with GPS coordinates for analysis in a geographical information system (GIS). Radar-wave velocities will vary with study area properties. Published velocity estimates were used to calculate depth from reflected radar-wave travel time (Beres and Haeni, 1991) for this study.

Step-Frequency Electromagnetic Induction

The FDEM method applied in this setting measured the combined electrical conductivity of sediments, surface and pore water, which is affected by depth, grain size, and mineral composition. FDEM surveys were used to indirectly measure the electrical conductivity of the riverbed with induced electromagnetic signals (Zohdy and others, 1974). The FDEM technique also may indicate the presence of electrically conductive contaminants such as dissolved major ions including sodium, chloride, and calcium, or elemental mercury, if concentrations are sufficient. If elemental mercury were present in sufficient quantity, its conductivity or low resistivity (98 × 10^-8 ohm meters (Giancoli, 1989)) could create a large FDEM response. FDEM was used successfully to identify a contaminant plume beneath a pond in southern New Hampshire (Ayotte and others, 1999). Results can be processed and inverted for interpretation of geology and water pore-water conductivity with depth. The Geophex GEM-2 Plus used in this study, is a portable multi-frequency electromagnetic sensor. Data from surveys with the GEM-2 Plus can be used to calculate the bulk apparent subsurface electrical conductivity and magnetic susceptibility (Geophex, Ltd., 2007).

Before and after each survey, FDEM data collection was tied into a common base station established for each of the 10 reaches in the study area to provide static data for comparison with the FDEM survey line data. Base station data are used to correct for FDEM drift (shift in instrument response with time). The survey and base station data were processed to remove irregularities in the data caused by excess FDEM noise. All data were linearly shifted, using the base station responses to correct for instrument drift that could occur during the survey period (13 days). Collection and data processing techniques in this study are similar to those used in Abraham and others (2006).

Data were collected in step mode (rapidly switching frequencies to apply maximum power to each), 10 frequencies were chosen for this study (570; 990; 1,770; 3,090; 5,490; 9,690; 17,070; 30,090; 53,010; and 93,450 Hz (hertz)). Lower frequencies provide deeper depth of investigation (Geophex, Ltd., 2007; Huang and Won, 2000; Won, Keiswetter, and others, 1996; Won, Choi, and Im, 2006). A presurvey environmental noise test was used to select frequencies that would minimize the effect of natural or anthropogenic electromagnetic noise in the area. Power-transmission lines were present in the immediate area of some reaches; the 60 Hz frequency associated with power lines was monitored throughout the survey and removed in subsequent data filtering.

Depth of water, conductivity of bed materials and background and local anthropogenic (such as power lines) noise will affect the success of an FDEM survey for a given frequency in a given reach. As a result, the quality of the

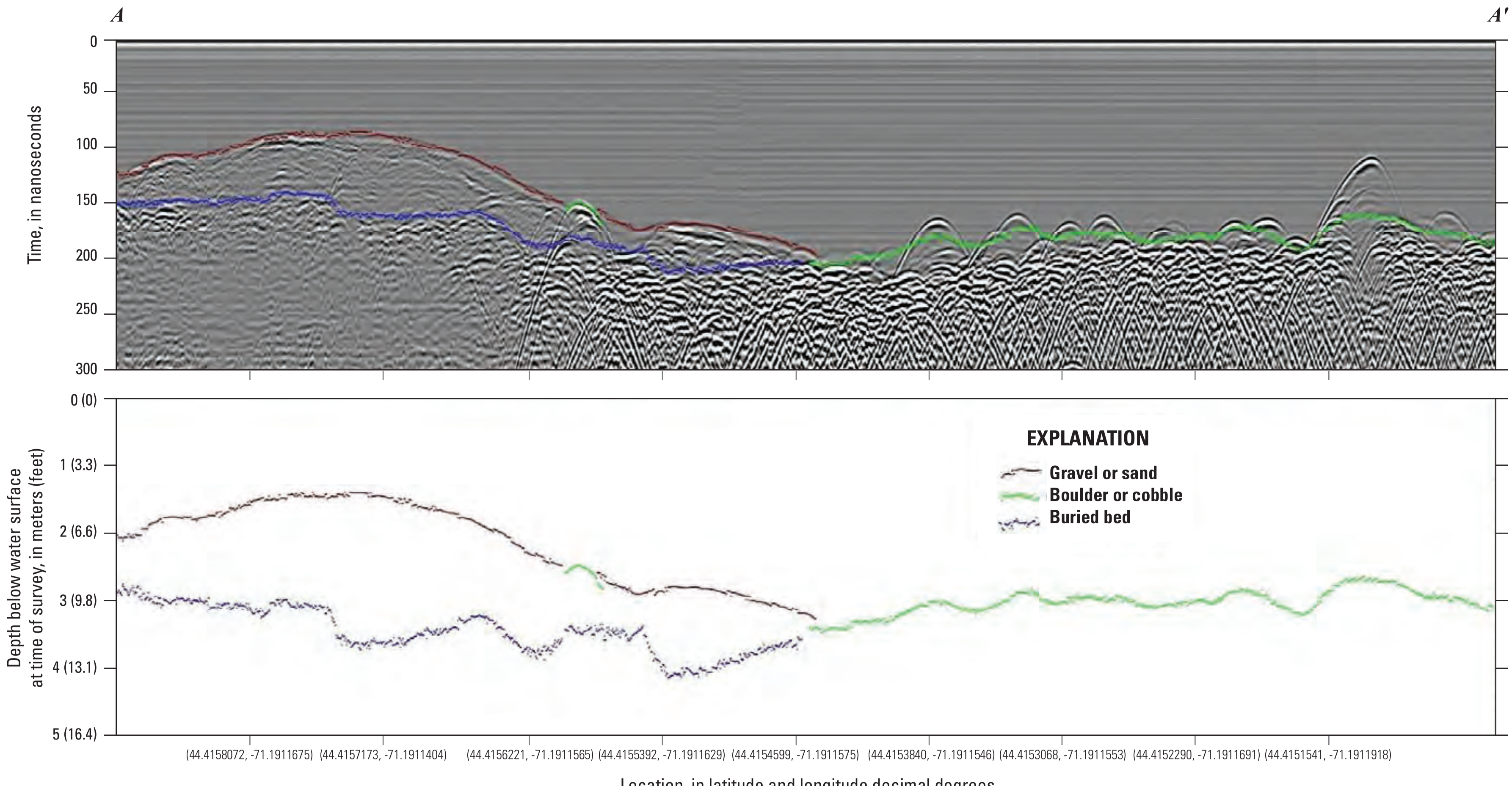


Figure 3. Example of a cross section showing ground-penetrating radar profile and interpretation in reach AR–7 upstream from the Brown Dam, Androscoggin River, Gorham, New Hampshire (location shown in figure 1).

data varies by frequency and reach. A consistent subset of frequencies was needed in order to compare data from reach to reach on the same scale. Plots of FDEM data by frequency for all survey lines were analyzed to pick three common frequencies with the lowest noise across the study area. A subset of the most stable frequencies (9,690; 17,070; and 30,090 Hz) was processed to create a data set of total conductivity using WinGEM version 3, 0, 0, 14 (Geophex, Ltd., 2007). FDEM data were trimmed in the vicinity of bridges and power lines because of the interference caused by the metal structures and electromagnetic fields.

To help understand conductivity variations with depth, the most stable five frequencies for a given survey were used along selected survey paths for inverse modeling of the data for select portions using WinGEM version 3, 0, 0, 14 (Geophex, Ltd., 2007) software to associate resistivity values with depth (fig. 4). Results of the inversion are given in terms of resistivity (inverse of conductivity). Resistivity values measured from bed sediments (about 200 ohm meters) and surface-water SC (SC) values (converted to about 300 ohm meters) were used to construct a 2-layered starting model. GPR riverbed depth interpretations overlaid on the FDEM inversion indicate a correlation with more resistive river water (green layer on top) and less resistive (blue layer) sediment through approximately 70 percent of the cross section (fig. 4).

At very low frequencies, electromagnetic induction response is due more to the magnetic properties of the subsurface than electrical properties, and the FDEM survey magnetic susceptibility responses are similar to a magnetometer survey (Won and Huang, 2004; Won and Keiswetter, 1997). Magnetic susceptibility was calculated using the raw in-phase component of the lowest frequencies used in the surveys (570; 990; 1,770; 3,090 Hz). When a magnetic response occurred, generally all four frequencies gave a similar response, though the lower frequencies indicate magnetic material more often than the higher frequencies. Magnetic susceptibility responses (lower frequency FDEM) were plotted on maps in reaches near the site in Berlin, N.H., to search for metal debris that may affect FDEM responses. During low water metal is observed in the river in the form of rusted nuts bolts and other debries. Mercury in an elemental liquid state is electrically conductive, but is not magnetic and would not create a magnetic susceptibility response. Magnetic susceptibility responses were not observed in reaches near downtown Gorham, but were observed in Shelburne downstream from the Gorham Dam in a rural setting. Different responses in Shelburne may be a result of variations in bedrock geology beneath the river (two mica granite) and are not associated with elevated electromagnetic conductivity. Determining bedrock properties and the mineralogy of sediments is beyond the scope of this report.

Sediment Sampling and Direct-Current Resistivity

SC measured during surface-water, pore-water and sediment sampling (with subsequent grain size analysis, table 1) collected as part of a parallel investigation (Jeffrey Deacon, U.S. Geological Survey, written commun., 2009) were used to help understand and interpret the results of the geophysical surveys. The DC resistivity of sediment samples was measured in the laboratory with pore water intact for comparison with FDEM results.

Environmental samples were collected during lower flow conditions in September 2009 and August 2010 using USGS surface-water sampling protocols (Wilde and others, 1999). Pore-water samples were collected with the use of a push-point sampler (PPS) according to protocols described in Zimmerman and others (2005). A PPS is designed to sample pore water with minimal disturbance to the sediment matrix. SC of sampled water was used to determine if discontinuity between surface water and pore water is achieved during sampling.

