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Groundwater Flow Delineation Study at the Massachusetts Military Reservation Using the Colloidal Borescope

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Environmental Sciences Division
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APPLICATION OF THE COLLOIDAL BORESCOPE IN A GROUNDWATER FLOW DELINEATION STUDY AT THE MASSACHUSETTS MILITARY RESERVATION

ABSTRACT

Observations of colloidal movement under natural conditions using the colloidal borescope were conducted at several sites in the vicinity of the Massachusetts Military Reservation (MMR) located on Cape Cod. The purpose of the study was to assess the reliability of the colloidal borescope and provide additional hydrogeologic data for site-characterization work. Because of the variability observed in groundwater flow at other sites, a well-characterized site was needed to test the borescope. Results of this work indicate that existing hydrologic information specific to the various sites tested at the MMR compares favorably with the borehole velocity data collected with the colloidal borescope. Direction measurements at the MMR, however, appear to be less reliable than at other sites tested. Most significant among factors potentially affecting direction measurements is the relatively flat hydraulic gradient at the MMR, which is an order of magnitude less than at other sites. This is due to the gentle topography and the relatively high permeability of the aquifer. Under these conditions, the geometric alignment of preferential flow paths could dominate flow direction. If the gradient is increased, flow will tend to parallel the hydraulic gradient. This report describes the field site and the colloidal borescope and discusses the results and conclusions of the field investigations.

1. INTRODUCTION

The colloidal borescope, developed at Oak Ridge National Laboratory (ORNL) in Grand Junction, Colorado, is capable of determining groundwater flow direction and rate *in situ*. Unlike conventional hydraulic testing methods, no water is extracted from the well and disposal costs are avoided. Because of the *in situ* advantage of the colloidal borescope, it was selected to measure groundwater flow rates in the Sandwich area at the Massachusetts Military Reservation (MMR) on Cape Cod.

Preliminary investigations have indicated that groundwater contamination is present in the Sandwich area. Because of the prolific aquifer underlying the area, a conventional pump test for measuring hydraulic properties would require the disposal of large quantities of potentially contaminated water. To avoid these costs and obtain the necessary hydraulic information, the colloidal borescope was tested at the site.

Since the colloidal borescope is an experimental instrument, it was necessary to perform tests at several sites on MMR where conventional hydraulic tests have been previously conducted. Using calibration data from these sites, flow rates could then be measured in the Sandwich area.

This report discusses the site background, describes the instrument, and presents the results of the field investigation.

2. SITE BACKGROUND

2.1 SITE HISTORY

The MMR is located in the western portion (western cape) of Cape Cod (Fig. 1). Several facilities, including those operated by the U.S. Coast Guard, U.S. Army National Guard, U.S. Air Force, U.S. Air National Guard, Veterans Administration, and Commonwealth of Massachusetts, are located within the reservation.

The reservation occupies about 22,000 acres, with the earliest military activity dating back to 1911. Most military operations, however, have occurred since 1935 and consisted of mechanized army training and military aircraft operations.

2.1.1 Areas of Study

The colloidal borescope studies focused on four areas located within and adjacent to the reservation. Area selection was based on the inventory of available hydrologic information and the need for additional hydrologic data. Three areas had sufficient hydrologic data available to assess the reliability of the borescope. The fourth study area (Sandwich area), however, lacked the necessary data to evaluate instrument reliability.

2.1.2 Geologic Setting

Topographic features of the Western Cape are controlled by two major surficial geologic units. Hummocky ridges dominate areas underlain by glacial moraines such as the Buzzards Bay moraine (BBM) and the Sandwich moraine (SM) (Fig. 2). Here, rapid changes in elevation of 18 to 30 m are common (Jordan 1988). In contrast, the topography of the outwash plains is generally flatter, and changes in elevations are limited to kettle holes that have pitted the ground surface. This area is called the Mashpee Pitted Plain (MPP).

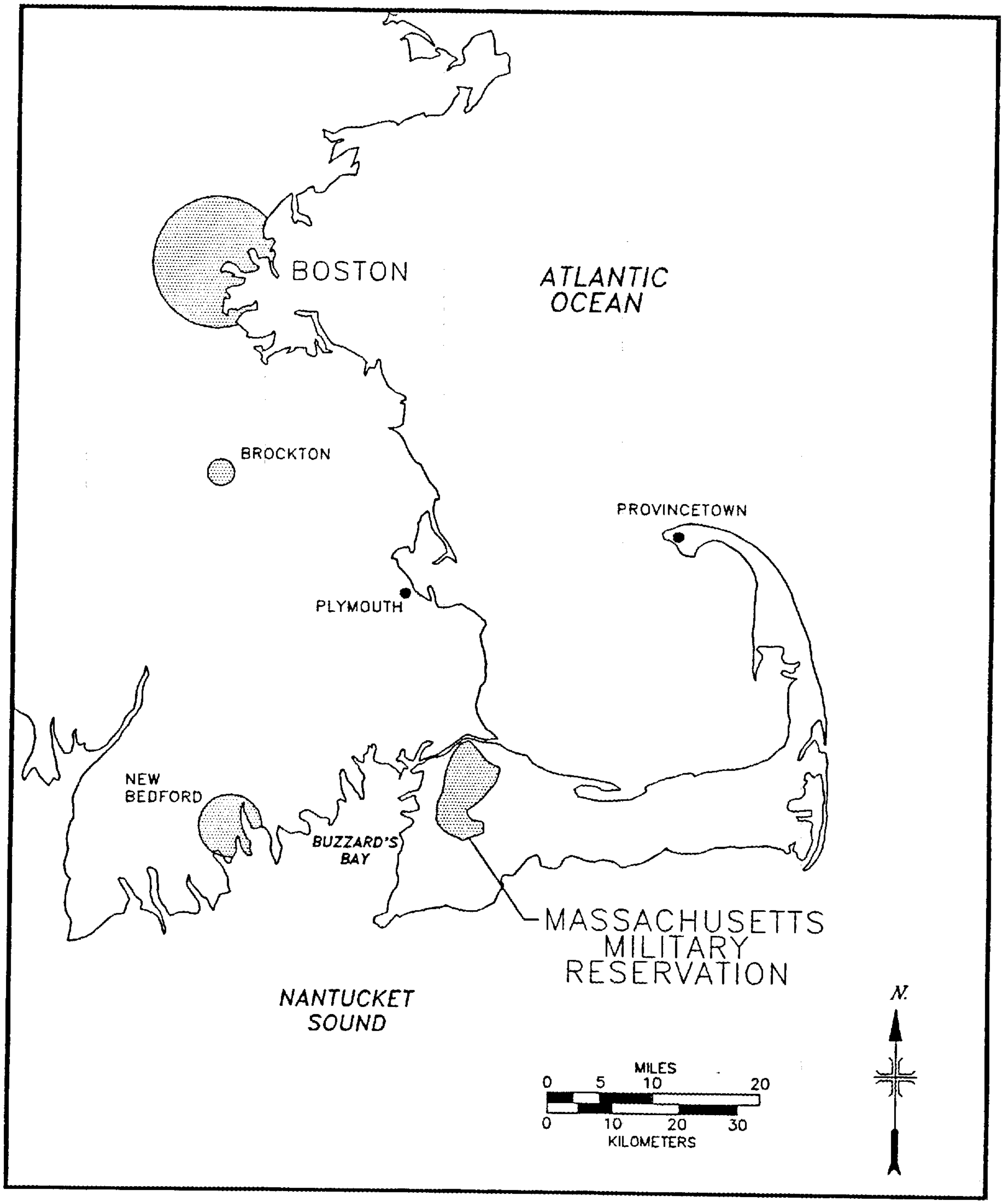

Fig. 1. Location map for the MMR on the Western Cape.