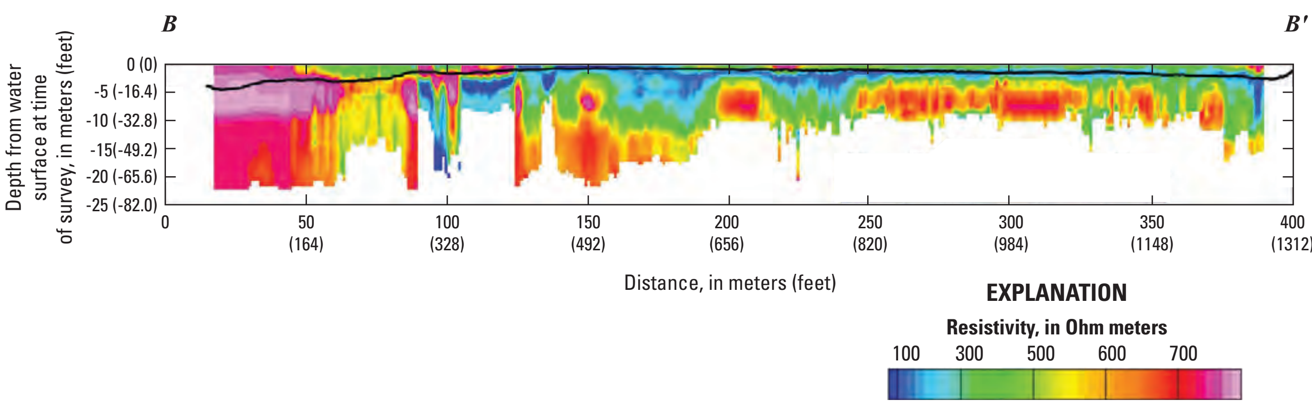


Figure 4. Example of a cross section showing inverted electromagnetic induction profile in reach AR–9 between the Gorham and Shelburne Dams, Androscoggin River, Shelburne, New Hampshire (location shown in figure 1). Solid black line represents riverbed measured with ground-penetrating radar.

Table 1. Surface, pore-water and sediment conductivity, direct-current resistivity test box results and sediment grain size.

[ID, identifier; SW, surface water; SC, specific conductance; mS/m, millisiemens per meter; PW, pore water; sediment conductivity, measured in direct-current resistivity test box; *, samples collected with core tube; EM, electromagnetic induction estimated in sample location; distance to EM survey in feet, distance to EM survey line in feet from sample location, 3-meter sample position accuracy; --, sample more than 65 feet from a survey line]

Reach name	Sample ID	Sample date	SW SC (mS/m)	PW SC (mS/m)	Sediment conductivity (mS/m)	Estimated EM (mS/m)	Distance to EM survey (feet)	Percent silt and clay
Wheeler Bay	AR–2_1	9/16/2009	2.7	11.2	8.9	--	--	69
Wheeler Bay	AR–2_2	9/16/2009	2.9	16.4	5.6	--	--	77
Wheeler Bay	AR–2_3	9/16/2009	2.4	8.2	7.1	--	--	62
Wheeler Bay	AR–2_4	8/23/2010	2.5	19.0	13.3*	--	--	74
Wheeler Bay	AR–2_5	8/23/2010	2.7	8.3	8.2*	--	--	63
Brodie Smith Dam	AR–4_1	8/27/2010	4.7	279.0	67.4*	73.2	38.1	27
Brodie Smith Dam	AR–4_2	8/27/2010	5.4	324.0	76.8*	72.8	27.2	59
Cross Power Dam	AR–5_1	8/27/2010	3.2	13.2	8.6*	--	--	60
Cross Power Dam	AR–5_2	8/27/2010	3.3	16.6	6.8*	3.8	46.9	25
Cascade Dam	AR–6_1	9/18/2009	3.0	24.5	5.4	2.2	32.5	28
Cascade Dam	AR–6_2	8/26/2010	3.2	41.4	7.8*	2.2	29.2	45
Cascade Dam	AR–6_3	8/26/2010	3.4	16.5	12.7*	6.7	63.0	50
Brown Dam	AR–7_1	8/26/2010	3.7	5.2	11.3*	6.5	54.1	56
Brown Dam	AR–7_2	8/26/2010	3.3	12.7	6.4*	--	--	74
Gorham Dam	AR–8_1	9/18/2009	3.6	14.8	3.5	1.2	33.1	51
Gorham Dam	AR–8_2	9/18/2009	3.4	15.7	3.6	4.5	0.0	37
Gorham Dam	AR–8_3	9/18/2009	3.4	10.8	2.5	--	--	80
Gorham Dam	AR–8_4	8/24/2010	3.4	6.1	3.4*	--	--	18
Gorham Dam	AR–8_5	8/24/2010	3.4	9.4	5.8*	4.7	17.1	59
Shelburne Dam	AR–9_1	9/17/2009	3.5	11.6	3.1	--	--	14
Shelburne Dam	AR–9_2	9/17/2009	3.5	45.8	3.9	--	--	3
Shelburne Dam	AR–9_3	9/17/2009	3.5	9.3	3.1	2.5	3.6	29
Shelburne Dam	AR–9_4	9/17/2009	3.8	15.8	3.9	3.3	28.9	28
Shelburne Dam	AR–9_5	8/24/2010	3.6	4.3	4.0*	2.0	49.2	33
Shelburne Dam	AR–9_6	8/25/2010	3.6	6.7	16.2*	2.9	27.6	33
Shelburne Dam	AR–9_7	8/25/2010	3.7	4.8	3.4*	--	--	38

Streambed sediment samples were collected within a few meters of pore-water sampling locations. Samples were extracted using a hand-held coring device or ponar (grab sampling device) to a maximum depth of 4 inches (10 cm) in 2009 according to USGS protocols (Shelton and Capel, 1994), and with a hand-held coring device to a maximum depth of 4 inches (10 cm) in 2010 according to Lutz and others (2008).

The resistivity of 26 sediment samples were measured with DC laboratory resistivity measurements following procedures outlined by Advanced Geosciences, Inc., (written commun., 2009). To measure the DC resistivity of sediment samples in the lab, DC is induced in the sample by two current electrodes, and the voltage is measured at two potential electrodes. Apparent resistivity is calculated from the resistance value and geometric factors corresponding to the sample box geometry. These data allow for the correlation of known riverbed material with a specific resistivity value and pore-water SC.

DC resistivity values were converted to conductivity for comparison with FDEM and pore-water SC results. Clay and silt have more conductive responses than sand and gravel although the SC of pore water can affect the results of FDEM surveys.

Interpretation of Riverbed Conductivity

Riverbed conductivity can be interpreted qualitatively from the processed results of FDEM surveys. The low ionic strength, low SC, and shallow depth (average 5.2 ft, (1.6 m)) of the Androscoggin River results in little contribution of the river water to the total FDEM conductivity value in the study area. Sediment conductivity in the study area is largely determined by riverbed-sediment type and pore-water SC, though sediment and pore-water sampling points were separated by as much as two meters and this should be considered when comparing the measurements. In general greater pore-water conductivity corresponds to greater sediment conductivity, but sediment conductivity will be affected by mineralogy and increase with decreasing grain size. Greater or varying pore-water conductivity also can mask the effects of grain size and mineralogy.

Average water and bed sediment conductivity (measured with DC resistivity in the lab) from 2009 sampling were used to determine skin depth (Won, 1980), which is the total depth of penetration of the FDEM field. Depth of investigation (Haung, 2005) was determined graphically for the three frequencies selected for the study-area-wide analysis. The depth of investigation is always less than the skin depth and is determined using the contrast between the host and target (water and sediment in this study). Correlation of depth measured from GPR and conductivity from FDEM surveys were analyzed to assess whether water depth was driving the FDEM response.

The effects of discharging groundwater on the riverbed pore-water quality were not known in this study area, but may be a factor in some locations near land-use features, such as roads. Groundwater conductance likely is considerably greater (hundreds of millisiemens per meter (mS/m)) near major roads because of the application of road salt (Harte and Trowbridge, 2010).

Estimation of Riverbed Properties by Reach

GPR and FDEM survey results were interpolated between survey lines to produce continuous grids of estimated GPR bed material type, bed thickness, water depth, and FDEM total conductivity. Magnetic susceptibility data from FDEM surveys was plotted with FDEM grid data to identify areas where conductive anomalies likely are associated with ferrous objects in the river (metal debris) as opposed to pore water or sediment related anomalies. Maps were produced for reaches adjacent to and downstream of the site to display sediment and conductivity distribution. Summary values for the upstream reference reach, Wheeler Bay are included in this report for comparison with other reaches, but it was not shown in a map since only a small portion of the reach was surveyed.

The TOPOGRID program (Environmental Systems Research Institute, 1999) was used in interpolation of GPR and FDEM survey results because the routine preserves data values and minimum and maximum values are not exceeded in the interpolated output grids. The interpolation extent was constrained using modified Androscoggin River area features from the high-resolution (1:24,000 scale) National Hydrography Dataset (NHD) (Simley and Carswell, 2009).

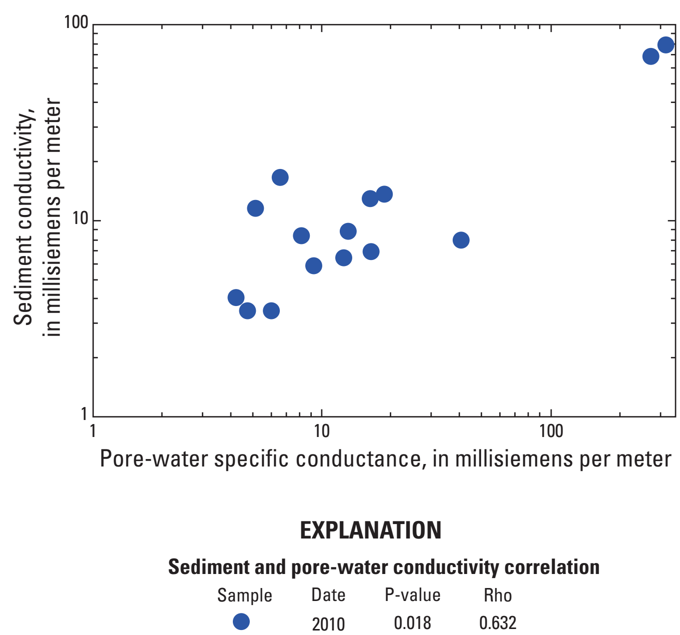


Figure 5. The relation between specific-conductance measurements from riverbed pore-water and resistivity values measured in the laboratory from co-located riverbed-sediment samples with intact pore water.

The polygon area features from NHD were edited to better represent the riverbank boundary depicted on high-resolution aerial photographs from the National Agriculture Imagery Program (NAIP) and to correspond with parts of reaches and anabranch channels that were surveyed.

GPR record interpretations and selection of velocity by material were standardized across the study area to provide georeferenced results in terms of water depth, bed material type, and bed thickness. GPR records were interpreted based on the methods presented in Beres and Haeni (1991), five materials that give a unique reflection pattern were selected for interpretation: (1) water, (2) silt and or sand, (3) sand and or gravel, (4) boulder and cobble or both, and (5) bedrock. Maps of estimated bed sediment were produced with silt, sand, and gravel grouped into one category and cobble, boulder, and bedrock in another. Results from GPR interpolations were extracted to produce cross sections of bed material and sediment thickness in selected locations.

Characteristics of Riverbed Sediment

In this report, the words “right” and “left” refer to directions that would be reported by an observer facing downstream. GPR and FDEM survey track lines (figs. 6–13) indicate where measurements were made and passed filtering quality control procedures, therefore, an estimated value should be considered with less confidence with increasing distance from a survey line.

Average water specific conductance (3.4 mS/m) and bed sediment (21.9 mS/m) conductivity from 2009 sampling were used to determine FDEM skin depth, which is the total depth of penetration of the field. Depth of investigation was determined graphıcally for the three frequencies selected for the study-area-wide analysis (table 2). Conductivity by reach was summarized to assess bulk differences in conductivity of the riverbed (table 3). Relatively consistent measurements of surface-water SC and a test of correlation between measured water depth and conductivity resulted in a widely-varying correlation coefficient (table 3). This correlation result adds confidence that the FDEM response was due to different riverbed material and pore-water SC as well as water depth, but not driven by water depth alone.

The effects of discharging groundwater on the riverbed pore-water quality were not known in this study area, but the median groundwater SC in Androscoggin and upper Connecticut River Basins in New Hampshire is 15.0 mS/m (Olimpio and Mullaney, 1997). This is greater than the median surface-water SC of 3.4 mS/m measured in this study, both are relatively low.

Cultural features, particularly bridges and power lines, affected the interpretation of geophysical surveys in some parts of the study area. Parts of reaches with FDEM surveys which could not be interpreted (black line, figs. 6–13) also may have areas of greater riverbed conductivity. For example, sediment sample AR–6–2, collected close to the river bank, had an elevated pore-water conductivity and lab conductivity (table 1). The sandbar that this sample was located on was not surveyed with FDEM and this large conductive value does not appear in the mapped data (fig. 9). FDEM data were removed from parts of reaches AR–4, AR–8, AR–9 because they were affected by power-line interference. Data also were removed in the vicinity of metal bridges that cross the river and affected FDEM data in parts of reaches AR–3, AR–5, AR–6, and AR–10.

Wheeler Bay, Reference Reach

Wheeler Bay (fig. 1) is located in reach AR–2 in a rural setting in the town of Dummer, N.H., approximately 11 mi upstream from the former Chlor-Alkali Facility Superfund Site. The Androscoggin River flows to the southeast through this reach. The Pontook hydroelectric dam (outside of study area) is located upstream from this reach. This reach is unaffected by site-related contaminants or the effects of urbanization, and is a reference reach for this study and ongoing biological, sediment, and biogeochemical studies of the Androscoggin River (U.S. Environmental Protection Agency, 2011). Geophysical surveys of this reach were completed to assess equipment responses in an environment unaffected by the site-related contaminants.

Table 2. Skin depth and depth of investigation values determined graphically for selected electromagnetic frequencies.

[Hz, hertz]

Frequency Hz	Water skin depth in meters (feet)	Sediment skin depth in meters feet)	Depth of investigation in water in meters feet)	Depth of investigation in sediment in meters (feet)
	Won, 1980		Huang, 2005	
9,690	100 (328)	50 (164)	10.1 (33.1)	8.0 (26.2)
17,070	75 (246)	40 (131)	9.9 (32.5)	7.0 (23.0)
30,090	50 (164)	20 (66)	8.0 (26.2)	4.9 (16.1)

Table 3. Estimates of electromagnetic conductivity summarized by reach and correlation with water depth.

Reach name	Reach code	Conductivity, in millisiemens per meter			Water depth and conductivity correlation
		Average	Minimum	Maximum	
Wheeler Bay	AR–2	2.6	0.1	9.4	0.21
Upstream of the Riverside Dam	AR–3	3.1	0.6	31.4	-0.31
Upstream of the Smith Dam	AR–4	10.1	0.9	194.9	-0.49
Upstream of the Power Dam	AR–5	4.2	1.7	10.2	-0.48
Power Dam to Cascade Dam	AR–6	2.7	0.8	7.1	-0.05
Cascade Dam to Brown Dam	AR–7	2.2	0.6	8.9	-0.03
Brown Dam to Gorham Dam	AR–8	0.9	0	7.1	-0.04
Gorham Dam to Shelburne Dam	AR–9	2.5	0	12.6	-0.36
Downstream of the Shelburne Dam	AR–10	1.7	0.9	3.5	0.56

The part of the reach that was surveyed in this study is about 1,000 ft long and varies in width between 300 and 1,000 ft. The wide channel in this reach is located at a bend in the river. River water is mostly pooled, and had an average depth of 4 ft and a maximum depth of about 15 ft during the time of the survey. Fine sediments have accumulated because of a wide riverbed area, lower streamflow velocity and the channel gradient in Wheeler Bay. Some boulders were observed on the riverbed on the right side of the channel where flow velocity is higher.

Grain size analysis of five sediment samples from Wheeler Bay (table 1) indicates between 62 and 77 percent of silt and clay, this is higher than most of the samples in the study. Silt and clay will increase the FDEM conductivity response, and processed GPR results indicate that this is the largest riverbed area covered with sediment (97.3 percent; gravel and finer) of all the reaches surveyed (table 4). FDEM values had an average of 2.6, a minimum of 0.1 and a maximum of 9.4 mS/m (table 3). Despite the larger percentage of fine sediment in samples (table 1) and interpreted from GPR (table 4), FDEM conductivity measurements from the bay were less than those from reaches within a few miles downstream from the site.

Reach AR–3, Between the Former Chlor-Alkali Facility Superfund Site and the Riverside Dam

Reach AR–3 (fig. 6) in the town of Berlin, N.H. is located between the Sawmill Dam, upstream to the north, and the Riverside Dam downstream to the south. This reach is adjacent to the former Chlor-Alkali Facility Superfund Site located on the left bank (east). This reach may be affected with site-related contaminants and also may be affected by other contaminants related to urbanization. The surrounding land has a long and varied history of industrial use. When the dam flood gates are shut, as they were during the surveys, most of the flow leaves the turbine building at the Sawmill Dam on the right bank and flows towards the left bank at the railroad bridge and back to the right bank at the Riverside Dam turbine intake. Minimal sediment accumulates in these areas.

The surveyed part of reach AR–3 is about 1,400 ft long and was between 200 and 250 ft wide. The narrow straight channel in this reach had an average depth of 6.8 ft and a maximum depth of about 15.8 ft during the time of the survey. This reach has limited areas for fine sediments to accumulate because of high streamflow velocity. Bedrock, with some boulders and scrap metal, is observed on the riverbed and bank along the left bank from the Sawmill Dam to about 650 ft downstream. Some fine sediment has accumulated among boulders along the left bank just downstream from the bedrock and near areas of visible groundwater seeps from the riverbank and iron dissolution onto the riverbed.

Reach AR–3 has the greatest estimated percent of bedrock and boulder riverbed material interpreted and extrapolated from GPR results (89 percent, table 4) of all the reaches surveyed. Fine sediment found on the upstream left bank and the downstream right bank have elevated electromagnetic conductivity that is interpreted to be from elevated bed pore-water SC (fig. 6). FDEM values had an average of 3.1, a minimum of 0.6 and a maximum of 31.4 mS/m (table 3). The maximum FDEM values from this reach were elevated above those of the reference reach , despite the limited fine material. This indicates that the river may be affected by contaminants or the effects of urbanization (road salt). FDEM data affected by a steel railroad bridge were removed, which is illustrated by the absence of the black FDEM survey track upstream from cross-section D–D' (fig. 6). FDEM magnetic susceptibility results indicate potential magnetic material near the two areas of fine sediment and at the upstream extent from the surveyed reach. This response likely is a result of metal debris on the riverbed.

Table 4. Percentage of fine sediment summarized by reach.

Estimates based on gridding of ground-penetrating radar interpretations					
Reach name	Reach code	Area of gravel or finer sediment,		Percent of reach area	
		in square meters	in square yards	Gravel or finer sediment	Cobble, boulder and or bedrock
Wheeler Bay	AR–2	933,256	1,116,954	97	3
Upstream from the Riverside Dam	AR–3	29,894	35,778	11	89
Upstream from the Smith Dam	AR–4	85,109	101,862	25	75
Upstream from the Power Dam	AR–5	354,077	423,772	61	39
Power Dam to Cascade Dam	AR–6	342,268	409,639	51	49
Cascade Dam to Brown Dam	AR–7	1,345,012	1,609,759	42	58
Brown Dam to Gorham Dam	AR–8	432,820	518,015	20	80
Gorham Dam to Shelburne Dam	AR–9	5,794,177	6,934,680	77	23
Downstream from the Shelburne Dam	AR–10	6,915,104	8,276,245	86	15
Total		**16,231,717**	**19,426,703**	**52**	**48**

Reach AR–4, Upstream from the Smith Dam

Reach AR–4 is located downstream of the Riverside Dam and upstream from the Smith Dam and Mason St. in Berlin, N.H. (fig. 7). Most of the land abutting this reach is urban or industrial, although there is a community park on the downstream left bank side. The Androscoggin River flows to the southwest through this reach. Most of the flow during these surveys was along the right bank, from the Riverside Dam turbine building outflow to the Smith Dam penstock intake on the right bank, downstream side from the Mason Street Bridge. Even though this reach is wide, the flow velocity was too high along the right side during the surveys to collect cross sections. As an alternative to cross sections, a counter clockwise survey (upstream on slow side, downstream on fast side) was used to collect data in the backwater from the dam. Five marker buoys were placed at approximately 20 foot intervals from the left bank (where current was at a minimum) to the center as points of reference for the survey navigation.