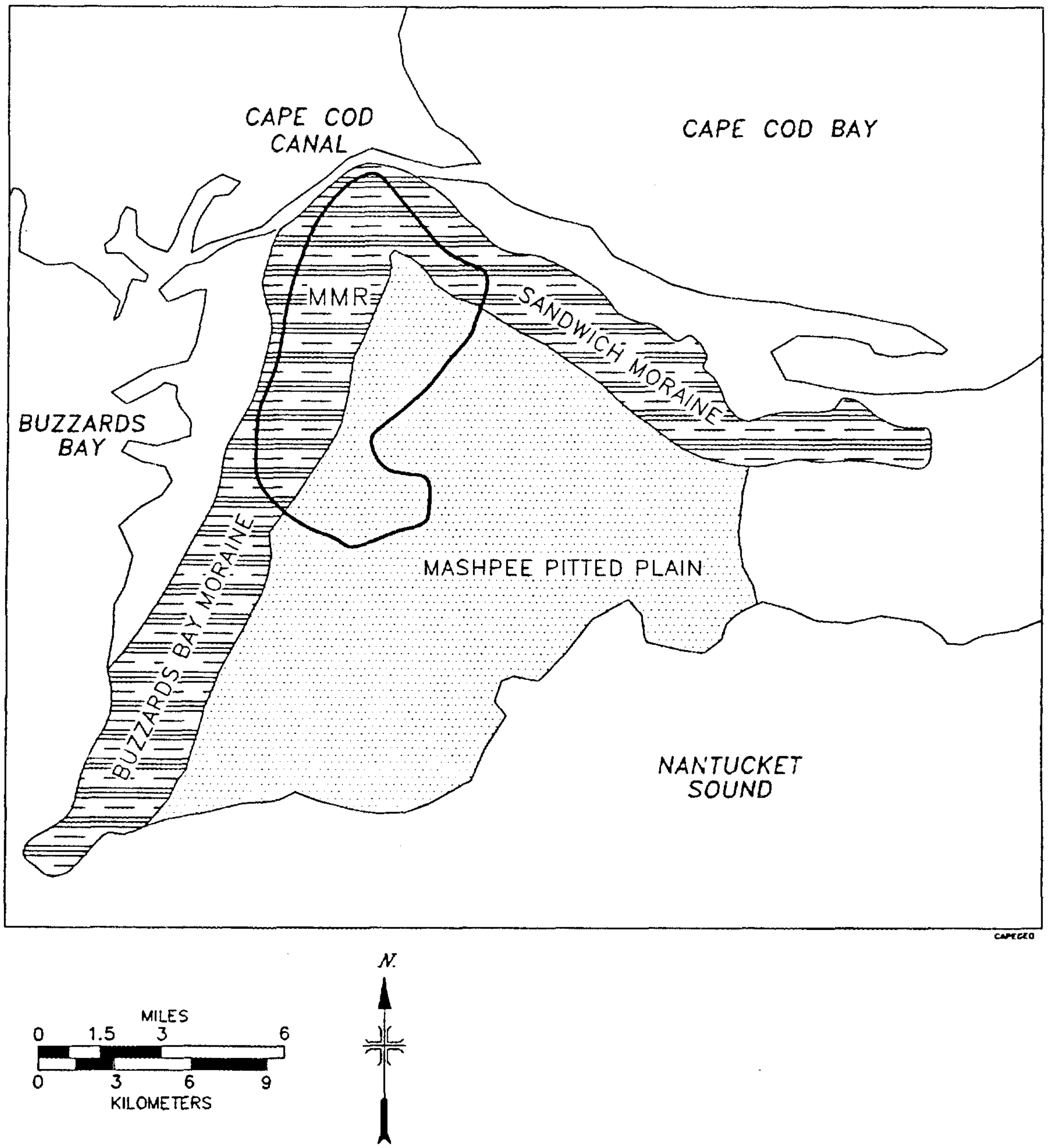

Fig. 2. Geologic map of the Western Cape.

MPP sediments range in approximate thickness from 69 m near the moraines to 30 m near the shore of Nantucket Sound. They are characterized by well-sorted sand and gravel, known as outwash, or stratified drift deposited by glaciofluvial transport in a proglacial environment (Jordan 1988). The MPP was deposited between the two adjacent glacial lobes as the sediment-laden meltwater from the two lobes flowed seaward (Oldale 1981). After the deposition of the MPP, the glacial lobes advanced creating the BBM and SM. Discontinuous sedimentary structures and other stratigraphic variations such as cross-bedding suggest that the geometry of the two advancing glacial lobes had a significant effect on the depositional environment of the MPP (Jordan 1988).

The fluvial processes that controlled the depositional environment of the Western Cape resulted in well-sorted sediments with relatively uniform grain-size distribution that are typically very permeable. The MPP is considered a relatively homogenous stratigraphic unit on a regional scale. However, local investigations of areas on the MMR suggest heterogeneities are present in the MPP. These heterogeneities result in variations in the permeability and in the ability of the sediments to conduct groundwater.

Previous geologic investigations beneath the MPP have encountered either fine-grained glaciolacustrine stratum or dense basal till beneath the outwash sediments. More information of the geology of Cape Cod is presented in publications by Oldale (1981) and Oldale and Barlow (1986).

2.1.3 Site Hydrology

It has been established in the literature that the thickness of the aquifer in the vicinity of the MMR is approximately 100 m of unconsolidated sediments. LeBlanc et al (1991) determined that the upper 30 m of the aquifer consist of permeable, stratified, sand and gravel outwash that is underlain by 70 m of fine-grained sand and silt. According to these investigators, the median grain size of the outwash is approximately 0.5 mm, and silt and clay content is less than 1%.

Based on the number of hydrologic investigations conducted in the area, there is a wide range of hydraulic conductivity (K) values for the outwash aquifer material (10 to 244 m/day). The range is attributable not only to the variability of measurement techniques but to the heterogeneity of the aquifer sediments as well. Review of the literature suggests a K value in the range of 110 m/day provides a realistic conductivity that can be applied to three of the study areas in this report. Analysis of the colloidal borescope data for the fourth site indicates the permeability for this area is considerably higher. This is supported by pumping test data from a nearby well that estimate a K value approaching 250 m/day in this area.

The literature reports effective porosity (n) values for the outwash sediments ranging from 0.20 to 0.40. Based on small-scale tracer tests and spacial moments analysis in a large-scale tracer test, LeBlanc et al. (1991) estimated an effective porosity of 0.39, which was used in the calculations presented in this report.

The hydraulic gradient (i) for each study area was determined using water-level and well-location information. The gradient values calculated are all within the range reported in the literature with one exception. The gradient calculated for the fourth study area is lower by one order of magnitude. Increased permeability in this area, as suggested by pumping test results in a nearby well, may account for the lack of influence this flatter gradient had on the observed borehole flow velocities. The general direction of flow for the aquifer is to the south, which is affected locally by kettle ponds.

2.2 INSTRUMENT DEVELOPMENT AND DESCRIPTION

The colloidal borescope was developed at ORNL as part of the Exploratory Studies Program. The instrument consists of two stainless steel housings that are connected by a threaded, multi-pin coupling. The upper housing or compass module contains a charge-coupled device (CCD) camera, an illumination source, and a fluid-filled ball compass. The lower housing or instrument module contains a second CCD camera, an optical magnification lens, and illumination sources. A diagram of the colloidal borescope is provided in Fig. 3. The device is approximately 100 cm long and has a diameter of 44 mm, facilitating insertion into a 5-cm-diameter observation well. After insertion into the observation well, the electronic image is transmitted to the surface by a 62-m fiber optic umbilical cable, where it is viewed on a 25-cm monitor and recorded on VHS tape for further analysis. The magnified image recorded on the VHS tape corresponds to a field of view of approximately 1 × 1.44 × 0.1 mm.

2.3 METHODS

2.3.1 Initial Setup of Equipment

The umbilical fiber optic cable is removed from the shipping container and uncoiled to remove any kinks and twists. It is important to keep the multi-pin connectors at both ends of the cable clean during this process. After the cable has been straightened, the multi-pin connector unions of the cable, the compass module, and the instrument module are inspected before connections are attempted. The cleanliness and integrity of the electrical pins, O-ring seals, alignment slots, and threaded couplings should be assessed to promote proper alignment and seal during assembly.

Following inspection of the multi-pin connectors, the compass module is attached to the male end of the umbilical cable. The instrument module is then attached to the male end of the compass module. If the multi-pin connectors are clean and aligned properly, they should slide together under moderate hand pressure. Threaded couplings should be hand tightened only; wrenching of the threaded couplings should not be attempted. If the threaded couplings become tight, the connector union is gently jiggled by hand while pressing the male/female couplings together. This should facilitate further tightening of the threaded coupling. If resistance is still apparent, the connection is disassembled and the pin alignment and cleanliness of threads reinspected. It is most important that these connections are not forced.