This surveyed reach was about 1,000 ft long and was between 150 to 550 ft wide. The channel in this reach had an average depth of 6.4 ft and a maximum depth of about 16.5 ft, during the time of the survey. Fine sediments have accumulated in many areas on the left side of the reach because of lower stream flow velocity and channel gradient. Cobbles, boulders and bedrock are found along the right bank and the upstream part of the left bank. Bedrock outcrop on the riverbed was confirmed in September 2009, when this reach was drained for maintenance, and the bed was exposed above water. A large silt and sand bar deposit with some cobbles and boulders were found on the downstream left bank.

The largest FDEM conductivity values measured in this study occur on the bed on the left side of the channel and indicate conductive pore water; metal within cobble and boulders near the left bank is indicated in the FDEM magnetometer response. Interpretation and extrapolation of GPR results was used to indicate approximately 25 percent of the riverbed area is covered by gravel or finer material (table 4); fine material is as much as 3 ft thick on top of an older buried bed (fig. 7B). Pore-water SC measured in this reach was the greatest in the study area, 279 and 324 mS/m (table 1) at sediment sample locations AR–4_1 and AR–4_2 (fig. 7). This reach has the largest FDEM values in the study with an average of 10.1, a minimum of 0.9 and a maximum of 195 mS/m (table 3). Zones of elevated FDEM conductivity are measured on a sandbar deposit on the downstream left side of the reach. Sediment samples collected near a FDEM survey line and measured in the laboratory had values of 67.4 and 76.8 mS/m, similar to estimated values (73.2 and 72.8 mS/m; table 1). FDEM values at this reach were elevated above those of the reference reach because of elevated pore-water SC within fine grained material. This indicates that the river may be affected by contaminants or the effects of urbanization (road salt). FDEM data were affected by power-line noise downstream (south) of cross-section E–E’ and were removed. FDEM data removal is illustrated by the absence of the black FDEM survey track where GPR survey tracks are present (fig. 7).

Reach AR–5, Upstream from the Cross Power Dam

Reach AR–5 is located upstream of the Cross Power Dam which controls the water level and flow in this reach. The Androscoggin River flows to the south through this reach, which is adjacent to a public park on the upstream left bank

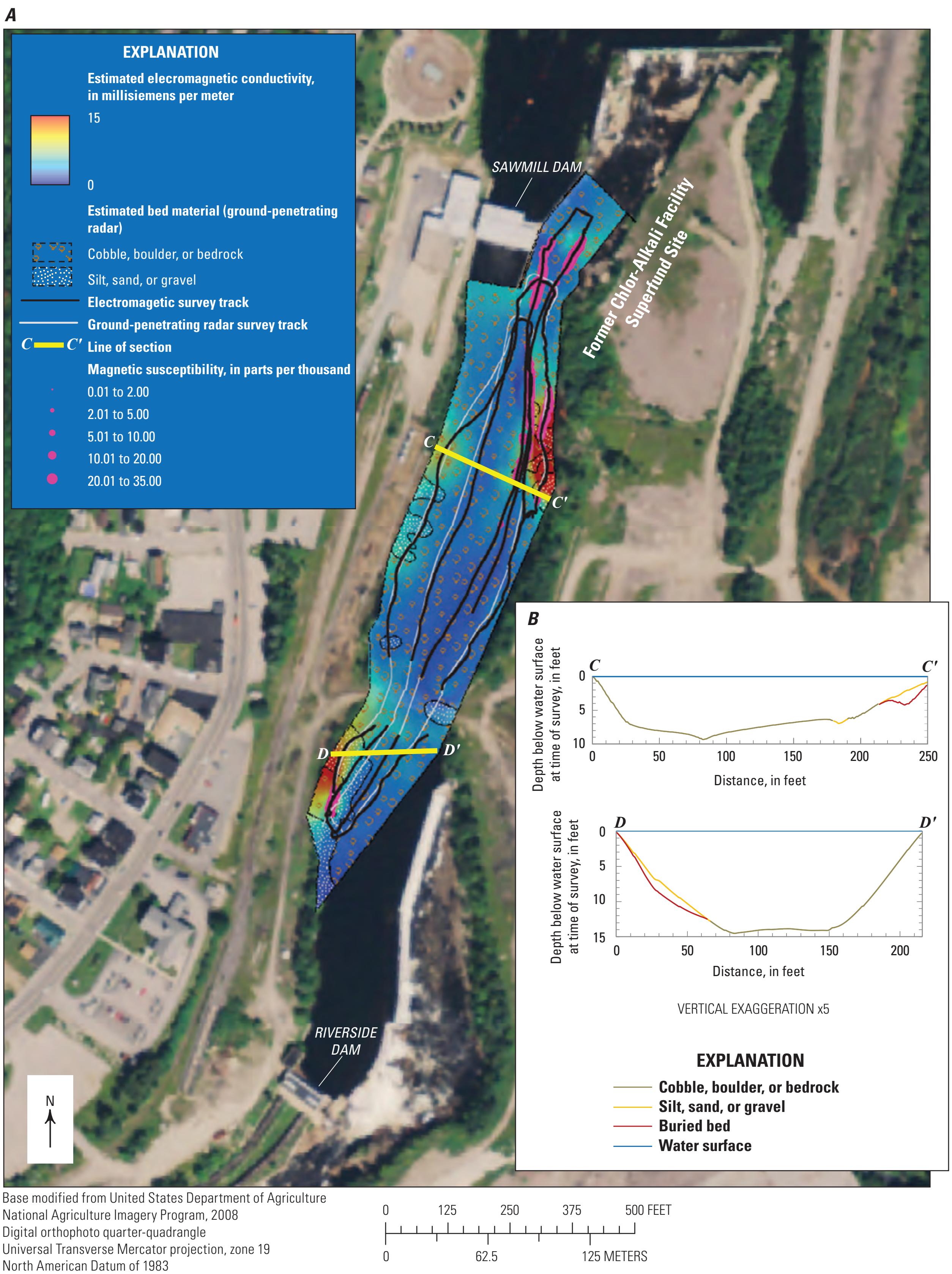


Figure 6. The results of geophysical surveys of riverbed-sediment characteristics in reach AR–3 from the former Chlor-Alkali Facility Superfund Site to the Riverside Dam, Androscoggin River, Berlin, New Hampshire.

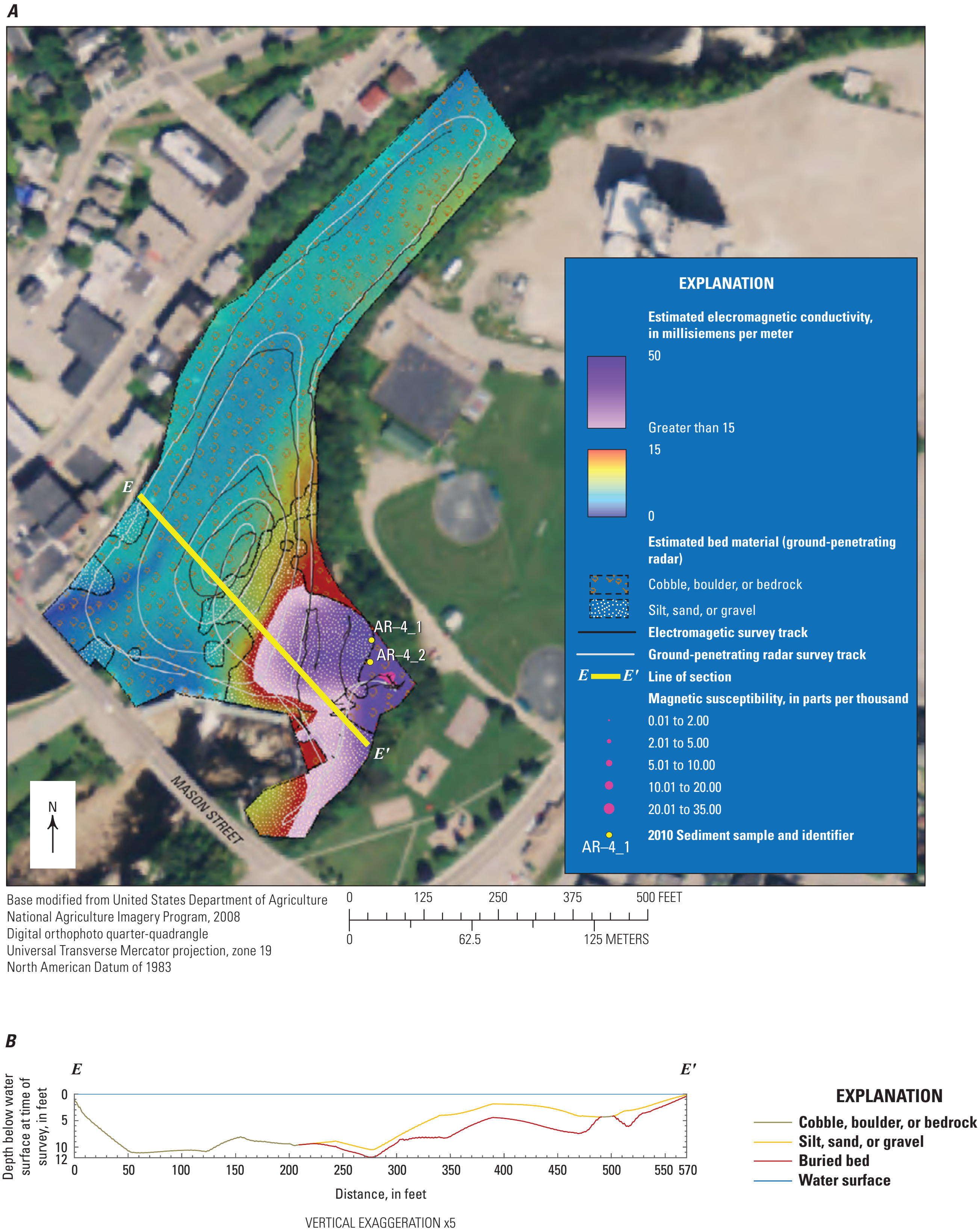


Figure 7. The results of geophysical surveys of riverbed-sediment characteristics in reach AR–4 upstream from the Brodie Smith Dam, Androscoggin River, Berlin, New Hampshire.

and urban land on the right bank including State Route 16. During the survey period, the strongest currents flowed along the right bank downstream from the hydropower discharge. During high streamflows, additional flow enters the reach from upstream the left bank. This flow is conveyed through a bedrock gorge with a steep gradient (100 ft/mi, fig. 2) from the Brodie Smith Dam.

This surveyed reach is about 2,000 ft long and between 150 and 400 ft wide, and the depth is 7.7 ft on average (more than 16.6 ft near the James Cleveland Bridge). Bedrock outcrops along much of the left and right bank upstream from the James Cleveland Bridge on Unity Street and was found on the left side of the channel downstream. Sandbars form along the upstream left bank, downstream left bank, and just downstream from the right bank abutment on the James Cleveland Bridge. This reach is wider and likely contains more sediment that was not measured downstream from the Cross Power Dam warning barrels.

Interpretation and extrapolation of GPR results indicate approximately 61 percent of the riverbed area in reach AR–5, upstream from the Cross Power Dam is covered by gravel or finer material (table 4). This reach has larger FDEM values than the Wheeler Bay reference reach with an average of 4.2, a minimum of 1.7 and a maximum of 10.2 mS/m (table 3). This indicates that the river may be affected by contaminants or the effects of urbanization (road salt). FDEM data were affected by the steel James Cleveland Bridge and were removed. FDEM data removal is illustrated by the absence of FDEM survey track lines where the GPR survey track lines occur (fig. 8). Fine sediments with conductive pore water are interpreted just upstream from the Cross Power Dam warning barrels. The greatest conductivity in the surveyed reach is at the downstream end, on the left bank (fig. 8). Fine sediment with conductive pore water accumulated at the upstream end from the reach in a bar along the left bank. At this point the natural steep gradient bedrock channel joins the hydropower penstock outflow entering the backwater from the Cross Power Dam. This sediment likely was suspended by high flows though this channel and the channel upstream near the site between the Riverside Dam and the Brodie Smith Dam. Sediment accumulated in this location because of the break in slope and bend in the channel. Road salt from the adjacent road may contribute to the FDEM response and large FDEM values near the downstream right bank.

Reach AR–6, Between Cross Power and Cascade Dams

Reach AR–6 is located between the Cross Power Dam upstream and the Cascade Dam downstream (fig. 9). The Androscoggin River flows to the south through this reach, which is bordered by urban residential use land, a railroad and State Route 16 on the left bank. The area surveyed upstream from the dam warning barrels is within the city of Berlin. The Cascade Dam is within the town of Gorham, slightly south of the town line with Berlin (fig. 1). The strongest current during the surveys was from the turbine outflow at the Cross Power Dam along the left bank, even though water was flowing over the dam. Upstream and just downstream from the railroad bridge, most of the flow in the channel is along the left bank. Flow is along the right bank closer to the Cascade Dam and warning barrels. Survey lines were set up in a clockwise pattern to take advantage of the flow traveling downstream with the stronger current along the left bank, and upstream on the side with the weaker current along the right bank.

This surveyed reach is about 2,000 ft long, and 250 to 350 ft wide, with a railroad bridge crossing the upstream segment. The channel in this reach had an average depth of 7.2 ft and a maximum depth of about 16.7 ft during the time of the survey. The Cross Power Dam is built on bedrock and large cobbles and boulders are seen at the toe of the dam. Because of the widening of the channel at the downstream end near the Cascade Dam warning barrels, there is considerable sediment accumulation just outside of the surveyed area on the left bank including a 600 ft long grass covered channel bar.

Interpretation and extrapolation of GPR results indicate approximately 51 percent of the riverbed area is covered by gravel or finer material (table 4). Even though the percentage of fine material (increases conductivity) is nearly one-half of that of the Wheeler Bay reference reach, the overall FDEM values are similar with an average of 2.7, a minimum of 0.8 and a maximum of 7.1 mS/m (table 3). The highest estimated FDEM values in this reach are likely a result of elevated pore-water conductivity as is indicated in pore-water measurements and DC resistivity test box measurement of sediment sample AR–6_2 (table 1). This sample was 8.9 meters from the FDEM survey line and does not appear to have an effect on the FDEM results. Fine sediments with greater FDEM conductivity are located on the downstream left bank side of the reach (fig. 9). FDEM data were affected by the steel railroad bridge and were removed. FDEM data removal is illustrated by the absence of the FDEM survey where the GPR survey tracks are downstream from Cross Power Dam and sediment samples AR–6_1 and 2 (fig. 9). Sediment sample AR–6_3 had an elevated pore-water conductivity and lab conductivity (table 1). This sample was collected close to the river bank on a sandbar outside the surveyed area. Therefore, the conductive feature does not appear in the mapped data (fig. 9).

Reach AR–7, Upstream from the Brown Dam

Reach AR–7 is located less than 6 mi downstream from the former Chlor-Alkali Facility Superfund Site and upstream from the Brown Dam (fig. 10). The intersection of State Routes 2 and 16 in Gorham (fig. 1) is downstream on the right bank side. The Androscoggin River flows to the south through this reach. The land on the left bank of this reach is a forested mountain; the land on right bank is urban, with business and residential use.

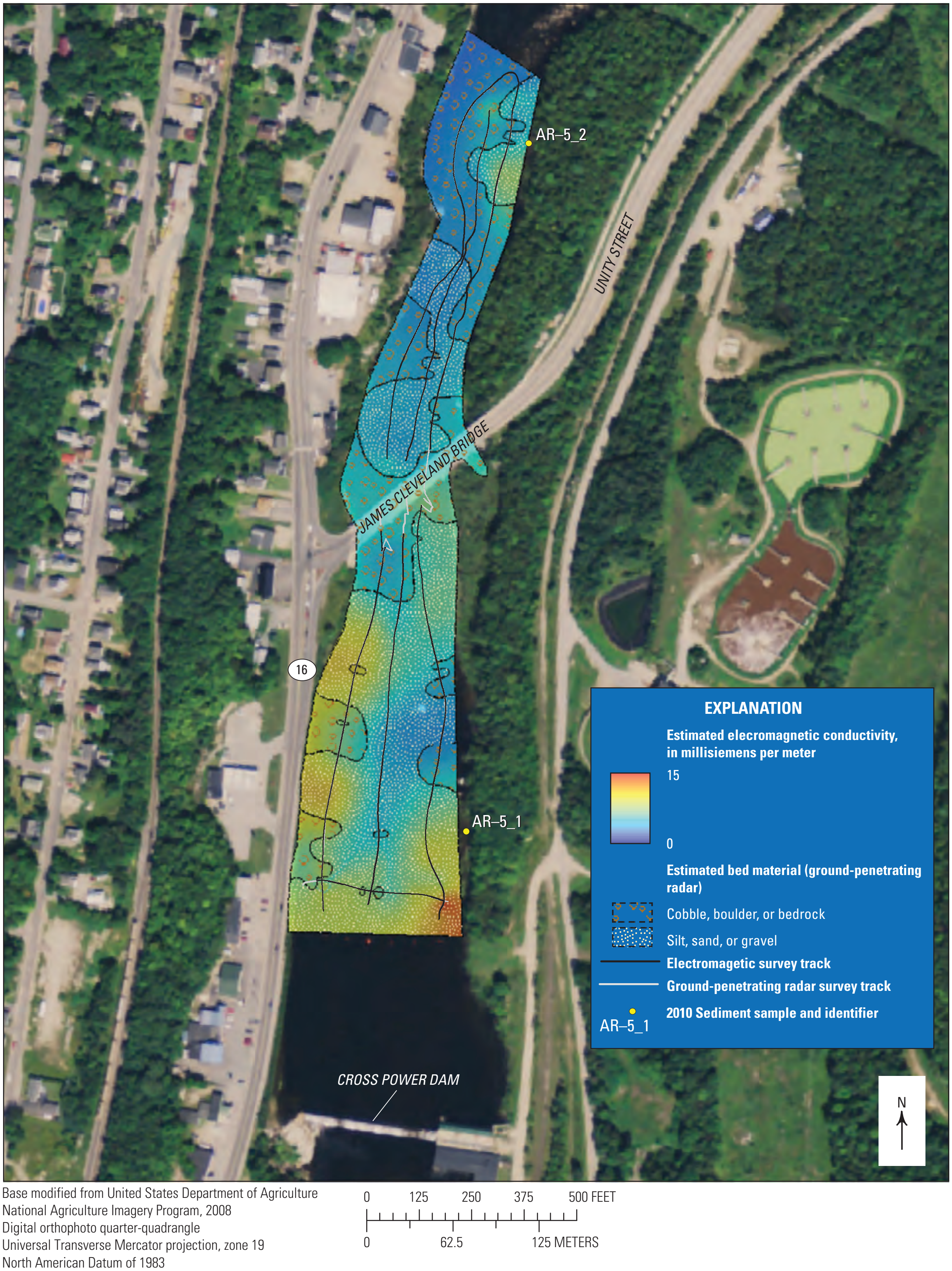


Figure 8. Results of geophysical surveys of riverbed-sediment characteristics in reach AR–5 upstream from the Cross Power Dam, Androscoggin River, Berlin, New Hampshire.