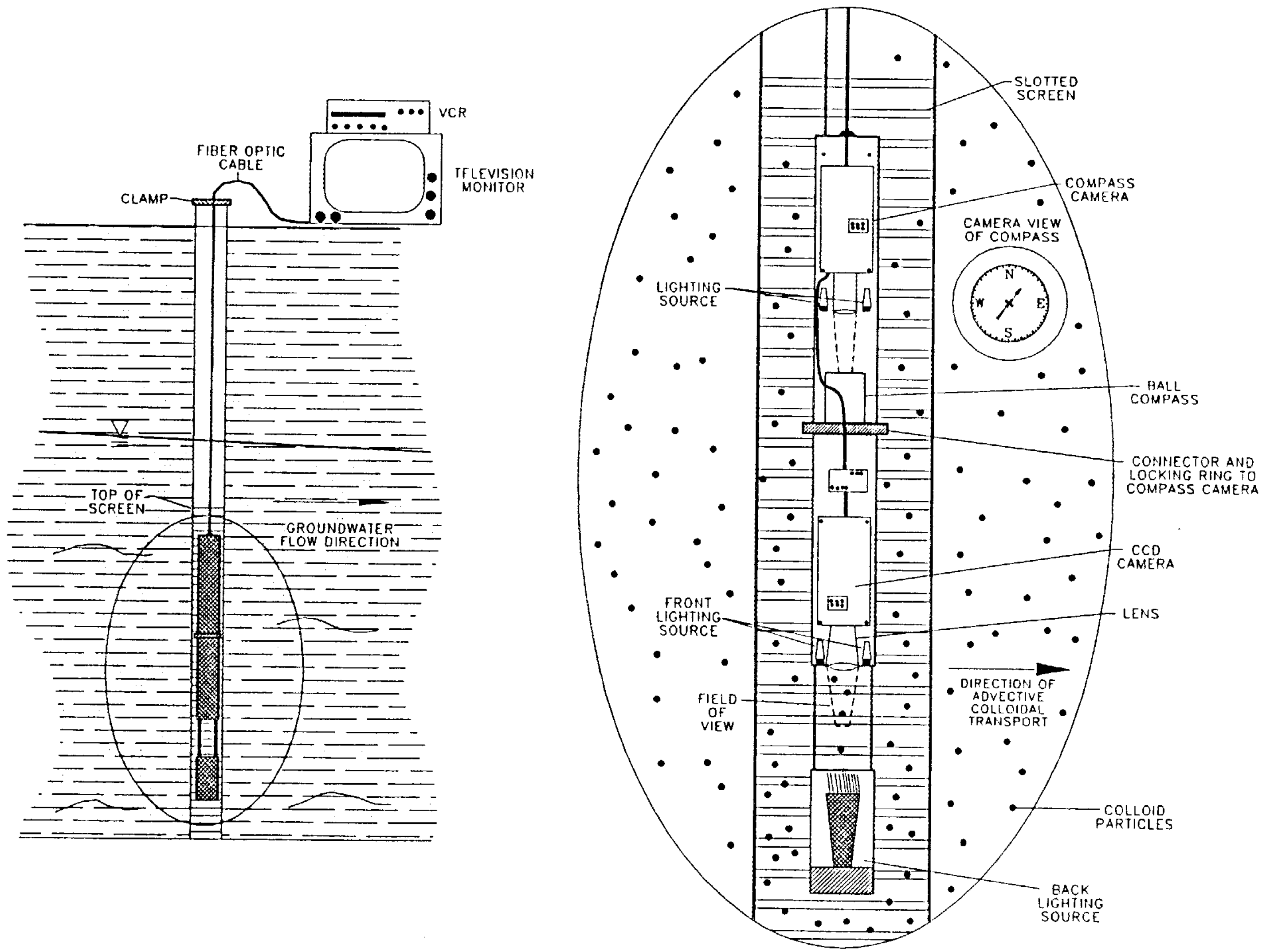

Fig. 3. Diagram of instrument.

COLLOIDAL BORESCOPE

Assessment of Colloid Movement and Groundwater Velocity in Monitoring Wells using Video Optic Techniques

TECHNOLOGY DATA SHEET

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THE TECHNOLOGY The instrument consists of a charge-coupled device (CCD) camera, an optical magnification lens, an illumination source, a down-hole compass to assess direction of natural flow, and a watertight stainless steel housing. The instrument is approximately 60 cm long, with a diameter of 44 mm. The electronic image is transmitted to the surface by a 33 m fiber optic cable. The image is viewed on a high resolution 25 cm monitor and recorded on VHS tape for further analysis. The magnified image corresponds to a 1.0 x 0.4 x 0.1 mm field of view.

BENEFITS The colloidal borescope provides a direct means of accurately determining groundwater flow direction and velocity in a more cost effective manner than conventional methodologies. The borescope measurement technique uses existing monitoring wells for assessment and thus avoids the cost of additional well installation. Data is obtained in minutes, as opposed to hours or days, to complete conventional groundwater flow measurements.

CAPABILITIES The colloidal borescope is capable of determining the vertical and spatial distribution of local groundwater velocity, both in magnitude and direction. The observational capabilities provide the potential for enhancing an understanding of porous flow at the most basic level. It is capable of measuring direction and velocities in low- and high-permeable material. The instrument could provide the basis for a stochastically based groundwater flow and transport model that more accurately describes the movement of contaminants in the subsurface. The instrument also provides the capability of observing flow processes at the pore scale. The instrument is capable of assessing local flow velocities ranging from 0 to 15 mm/sec, which greatly exceeds even the fastest groundwater flow velocities in monitoring wells.

APPLICATIONS The borescope is used as in-situ instrumentation capable of directly observing colloidal size particles and subsequent groundwater flow direction and rate. Current applications include: site characterization by determining preferential flow paths and fractures; assessing heterogeneities associated with porous media; establishing the existence of immiscible contaminant layers and their associated flow properties; assessing the efficiency of groundwater remediation programs by determining the effective radius of influence of groundwater extraction systems; determining the amount of biological activity present in a bioremediation system; and evaluating the effects of sampling on colloidal concentrations. Potential applications include providing physical observation capabilities necessary to develop and confirm new, more accurate theoretical models of the porous media flow process and assessing the effects of water sampling techniques on natural colloidal concentrations.

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LIMITATIONS Colloidal density is greatly affected by perturbations caused by instrument insertion. A period of 30 min. is generally required for transient turbulence to decline. Flow under low gradient conditions is not in a uniform, consistent direction.

REQUIREMENTS Complete well records, a thorough understanding of well construction and development techniques are essential. The operation of the instrument and data interpretation is straight forward.

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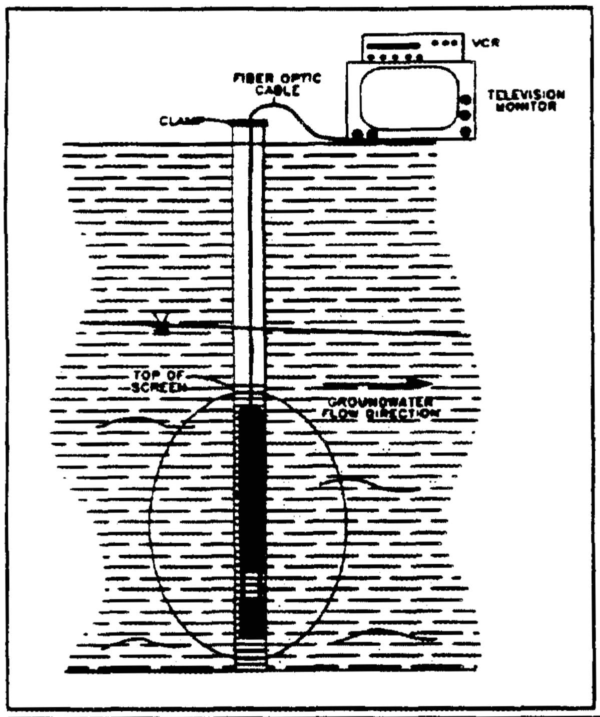
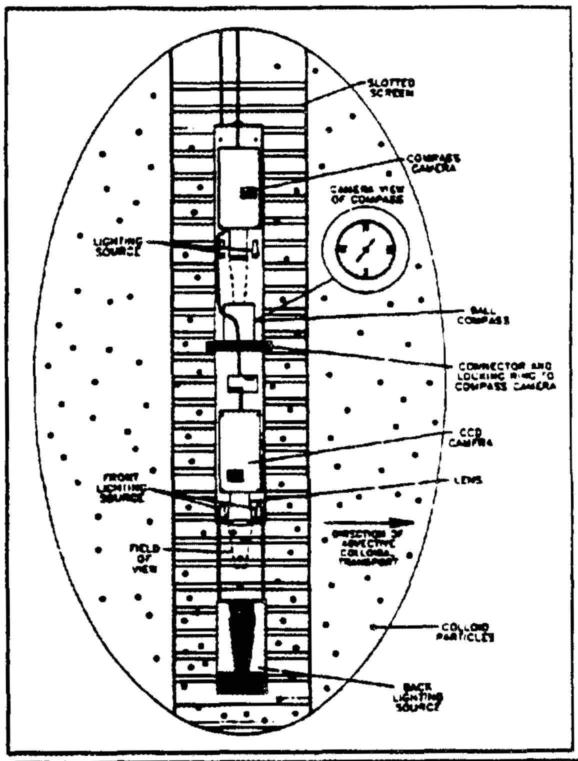
ILLUSTRATIONS





Prepared by the Integrated Program for Characterization, Monitoring and Sensor Technology and the Technology Integration Program, Ames Laboratory, Iowa State University, Ames, Iowa 50011, (515) 294-4986. The information for this Technology Data Sheet was provided by Scott List, Oak Ridge Institute for Science and Education.