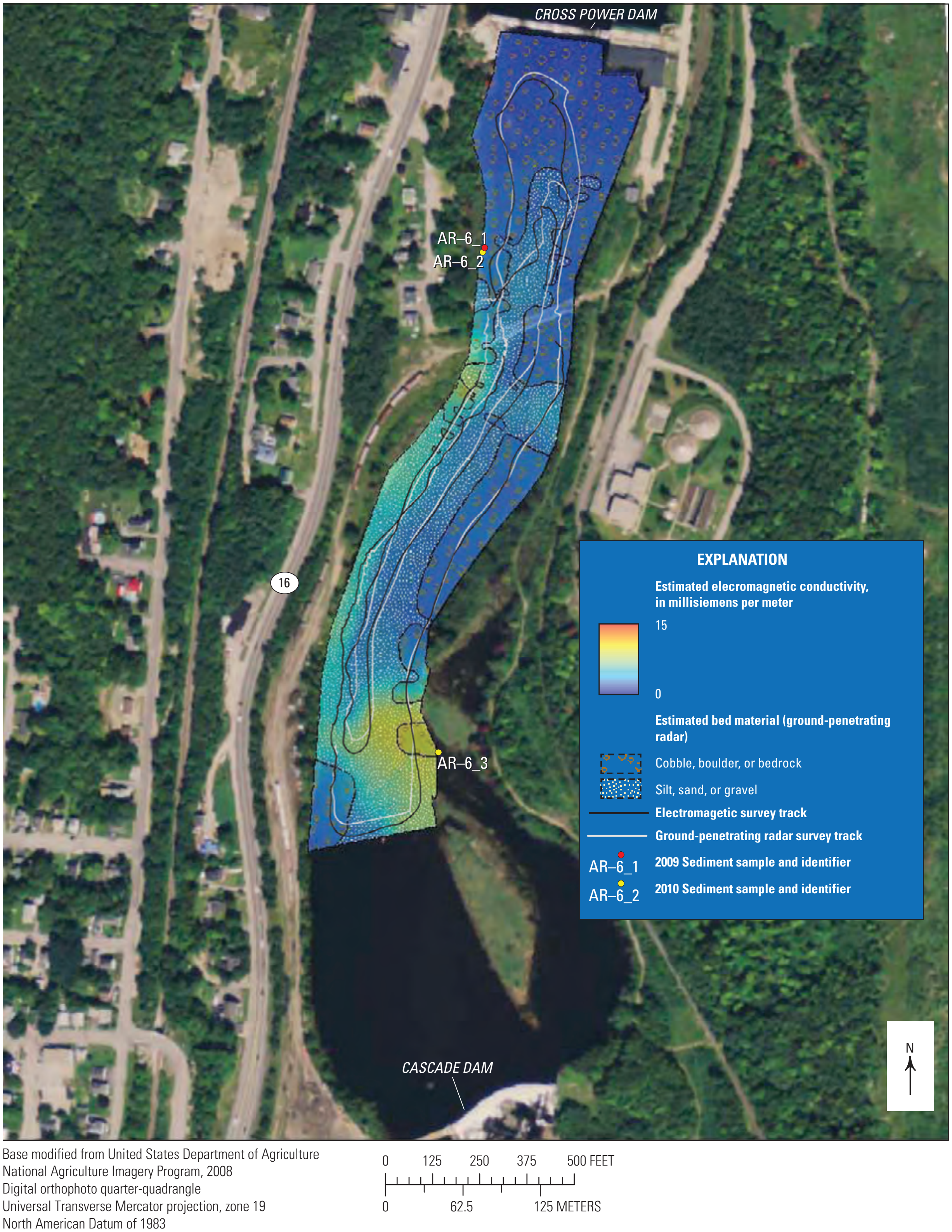


Figure 9. Results of geophysical surveys of riverbed-sediment characteristics in reach AR–6 between the Cross Power and Cascade Dams, Androscoggin River, Gorham, New Hampshire.

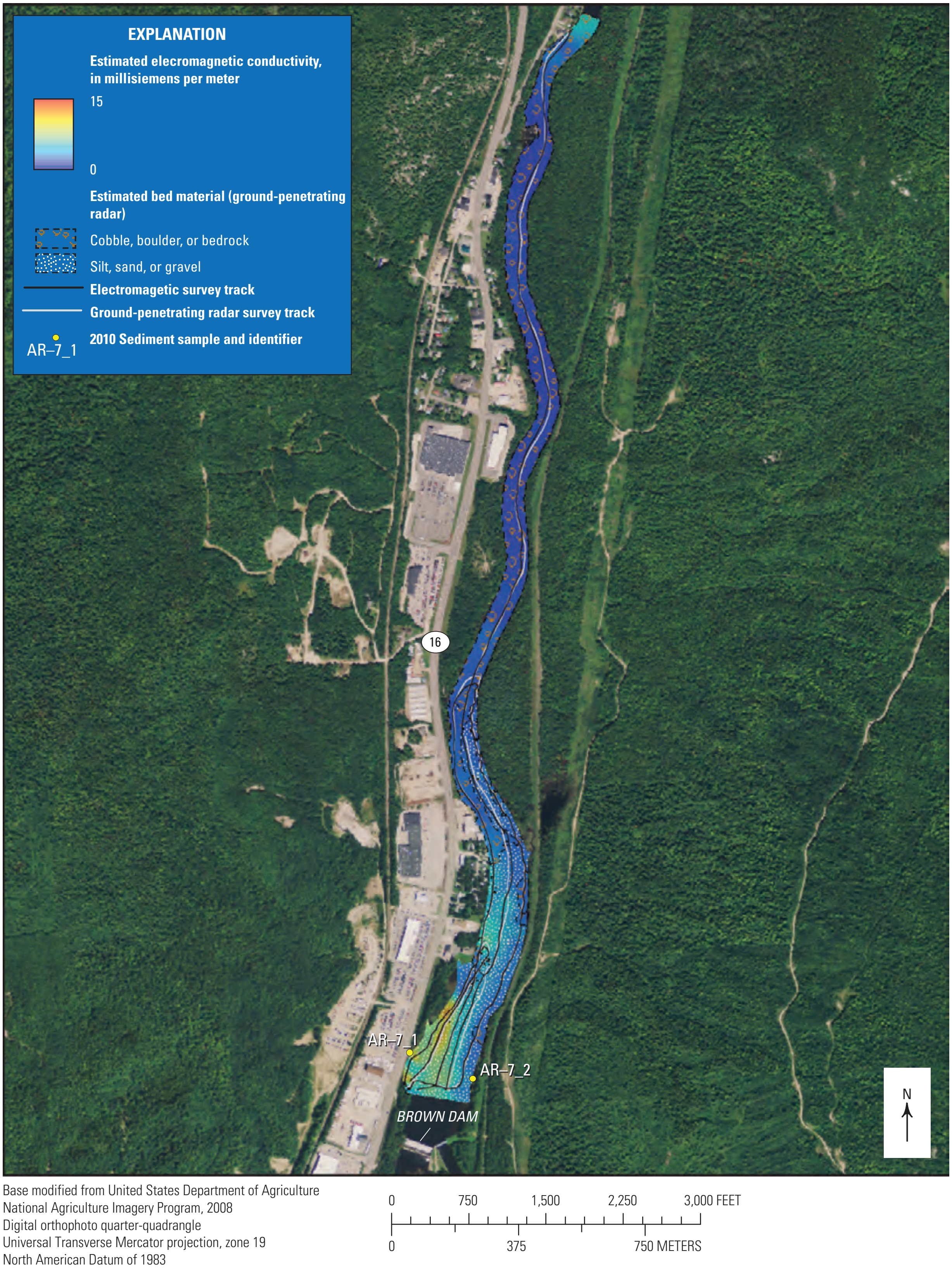


Figure 10. Results of geophysical surveys of riverbed-sediment characteristics in reach AR–7 upstream from the Brown Dam, Androscoggin River, Gorham, New Hampshire.

The area of the reach surveyed is about 2 mi long and between 230 and 600 ft wide. The channel had an average depth of 4.6 ft and a maximum depth of about 13.1 ft during the time of the survey. Upstream, the channel is incised and has a low sinuosity and large boulders on the riverbed. The gradient of the channel in the surveyed reach is steep (10 ft/mi, fig. 2) in the upstream two thirds and it has the longest continuous riffle of all reaches studied. The wide channel at the downstream end of this reach had many areas with the potential for fine sediments to accumulate because of lower stream flow velocity and channel gradient.

Interpretation and extrapolation of GPR results indicate that approximately 42 percent of the riverbed area is covered by gravel or finer sediment (table 4). Gravel and finer sediment was estimated to be on the riverbed across most of the channel from the Brown Dam warning barrels to about 2,200 ft upstream along the right bank and to 3,700 ft upstream from the barrels along the left bank side (fig. 10). Fine sediment identified with GPR, and conductive pore water identified by FDEM, was estimated to be between the warning barrels and 1,000 ft upstream along the right bank side. This reach has an estimated area of fine sediments more than three times larger than any of the reaches upstream (table 4). Even though the percentage of fine material (increases conductivity) is less than one-half of that estimated for the Wheeler Bay reference reach, the FDEM values are similar with an average of 2.2, a minimum of 0.6 and a maximum of 8.9 mS/m (table 3). Estimated FDEM values in this reach likely are elevated by conductive pore water. Large FDEM values on the furthest downstream right bank part of the reach may be affected by road salt runoff from the adjacent road.

Reach AR–8, Between the Brown and Gorham Dams

Reach AR–8 begins approximately 6 mi downstream from the former Chlor-Alkali Facility Superfund Site, downstream from the Brown Dam. The town of Gorham is on the right bank with urban and residential land use; the left bank abuts a forested mountain with the remnants of a lead mine near Mascot Pond (fig. 1) and a power-line cut. The Androscoggin River generally flows to the southeast through this reach. The river valley and channel orientation changes from roughly a north–south trend upstream, to an east–west trend between the Brown and Gorham Dams (fig. 11).

The surveyed part of this reach is about 2 mi long and is narrow, approximately 150 ft wide, for most of the length. The channel is wider at the downstream end (350 ft) at a bend in the channel near the warning barrels for the Gorham Dam. The channel in this reach had an average depth of 2.9 ft and a maximum depth of about 16.2 ft (at the downstream end at the bend and bedrock on the left bank) during the time of the survey. Boulders and rapids at the upstream segment grade into riffle and gravel and finer sediment, with bedrock exposure at the downstream segment along the left bank near the power-line cut and near the bend in the channel upstream from the Gorham Dam. Halfway down the reach, the river is anabranching, creating several channels. Sediment properties were estimated only for the channel surveyed and were not extrapolated to other sections of anabranching channels.