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After connecting the female end of the cable to the video monitor/control console, the video recorder may be connected. The video in/out signal from the video recorder is connected to the video monitor/control console via the video signal cables supplied with the video recorder.

Finally, the measuring tape is attached to the instrument module to assess the depth of the field of view in the well. The zero mark of the measuring tape is positioned at the focal point of the instrument, approximately midway between the back lighting source and the optic window of the instrument. The measuring tape is then secured to the cable approximately 1 m above the cable/compass module union. The lower end of the measuring tape is folded back and secured to the cable. Any loose folds or loops in the measuring tape that may catch on protrusions extending into the well bore must be secured.

Once electrical power is connected to the video monitor/control console and the video recorder, the instrument is ready for insertion into the observation well to record flow data.

Prior to insertion into the observation well, the compass module and instrument module are aligned with the top of the instrument camera corresponding to magnetic north as indicated by the compass module. A notch has been scribed in the instrument housing that corresponds to the top of the instrument camera. Once the alignment is completed, a mark is made on the compass module that matches the notch on the instrument module. A toggle switch on the monitor allows the operator to change between "compass view" and "forward view" to verify the alignment procedure. The multi-pin union connecting the compass and instrument modules is tightened to prevent any further rotation of the modules. The alignment of the modules is periodically checked during use to prevent the collection of erroneous directional data.

2.3.2 Recording Field Measurements

After locating the observation well, a water-level measurement is taken and recorded in the field notebook. The borescope instrument is lowered into the well to the desired depth and secured at the surface with a clamp. The monitor is turned on and the "compass view" switch is toggled. The borescope is then rotated by turning the cable until the compass needle points to the top of the monitor. The "forward view" switch is toggled, and flow is observed until steady, consistent movement is obtained. The recorder is turned on, the prenumbered VHS tape inserted, and approximately 15 min. of data recorded. Before the recording of colloids begins, the "compass view" switch is toggled, and the compass direction is recorded for approximately 30 s. Then, without turning off the recorder, the "forward view" switch is toggled, and the recording of colloids begins. After the colloid recording is complete, the "compass view" is toggled, and the compass direction is recorded again without stopping the tape. The field notebook is used to record the date of colloid measurement, the VHS tape number, the well number and location, the depth of the interval being recorded, the depth to water, and the time recording begins and ends for each well or depth interval measured. Also noted are the general direction of flow, degree of observed vertical flow, any changes of flow direction observed while recording, and any other observations useful to the analysis of the data. Any changes in procedures are also recorded in the field notebook.

2.3.3 Data Analysis

Measurement of colloid velocity in the well bore is accomplished by analysis of the recorded images. This analysis begins by connecting the video monitor/control console to a VHS recorder equipped with a jog/shuttle that permits a frame-by-frame analysis. Data recorded in the field notebook are used to verify which VHS tape is being analyzed by comparing the VHS tape number, the observed flow directions, and the recording lengths of specified intervals. Once the verification is complete, the actual data analysis begins by viewing the recorded compass direction at the beginning of the recording. A straight edge and a felt-tip pen are used to record the compass direction on the video monitor screen. The tape is then fast-forwarded to the compass recording at the end of that particular recording segment to determine if there was any movement of the instrument during the recording. If these directions do not coincide, the compass direction recorded at the end of the segment is marked on the monitor screen, and the first compass direction mark is erased.

The tape is then rewound to the first compass recording and allowed to play at normal speed. After a colloidal particle is selected, the tape is stopped using the jog shuttle, the position of the colloid is noted on the screen, and the tape is advanced 40 frames. The position of the colloid is again noted on the screen. The distance between the colloid's initial position and final position is measured and recorded in centimeters. To determine the direction of colloid movement, a straight line connecting the initial and final colloid positions is drawn to intersect the compass direction line previously marked on the screen. A protractor is used to measure the angle, and the bearing is recorded. The bearing recorded should then be adjusted for the known magnetic declination applicable to the location. To obtain representative data on colloid velocity and direction for that particular recorded interval, the above procedure is repeated eight to twelve times by advancing the tape 1 to 2 min between individual colloid measurement. The mean of the distances recorded is calculated and then divided by the number of frames used (40 frames) during each measurement to obtain a value in cm/frame. To obtain a value in cm/s and to correct for the magnification factor of 140X, the cm/frame value is multiplied by 0.214 frames/s. This latter coefficient is derived by multiplying the speed of the tape (30 frames/s) by the inverse of the magnification factor (1/140).

While observed colloidal movement has been generally uniform, some slight perturbations do exist. In order to smooth out these perturbations and obtain a more representative value of the macroscopic average flow velocity, numerous colloid velocity measurements at specific flow depths are needed. Therefore, the representativeness of the macroscopic average for a particular area is generally a function of the number of measurements made at a specific flow depth. Colloid velocity is thus expressed as the mean of a specific set of measurements.

2.3.4 Calibration Coefficient

Because groundwater flows from a porous medium of finite permeability and porosity to a cylinder of infinite permeability and a porosity of one, potential flow theory indicates higher flow velocities in the borehole by a factor of two. Drost et al. (1968) predicted flow velocities in the borehole four times higher than the adjacent porous medium. Cronk (1992) has proposed a continuum approach that can explain flow velocities higher then those predicted either by Drost et al. (1968) or by potential flow theory. Previous field measurements have shown borehole velocities to be 15 to 25 times higher than those of the adjacent porous medium. To date, no obvious explanation for the observed high velocity field in the well bore has been developed; however, valuable insight has been gained concerning the physical mechanisms governing flow at the pore scale.

In order to equate bore hole velocity with seepage velocity, a calibration coefficient is needed. Obtaining the coefficient was a major goal of this investigation. The calibration coefficient (F_c) is calculated by combining Eqs. (1) (Darcy's Law) and (2) to produce Eq. (3):

$$(\bar{v}) = \frac{Ki}{n} \tag{1}$$

$$(\bar{v}_B) = (\bar{v}) F_c \tag{2}$$

$$(\bar{v}_B) = \frac{Ki}{n} F_c \tag{3}$$

Solving for F_c yields Eq.(4):

$$F_c = \frac{(\bar{v}_B) n}{Ki} \tag{4}$$

The variables in the above equations are defined as follows:

$(\bar{v}_B)$ = average velocity in borehole,
K = hydraulic conductivity,
i = hydraulic gradient,
n = effective porosity,
F_c = calibration factor relating borehole velocity to seepage velocity,
$(\bar{v})$ = average seepage velocity.

2.4 RESULTS AND DISCUSSION

2.4.1 Field Measurements

Field measurements at the four study areas were collected in September and December 1991. These areas are known as the CS-4/Vicinity area, the Sewage Treatment Plant (STP), the Sandwich area, and the 603 Wells/Crane Wildlife area and are illustrated in Fig. 4.

Colloid measurements were collected from 53 depth intervals in 28 wells. Several measurements were collected in the same well bore at different depths. Colloid measurements were attempted on an additional 29 intervals in 25 wells but were not achieved for various reasons, including bad recordings (too dark), swirling or vertical flow, lack of measurable colloids, and sediment-filled screens in wells. Water-level data collected from 44 wells were used to construct study-area potentiometric maps (Figs. 5 through 8) and to calculate area-specific hydraulic gradients. Hydraulic borehole colloid velocity and seepage conductivity measurements and well logs were provided by Hazardous Waste Remedial Actions Program (HAZWRAP).