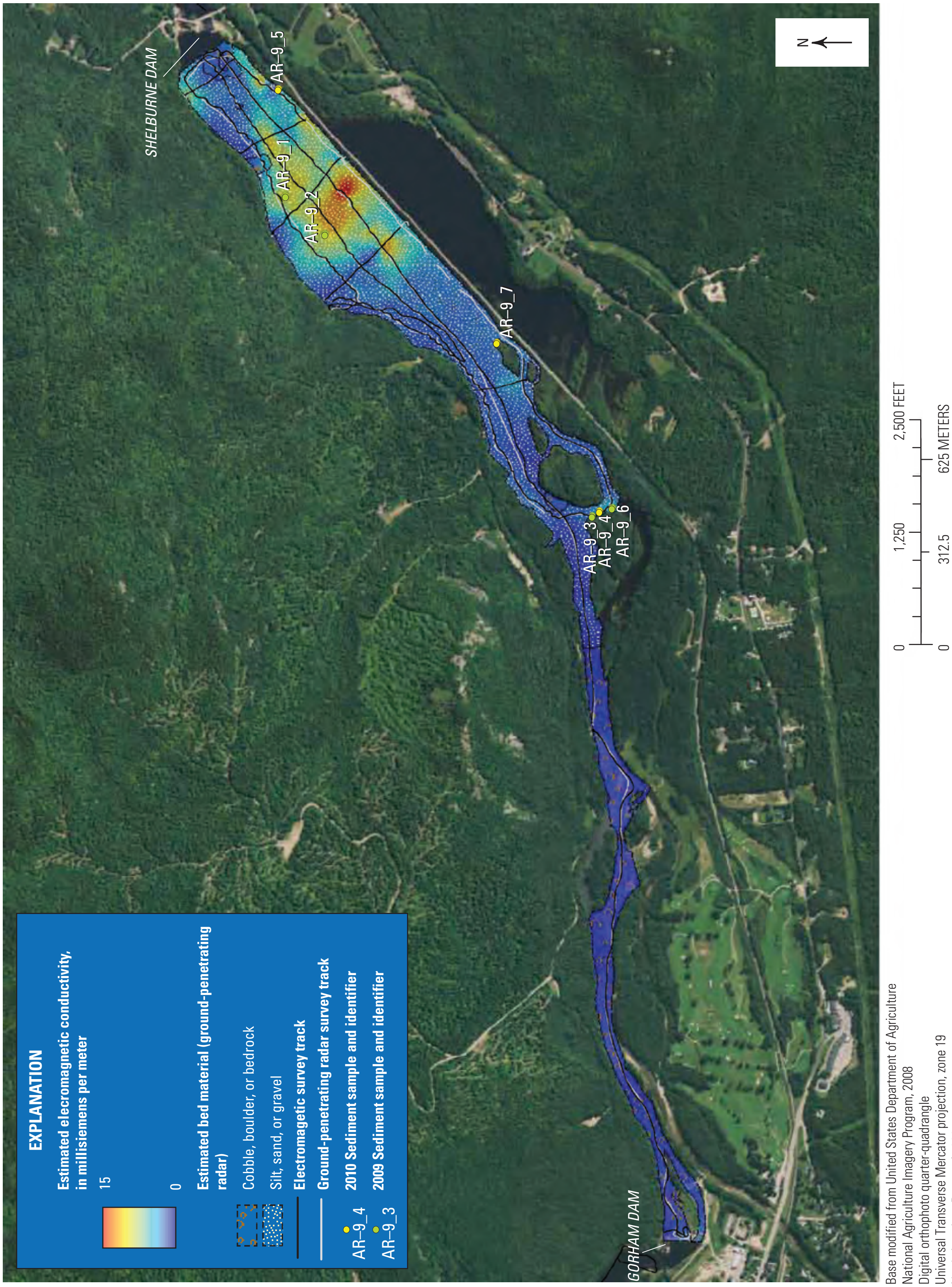
This reach has the lowest estimated percent of fine bed sediment (table 4) in the study, 20 percent, with the exception of the steeper gradient reach AR–3 at the former Chlor-Alkali Facility Superfund Site. The average and minimum estimated FDEM conductivity were the smallest in the study (table 3), indicating less conductive pore water. This reach has lower FDEM values than the Wheeler Bay reference reach with an average of 0.9, a minimum of less than 0.1 and a maximum of 7.1 mS/m (table 3). The estimated bed sediment conductivity near State Route 16 (fig. 1) along the right bank at the upstream end from this reach is slightly elevated even though the material is cobble and boulders, this may be because of road salt affected groundwater. At the downstream end of this reach the river bends 90 degrees at a large bedrock outcrop just upstream from the dam. Fine sediments have accumulated on the left bank, north of the outcrop and have an elevated conductivity (fig. 11) that may be due to elevated SC in the pore water. Sediment samples collected within 5 meters of an FDEM survey line and measured in a laboratory DC resistivity test box had values of 3.6 and 5.8 mS/m that were close in value to an estimated FDEM of 4.5- and 4.7-mS/m, respectively (table 1). Fine sediments with a lower conductivity have accumulated on the right side of the channel. FDEM data were affected by power-line noise at the upstream end and downstream (south) in the locations of power lines crossing the river and were removed. FDEM data removal is illustrated by the absence of the FDEM survey track in the location of the GPR survey track (fig. 11).

Reach AR–9, Between the Gorham and Shelburne Dams

Reach AR–9 begins slightly more than 8 mi downstream from the former Chlor-Alkali Facility Superfund Site and is located between the Gorham Dam upstream and the Shelburne Dam at the downstream end of the reach. The Androscoggin River flows to the east and northeast through this reach; through forested mountain areas. The Gorham Dam is located about .5 mi upstream from the Shelburne town line (fig. 1) and is keyed into bedrock outcropping on the left bank. The Androscoggin River upstream of the Shelburne Dam, at the downstream end of the surveyed reach (fig. 12), is the largest body of pooled water in the study area.

This reach is almost 3 mi long and varies between 200 and 1,500 ft wide. The area of the channel surveyed is the second largest in the study (table 4). The first one-half of this reach is incised and contains boulders with rapids grading into braided deposits of gravel with riffles. A large volume of fine sediment has been deposited in the middle of the reservoir in a delta-like formation where it is wide, has a low gradient, and

Figure 11. Results of geophysical surveys of riverbed-sediment characteristics in reach AR–8 between the Brown and Gorham Dams, Androscoggin River, Gorham, New Hampshire.



Base modified from United States Department of Agriculture
National Agriculture Imagery Program, 2008
Digital orthophoto quarter-quadrangle
Universal Transverse Mercator projection, zone 19
North American Datum of 1983

Figure 12. Results of geophysical surveys of riverbed-sediment characteristics in reach AR–9 between the Gorham and Shelburne Dams, Androscoggin River, Shelburne, New Hampshire.

flow velocity decreases. This sediment is on top of pre-dam braided/anabranching channel deposits. The river channel had an average depth of 5.7 ft and a maximum of 16.6 ft during the time of the survey. Extensive bedrock outcrop observed at the downstream base of the Shelburne Dam likely extends to the upstream side in the riverbed (fig. 12).

More than 77 percent of the area of the bed surveyed in this reach is estimated to be gravel or finer material (table 4). Deeper channels convey most of the flow along the left bank, but another deep channel is on the right side (fig. 4). Fine sediment with conductive pore water is found at a large area in the center of the water body (fig. 12). With the exception of the reach behind the Brodie Smith Dam, this reach has the second greatest pore-water SC measured, 45.8 mS/m (table 1). This reach has a similar average (2.5 mS/m), but larger maximum FDEM values (maximum of 12.6 mS/m) than the Wheeler Bay reference reach (table 3). This reach had the third greatest maximum FDEM conductivity value measured in this study (table 3). A sediment sample collected within 5 meters of an FDEM survey line had a laboratory conductance of 3.1 mS/m similar to the estimated FDEM of 2.5 mS/m (table 1). FDEM data were affected by power-line noise at the downstream end of reach AR–9 in the locations of power lines that run parallel to the railroad tracks on the southeast side of the Shelburne Reservoir between sediment samples AR–9–7 and AR–9–5 and were removed (fig. 12).