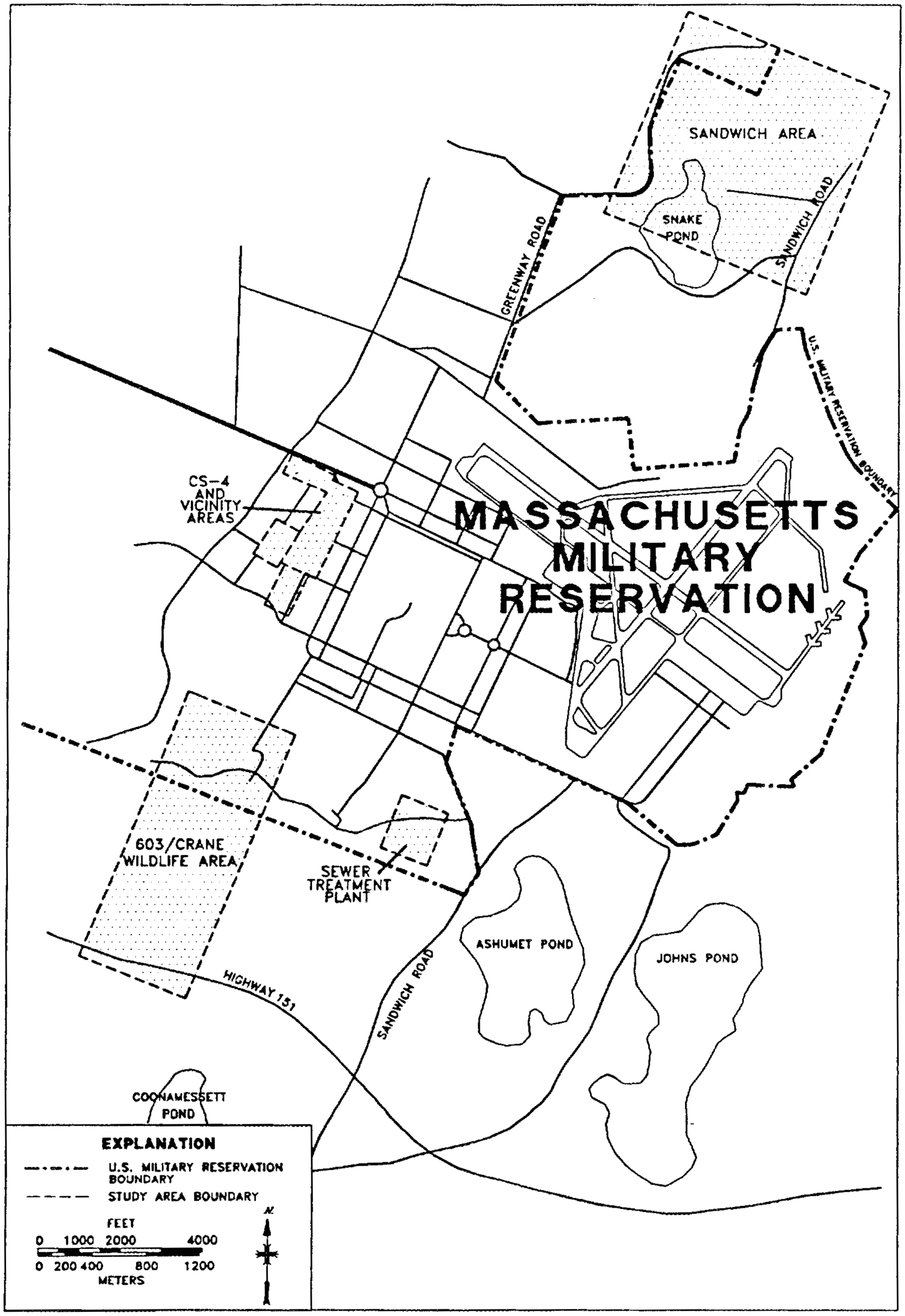
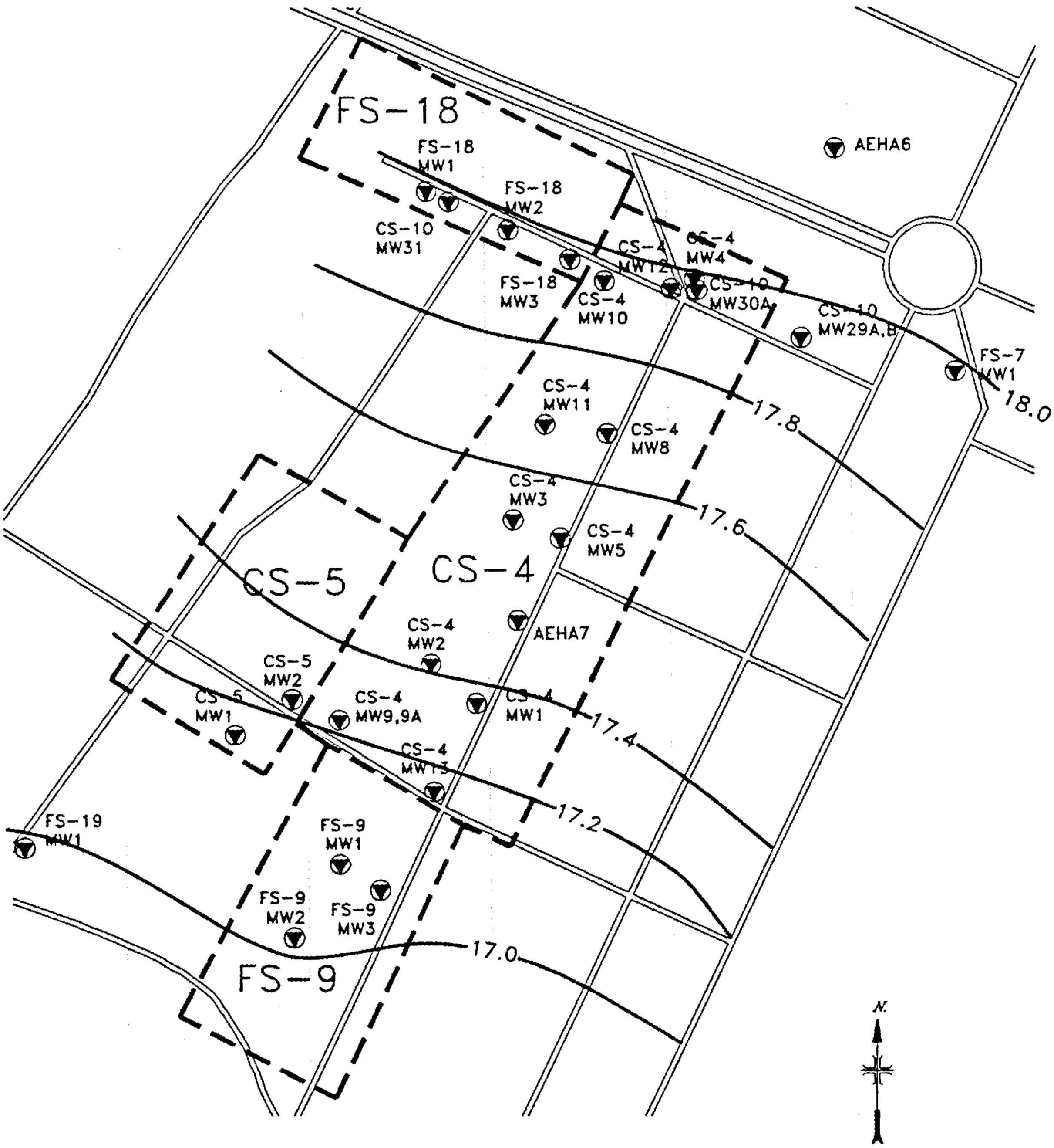


Fig. 4. Location map of the four study areas at MMR.



MONITORING WELL LOCATION

— 17.0 — POTENTIOMETRIC SURFACE CONTOUR
CONTOUR INTERVAL 0.2 METERS
SEPTEMBER 1991

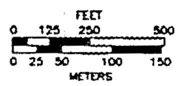


Fig. 5. Potentiometric map for CS-4 and vicinity.