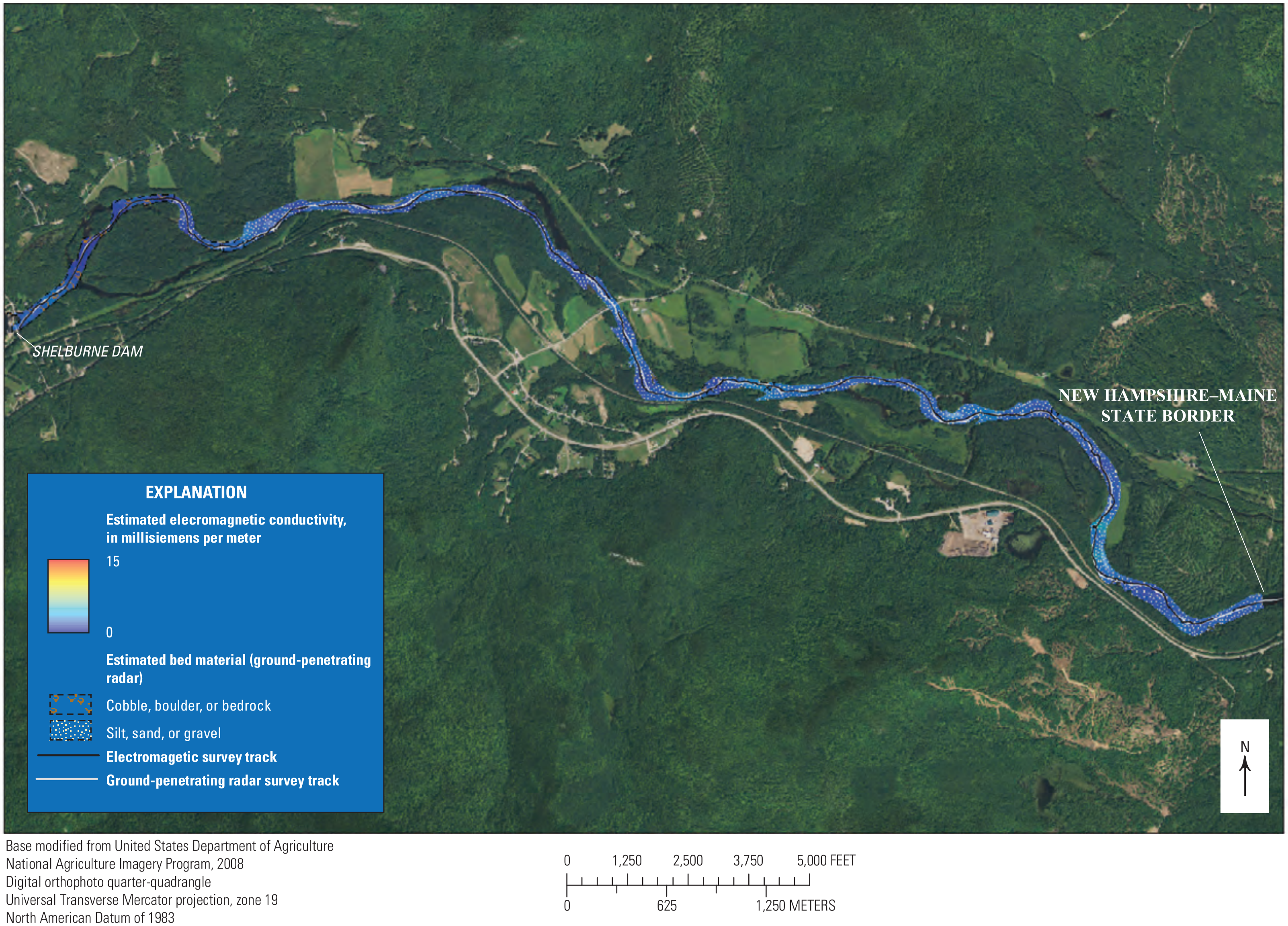
At the Gorham Dam, at the upstream end of this reach, the river intersects an area of intrusions of two-mica granite (Devonian) into the older metasedimentary rocks of the Littleton (Early Devonian) and Madrid Formations (Upper Silurian (?)) (Billings and Billings, 1975; Lyons and others, 1997). The contacts are typically approximate because of the thick glacial drift (Billings and Billings, 1975) and can be found throughout most of this reach. Abundant magnetic susceptibility anomalies (not shown) in this reach may be because of this contact, representing a change in minerals in the bedrock, and the presence of bedrock near or at the streambed surface.

Reach AR–10, Downstream from the Shelburne Dam to the New Hampshire–Maine Border

Reach AR–10, in Shelburne, N.H., begins approximately 11 mi downstream from the former Chlor-Alkali Facility Superfund Site at the Shelburne Dam and extends to the New Hampshire–Maine State border. The Androscoggin River generally flows to the east and southeast through this reach. The valley and flood plains widen in this reach and are forested and agricultural (fig. 13). The first mile downstream from the Shelburne Dam has riffle and rapids grading into fast moving water.

Reach AR–10 is more than 6 mi long, the longest reach surveyed in the study and is braided and meandering with some anabranching. This reach varies between 150 and 400 ft wide. The channel had an average depth of 2.5 ft and a maximum depth of about 14 ft during the time of the survey. There are many areas for fine sediments to accumulate because of lower stream flow velocity and channel gradient. The river bed is made up of boulders and bedrock within a mile downstream from the Shelburne Dam and grades into gravel silt and sand further downstream (fig. 13). Glacial fluvial gravels, sands, silts and clay can be seen in riverbank cuts, outcrops of bedrock are seen on the right bank at the downstream end of the reach.

Interpretation and extrapolation of GPR results indicate that bed material is estimated to be gravel or finer for 86 percent of the area surveyed (table 4). This reach has smaller FDEM values than the Wheeler Bay reference reach with an average of 1.7, a minimum of 0.9 and a maximum of 3.5 mS/m (table 3). Glacial fluvial silts and clays, observed in cut banks, may elevate the minimum estimated FDEM conductivity. The estimated FDEM conductivity in this reach has the smallest maximum in the study area and the second smallest average (table 3) indicating lower SC pore water in the bed sediments. FDEM data were affected by power-line noise approximately 1.5 mi downstream and interference from a metal bridge at approximately 3 mi downstream and the data were removed. FDEM data removal is illustrated by the absence of the black FDEM survey track in the location of the grey GPR survey track (fig. 13).



Base modified from United States Department of Agriculture
National Agriculture Imagery Program, 2008
Digital orthophoto quarter-quadrangle
Universal Transverse Mercator projection, zone 19
North American Datum of 1983

Figure 13. Results of geophysical surveys of riverbed-sediment characteristics in reach AR–10 downstream from the Shelburne Dam to the New Hampshire–Maine State border, Androscoggin River, Shelburne, New Hampshire

Summary and Conclusions

The U.S. Geological Survey (USGS), in cooperation with Region I of the U.S. Environmental Protection Agency (USEPA), used geophysical methods to survey riverbed sediments in the Androscoggin River downstream from the former Chlor-Alkali Facility Superfund Site in Berlin, New Hampshire. Results were processed and presented in tables, maps, and cross sections to assess sediment electrical conductivity, pore-water specific conductance (SC), and potential contaminant distribution in riverbed sediments. The site was listed on the USEPA National Priorities List in 2005 and has been the subject of continuing investigations to determine the nature and extent of dissolved phase and adsorbed mercury and methyl mercury contamination.

The river reaches surveyed in this study ranged from pooled water conditions to fast moving water flow conditions that varied with channel geometry, dam operation, and runoff. Results of ground-penetrating radar (GPR) and multifrequency electromagnetic (FDEM) surveys were used to estimate the extent and nature of riverbed sediments. In general, wider, less steep gradient reaches have more fine sediment, and were measured with additional surveys in this study, whereas narrow steep gradient reaches had less sediment. SC measured during surface-water, pore-water, and sediment sampling (with subsequent grain size analysis), collected as part of a parallel USGS investigation, were used in processing and interpretation of surface geophysical surveys. The electrical resistivity of sediment samples was measured in the laboratory with pore water intact for comparison with FDEM survey results.

Geophysical surveys of the reference reach, Wheeler Bay, (upstream end of reach AR–2), were completed to assess equipment responses in an environment unaffected by site related contaminants. The reference reach, Wheeler Bay, had the largest percentage (97) of fine-grained (gravel and finer) sediment covered riverbed area. The electromagnetic (FDEM) values of this reach were an average of 2.6, a minimum of 0.1, and a maximum of 9.4 millisiemens per meter (mS/m) (table 3).

Reaches AR–3, AR–4, and AR–5 had estimated FDEM conductivities elevated above the reference reach despite the lower percent of sediment covered riverbed areas (11, 25, and 61 percent, respectively). Reach AR–3, between the former Chlor-Alkali Facility and the Riverside Dam, had small areas of fine sediment, found on the upstream left bank and the downstream right bank, with an elevated FDEM conductivity (31.4 mS/m maximum). The larger FDEM conductivity (fig. 6) was likely because of elevated riverbed pore-water SC. Reaches AR–4 and AR–5 were located downstream from steep gradient (100 ft /mi) bedrock gorges that convey high flows from the reach adjacent to the site to pooled areas behind dams. Reach AR–4, upstream from the Brodie Smith Dam had the largest pore-water SC, FDEM and lab-measured sediment conductivity values measured in the study. Pore-water SC measured in this reach was 279 and 324 mS/m (table 1) at sediment sample locations AR–4_1 and AR–4_2 (fig. 7) on a sandbar near the left bank. These sediment samples had laboratory-measured sediment conductivity values of 67.4 and 76.8 mS/m, similar to nearby estimated FDEM values of 73.2 and 72.8 mS/m (table 1). The largest conductivity measured with FDEM in reach AR–5 was 10.2 mS/m on the downstream left side (fig. 8). This reach is wide and likely contains additional conductive sediment that could not be measured by geophysical surveys in this study, downstream from the Cross Power Dam warning barrels.

Reach AR–6 and AR–7 had FDEM values similar to the reference reach, despite having a smaller percentage of riverbed areas covered with sediment (51 and 42 percent). Elevated FDEM values, on the downstream left bank of reach AR–6 and the downstream right bank of reach AR–7 (figs. 9 and 10), indicates that fine-grained and conductive sediment was deposited in these areas. Sediment downstream from the dam warning barrels in these reaches was not surveyed in this study.

Reach AR–8 and AR–10 had smaller FDEM values than the reference reach. Reach AR–8 had a lower percentage (20 percent) of riverbed area covered with sediment than all of the other reaches, with the exception of AR–3. Reach AR–10 had the largest area and a larger percentage (86 percent) of riverbed area covered with sediment than all of the other reaches in the study with the exception of the reference reach AR–2 (table 4).

Reach AR–9 between the Gorham and Shelburne Dams contains the largest body of pooled water in the study area, the Shelburne Reservoir. The first one-half of the reach has cobble, boulder and bedrock bed material; although more than 77 percent of the area of the riverbed surveyed in reach AR–9 is estimated to be covered by gravel or finer material (table 4). The sediment in reach AR–9 had a maximum estimated FDEM conductivity of 12.6 mS/m (table 3), greater than all of the other reaches except for AR–3 and AR–4 (nearby and within a mile downstream from the former Chlor-Alkali Facility Superfund Site). In addition to large FDEM values, this reach had the second greatest pore-water SC measured, 45.8 mS/m (table 1).

Through combining results and analysis from ground-penetrating radar (GPR) and FDEM surveys, with sediment pore water and laboratory measured conductivity, detailed riverbed-sediment characterizations were made. Results from GPR surveys were used to image and measure the depth to the riverbed, depth to buried riverbeds, riverbed thickness and to interpret material-type variations in terms of relative grain size. Fifty two percent of the riverbed in the study area was covered with gravel and finer sediments. GPR surveys are affected by contrasts in the electrical properties of water and sediment. The electrically resistive river water and sediment in this study area were conducive to the penetration of the GPR and FDEM signals and allowed for effective sediment characterization by geophysical methods.

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