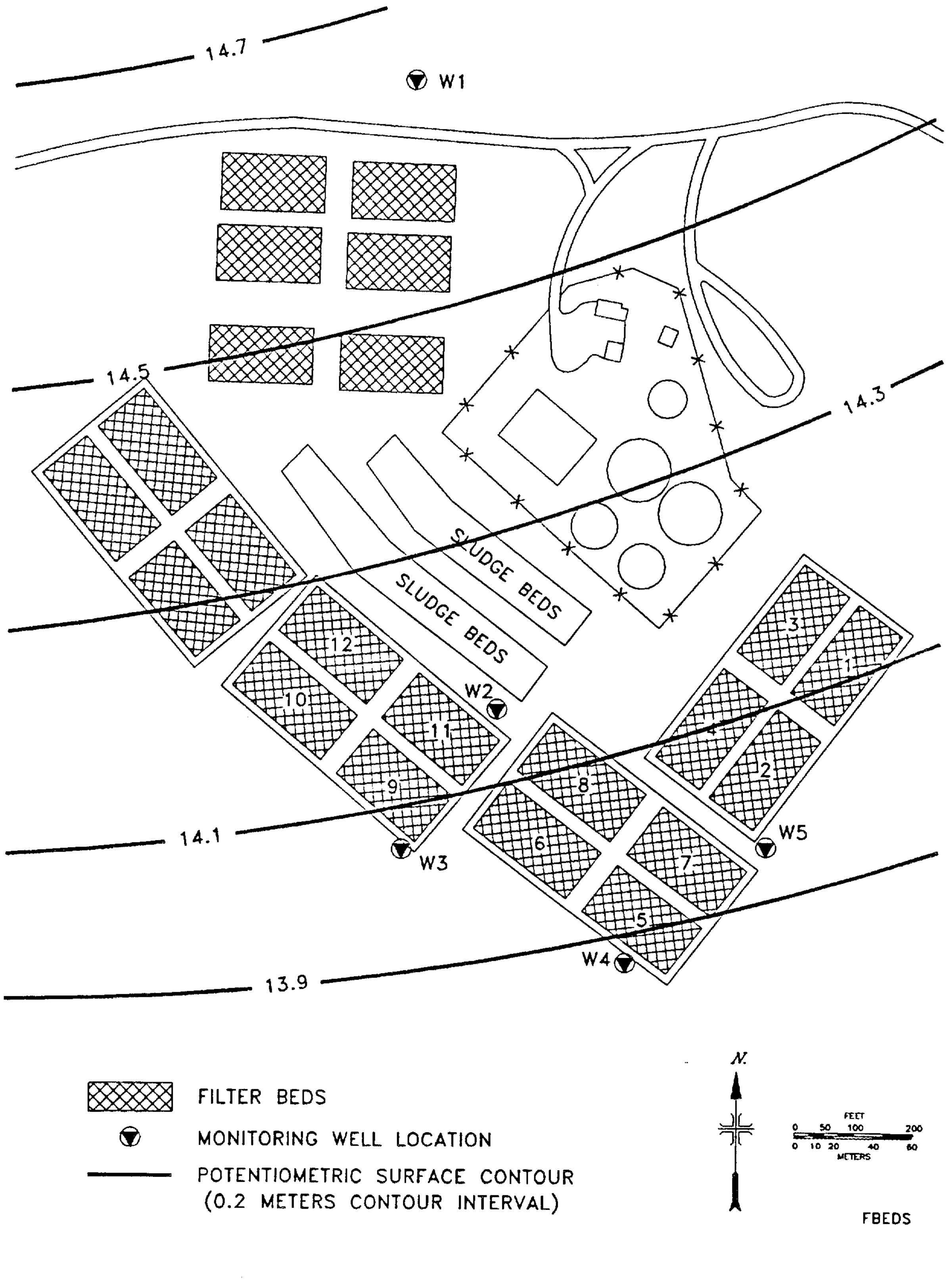


Fig. 6. Potentiometric map for STP.

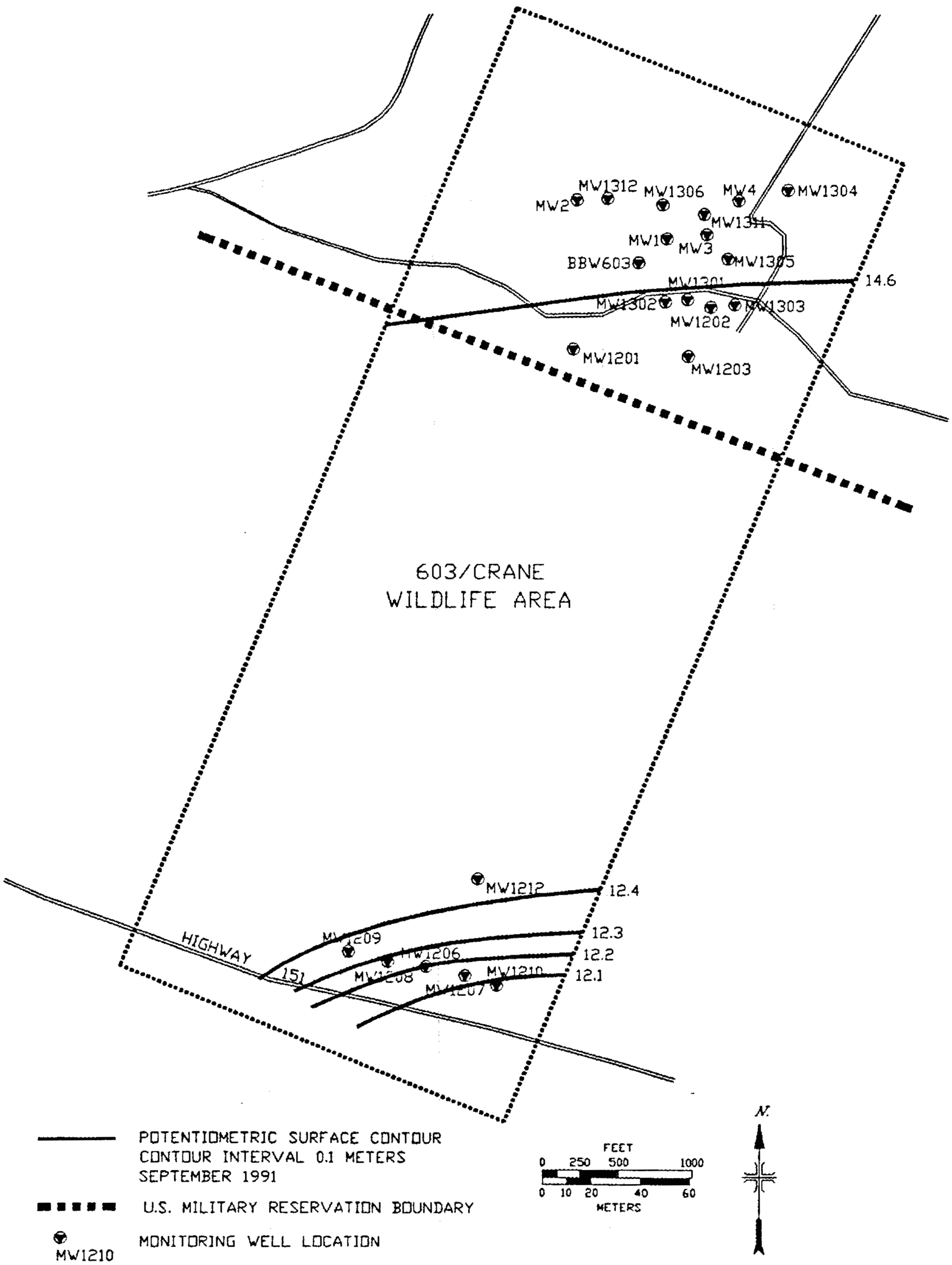


Fig. 7. Potentiometric map for the 603 Well/Crane Wildlife area,

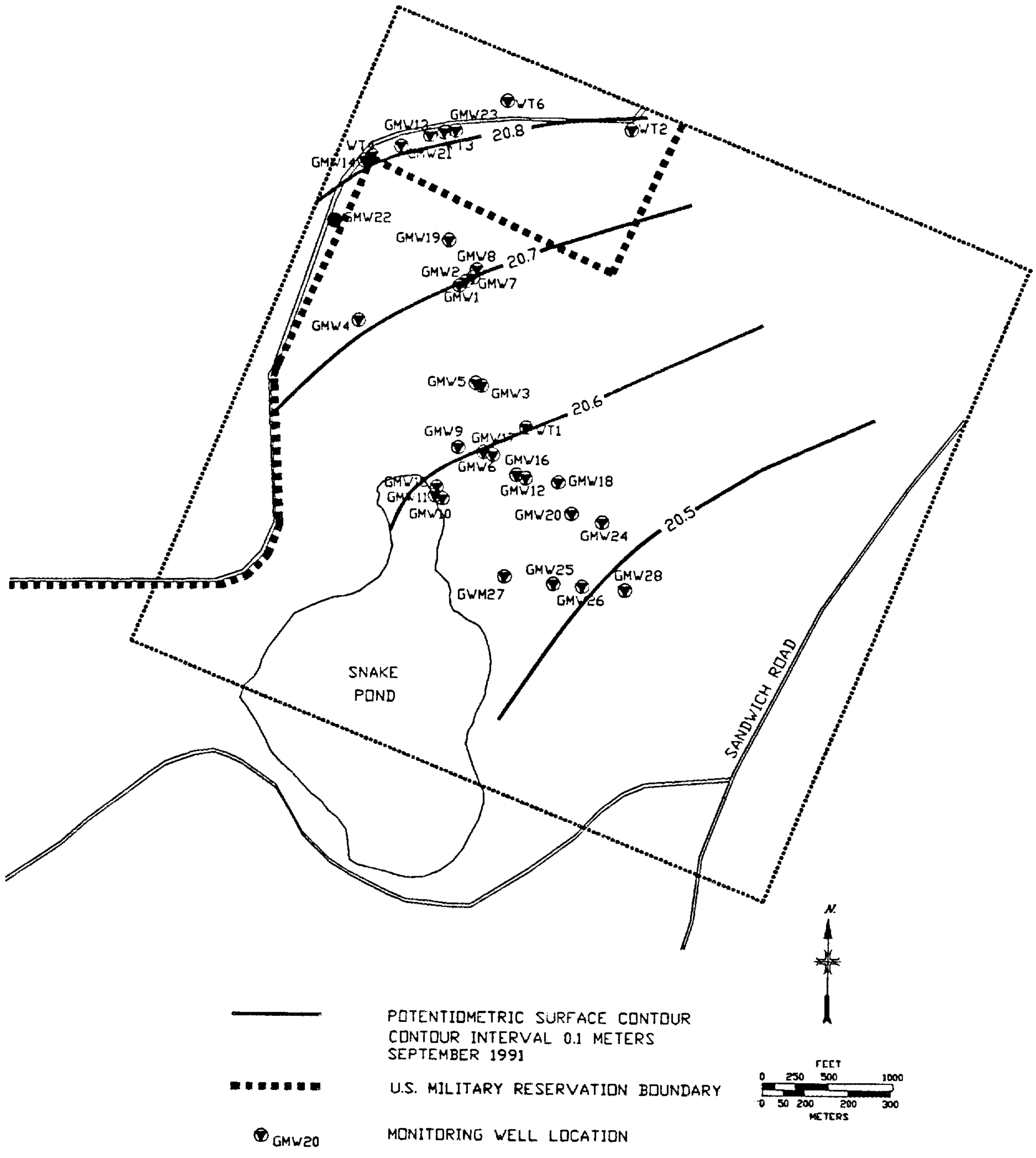


Fig. 8. Potentiometric map for the Sandwich area.

2.4.2 Data Analysis

Results from the colloid measurements performed at the four study areas are presented in the Tables 1, 2, 3, and 4. Data presented include the well number, the depth of the interval measured below casing level (BCL), the elevation of the interval measured above mean sea level, the bearing of the observed flow direction, and the observed borehole colloid velocity in cm/s. At the bottom of each table are the means and standard deviations of the borehole colloid velocities for the specific study area.

The variability in flow directions suggests that certain hydrologic parameters may present significant problems for the instrument's reliability. The relatively flat hydraulic gradient at the site, which is up to two orders of magnitude less than at other sites, may potentially affect direction measurements. Considering the relatively gentle topography and high permeability of the aquifer, geometric alignment of preferential flow paths may be dominating flow direction. If the gradient were increased, the preferential flow paths should parallel the hydraulic gradient.

Gradient calculations for each of the areas are presented in Table 5. Calibration coefficients (F_c) calculated by comparing borehole flow velocities determined by the instrument with existing hydrologic information from the site are in good agreement. The F_c is determined by dividing the product of the mean bore-bore colloid velocity ($\bar{v}_B$) and the effective porosity (n) by the product of the hydraulic conductivity (K) and the hydraulic gradient (i) as shown in Eq. (4). The F_c is a particularly sensitive number because it expresses the relationship between velocities of adjacent porous media. The accuracy and reliability of the instrument are profoundly affected when incorrect values for K, n, and i are used. Therefore, basic assumptions relating to the validity of the existing hydrologic data are made in the reliability testing of the colloidal borescope.

A review of the literature indicated that a K value of 110 m/day and an n value of 0.39 should be used to represent three of the study areas. The hydraulic gradient was calculated using water-level data gathered at each site. It should be noted that the gradient values for three of the four study areas are in good

Table 1. Data summary sheet: CS-4 and vicinity areas

Well number	Interval BCL[a], m	Interval elev[b], m	Flow direction	Flow velocity, cm/s
FS18-MW1	21.33	17.24	S11E S03W	0.0072
FS18-MW1	21.64	16.93	S67W S32E	0.0083
FS18-MW1	21.94	16.63	N87W S67W	0.0080
FS18-MW2	21.49	17.58	S89W S66W	0.0039
FS18-MW2	21.79	17.28	S20W S30W	0.0065
FS18-MW2	22.09	16.98	S04W S35W	0.0080
FS7-MW1	23.32	17.08	S23E S61E	0.0041
FS7-MW1	23.47	16.93	N70E N87E	0.014
FS7-MW1	23.62	16.78	EAST S59W	0.0064
FS7-MW1	23.93	16.47	No distinct flow	ND
CS4-MW1	23.16	16.57	S15W S04W	0.0094
CS4-MW3	23.16	16.57	N08W N04E	0.014
CS4-MW4	23.16	17.73	N06E N21E	0.010
CS4-MW9	22.58	16.33	N21E N20E	0.0074
CS4-MW10	23.77	17.48	S66E N43E	0.013
CS4-MW11	22.55	17.02	N31E N20E	0.013
FS9-MW3	21.64	16.35	S46W S35W	0.012
FS19-MW1	19.81	16.07	N05E S57E	0.018
CS5-MW1	22.25	16.11	S58E S64E	0.018

mean = 0.011 cm/s
σ = 0.004 cm/s

[a] BCL = below casing level.
[b] elev = elevation above mean sea level.
ND = not detected.

Table 2. Data summary sheet: Sewage Treatment Plant (STP)

Well number	Interval BCL[a], m	Interval elev[b], m	Flow direction	Flow velocity, cm/s
W2	8.23	13.20	S73W S87W	0.034
W2	10.97	10.46	N35W N01W	0.009
W2	12.50	8.93	S69W S78W	0.029
W2	14.02	7.41	S65W S46W	0.014
W2	15.54	5.89	S66E S48W	0.017
W2	17.07	4.36	S77E S60E	0.013
W2	18.59	2.84	S27E S23E	0.010
W2	20.12	1.31	S20E S35E	0.0062
W3	13.11	11.43	S89W N63W	0.011
W3	14.63	9.91	N25E N35E	0.024
W3	16.15	8.39	S80W WEST	0.014
W3	17.68	6.86	S67W S55W	0.024
W3	22.25	2.29	S50E S70E	0.022
W4	16.15	12.20	S69E N89E	0.014
W4	17.68	10.67	S75E N81E	0.0069
W4	22.25	6.10	N55E N75E	0.019
W4	23.77	4.58	N24W N37W	0.016
W4	25.30	3.05	N71W N85W	0.012
W4	26.82	1.53	S63W S76W	0.012
W5	22.86	6.73	N07E N15E	0.015
W5	24.39	5.20	N11E N15E	0.013
W5	25.91	3.68	N42E N21E	0.0082

mean = 0.016 cm/s
σ = 0.007 cm/s

[a] BCL = below casing level.
[b] elev = elevation above mean sea level.

Table 3. Data summary sheet: MW603 Site/Crane Wildlife area

Well number	Interval BCL[a], m	Interval elev[b], m	Flow direction	Flow velocity cm/s
MW1202D	20.73	11.61	N53E N73E	0.0106
MW1202E	17.98	14.39	N05W N45E	0.0103
MW603B	32.00	-0.53	N49E S06W	0.011
MW603C	25.91	5.67	N84W N46W	0.00974
MW603E	17.83	13.88	N69E N29E	0.0113
MW1213	42.37	-12.81	No distinct flow	ND

mean = 0.011 cm/s
σ = 0.00061 cm/s

[a] BCL = below casing level.
[b] elev = elevation above mean sea level.

ND = not detected

Table 4. Data summary sheet: Sandwich Gate and Camp Good News area

Well number	Interval BCL[a], m	Interval elev[b], m	Flow direction	Flow velocity cm/s
GMW23	48.77	-0.35	N29E N69E	0.0113
GMW22	35.66	-2.32	S66E N54E	0.00515
GMW1	41.76	7.31	S16W S48E	0.0094
GMW2	28.65	20.36	N15W N32W	0.0136
GMW7	56.39	-7.40	N40E North	0.0093
GMW13	26.21	19.98	No distinct flow	ND

mean = 0.0098 cm/s
σ = 0.00311 cm/s

[a] BCL = below casing level.
[b] elev = elevation above mean sea level.

ND = not detected

Table 5. Gradient calculations

Gradient for CS-4/vicinity areas:

$$\frac{17.92\text{ m} - 17.19\text{ m}}{495.28\text{ m}} = 0.0015$$

Gradient for STP:

$$\frac{14.17\text{ m} - 13.87\text{ m}}{117.34\text{ m}} = 0.0026$$

Gradient for the Sandwich area:

$$\frac{20.88\text{ m} - 20.42\text{ m}}{1066.75\text{ m}} = 0.00043$$

Gradient for the 603 Wells/Crane Wildlife area:

$$\frac{14.65\text{ m} - 12.16\text{ m}}{1341.1\text{ m}} = 0.0019$$

agreement with the literature. The gradient in the Sandwich area, however, is lower by an order of magnitude. Continuity would dictate that if a groundwater system exhibits different hydraulic gradients, then the permeability must vary proportionally in these areas. Evidence of a higher *K* value is provided by pumping-test data from a well located within a few miles of the Sandwich area. Therefore, a *K* value of 244 m/day was used for F_c calculations in the Sandwich area.

Borehole logs for all wells in the four areas of study relative to this report were examined to determine the measurement interval depth and verify that the sediments adjacent to the screened intervals corresponded to the outwash sediments. The elevation of the intervals measured (Tables 1, 2, 3, and 4) ranges from a high of 20.36 m above mean sea level to a low of 12.81 m below mean sea level.

3. CONCLUSIONS

Mixed results in measured groundwater flow direction and velocity were obtained from the field tests conducted at the MMR using the colloidal borescope. The goal of obtaining a calibration coefficient for flow in the borehole versus flow in the adjacent porous medium was met with partial success. Calibration coefficients in areas where the hydraulic conductivity is relatively uniform were in excellent agreement (Table 6). The Sandwich area showed a significant variance when compared to the other areas. There is evidence, specifically a pumping test in an adjacent area, of a higher hydraulic conductivity that, when incorporated into Eq. (4), would yield a calibration coefficient comparable to those of the other sites tested at the MMR. This would indicate that groundwater flow velocity in the Sandwich area is similar to velocities at the other sites across the MMR. In fact, hydraulic conductivity values based on borescope measurements may be 30% higher than the pump test value for the Sandwich area. Assuming that the hydraulic conductivity values from nearby areas used to determine the calibration coefficients are realistic, field tests at the MMR are encouraging with respect to

Table 6. Velocity calibration coefficient calculations

The calibration coefficient (F_c) is calculated by combining equations 5 and 6 to produce equation 7:

$$(\bar{v})=\frac{Ki}{n} \tag{1}$$

$$(\bar{v}_B)=(\bar{v})F_c \tag{2}$$

$$(\bar{v}_B)=\frac{Ki}{n}F_c \tag{3}$$

Solving for Fc yields equation 8:

$$F_c=\frac{(\bar{v}_B)n}{Ki} \tag{4}$$

where:

$(\bar{v}_B)$ = average velocity in borehole, cm/s

K = hydraulic conductivity, m/d

i = hydraulic gradient, ft/ft

n = effective porosity,

F_c = calibration factor relating borehole velocity to seepage velocity,

$(\bar{v})$ = average seepage velocity, m/d

Table 6. (continued)

Calibration coefficient calculation for CS-4 and vicinity areas:

$$F_c = \frac{(0.010 \text{ cm/s})\ (0.39)}{(110 \text{ m/d})\ (100 \text{ cm/s})\ (\frac{d}{86{,}400s})\ (0.0026)} \tag{9}$$

$F_c = 20$

Calibration coefficient calculation for STP:

$$F_c = \frac{(0.016 \text{ cm/s})\ (0.39)}{(110 \text{ m/d})\ (100 \text{ m/s})\ (\frac{d}{86{,}400s})\ (0.0026)} \tag{10}$$

$F_c = 19$

Calibration coefficient calculation for the Camp Good News/Sandwich Gate area:

$$F_c = \frac{(0.0098 \text{ cm/s})\ (0.39)}{(244 \text{ m/d})\ (100 \text{ cm/s})\ (\frac{d}{86{,}400s})\ (0.00043)} \tag{11}$$

$F_c = 31$

Calibration coefficient calculation for the 603 Area/Crane Wildlife area:

$$F_c = \frac{(0.011 \text{ cm/s})\ (0.39)}{(110 \text{ m/d})\ (100 \text{ cm/s})\ (\frac{d}{86{,}400s})\ (0.0019)} \tag{12}$$

$F_c = 18$

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measuring groundwater velocity.

As encouraging as the groundwater velocity data are, groundwater flow directions are equally puzzling. For all sites tested, there is no discernable direction for groundwater flow as observed using the colloidal borescope. Groundwater flow directions did not match flow directions predicted from area potentiometric maps. These results contradict earlier tests conducted at field sites in Kansas City, Mo, Portland, Maine, and Georgetown, S.C. Measurements taken in Oak Ridge, Tenn., however, did not yield expected groundwater flow directions. This discrepancy in flow direction suggests that the relatively flat hydraulic gradient at the MMR results in the geometric alignment of preferential flow paths that could dominate flow direction. If the gradient is increased, flow will tend to parallel the hydraulic gradient.

It is apparent from the tests conducted at the MMR that there is variability in the results obtained by the colloidal borescope. This variability may be due to the natural heterogeneities inherent in a porous medium, the influences of well construction, and the microscopic scale of flow measurements in describing a macroscopic flow system. The agreement of flow velocities and the reliability of flow directions measured at other field sites strongly indicate that flow observations of colloids in a wellbore are representative of groundwater flow in the adjacent porous medium. The variability in measurement, however, suggests that many measurements, statistically analyzed, are necessary for reliably predicting groundwater flow and velocity.

At present, laboratory tests are underway to assess the influences of well construction, varying lithologies, and measurement depths of observed flow. Plans have been made to obtain funding to automate data analysis using image processing technology. With rapid data analysis, it will be possible to obtain the amount of data needed to statistically analyze the variability in measurements, thereby assessing the reliability of the colloidal borescope as an effective field instrument for measurements of groundwater flow direction and velocity.

REFERENCES

Cronk, Tom A. 1992. *A Theoretical Investigation of the Relationship Between Flow Velocities in a Well Bore and Specific Discharge Velocities in the Surrounding Porous Media.* M.S. Thesis, Colorado State University, Fort Collins, Colo.

Drost, W., D. Klotz, A. Koch, H. Moser, F. Neumaier, and W. Rauert. 1968. Point dilution methods of investigating groundwater flow by means of radioisotopes. *Water Resources,* 4(1):125-146.

Jordan, E. C. 1988. *Hydrogeologic Summary Report, Task 1-8.* Draft. Installation Restoration Program, Massachusetts Military Reservation. E. C. Jordan Co., Portland, Maine for Oak Ridge National Laboratory, Oak Ridge, Tenn.

LeBlanc, D. R., S. P. Garabedian, K. M. Hess, L. W. Gelhar, R. D. Quadri, K. G. Stollenwerk, and W. W. Wood. 1991. Large-scale natural gradient tracer test in zand and gravel, Cape Cod, Massachusetts, 1. Experimental design and observed tracer movement. *Water Resources Research,* 27(5):895-910.

Oldale, Robert N. 1981. *Pleistocene Stratigraphy of Nantucket, Martha's Vineyard, The Elizabeth Islands, and Cape Cod, Massachusetts.* U. S. Geological Survey, Reston, VA.

Oldale, Robert N., and Roger A. Barlow. 1986. *Geological Map of Cape Cod and the Islands, Massachusetts.* Department of the Interior, U. S. Geological Survey, Reston, VA.

ACRONYMS AND ABBREVIATIONS

BBM	-	Buzzards Bay moraine
BCL	-	below casing level
CCD	-	charge-coupled device
HAZWRAP	-	Hazardous Waste Remedial Actions Program
MMR	-	Massachussets Military Reservation
MPP	-	Mashpee Pitted Plain
ORNL	-	Oak Ridge National Laboratory
SM	-	Sandwich moraine
STP	-	Sewage Treatment Plant

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