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Using flowmeter pulse tests to define hydraulic connections in the subsurface: a fractured shale example

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Abstract

Cross-borehole flowmeter pulse tests define subsurface connections between discrete fractures using short stress periods to monitor the propagation of the pulse through the flow system. This technique is an improvement over other cross-borehole techniques because measurements can be made in open boreholes without packers or previous identification of water-producing intervals. The method is based on the concept of monitoring the propagation of pulses rather than steady flow through the fracture network. In this method, a hydraulic stress is applied to a borehole connected to a single, permeable fracture, and the distribution of flow induced by that stress monitored in adjacent boreholes. The transient flow responses are compared to type curves computed for several different types of fracture connections. The shape of the transient flow response indicates the type of fracture connection, and the fit of the data to the type curve yields an estimate of its transmissivity and storage coefficient. The flowmeter pulse test technique was applied in fractured shale at a volatile-organic contaminant plume in Watervliet, New York. Flowmeter and other geophysical logs were used to identify permeable fractures in eight boreholes in and near the contaminant plume using single-borehole flow measurements. Flowmeter cross-hole pulse tests were used to identify connections between fractures detected in the boreholes. The results indicated a permeable fracture network connecting many of the individual boreholes, and demonstrated the presence of an ambient upward hydraulic-head gradient throughout the site. Published by Elsevier Science B.V.

Keywords: Fractured rock aquifer; Flowmeter logging; Borehole flow modeling

1. Introduction

The distribution and migration of contaminants in heterogeneous fractured-rock aquifers is almost impossible to predict on the basis of data from a few individual boreholes. Various down-hole-imaging systems can provide effective samples of fractures and their orientations where those fractures intersect boreholes (Williams and Johnson, 2000). However, numerous studies show that local fracture aperture or fracture density has little if any correlation with fracture permeability (Long et al., 1982; Paillet et al., 1987; Paillet, 1998). Some studies also show that the local orientation of permeable fractures may be very different from the large-scale orientation of the subsurface flow paths to which those fractures are connected (Hardin et al., 1987). Surface-geophysical measurements can, in theory, be used to show how individual sets of fractures identified in boreholes are

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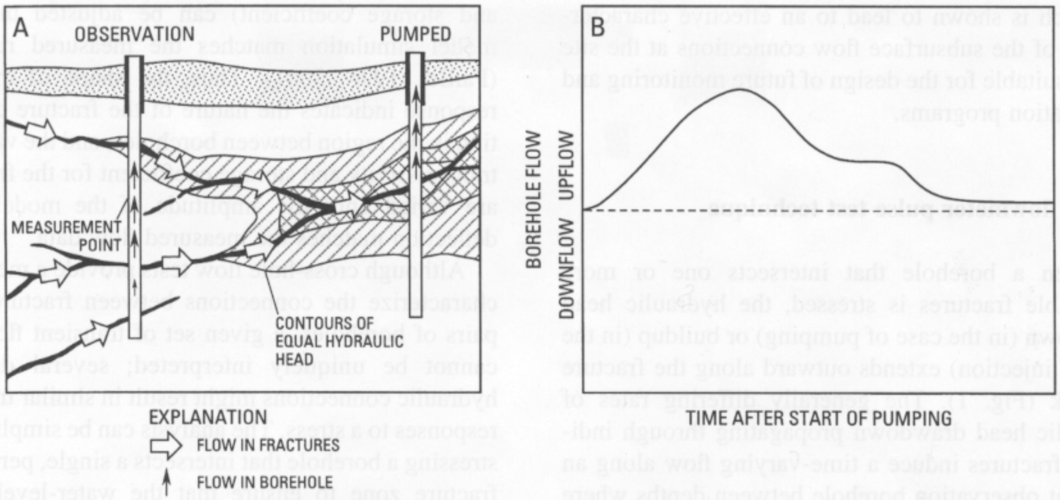

Fig. 1. Schematic illustration of: (A) propagation of drawdown outward from a pumped borehole induces vertical flow in an observation borehole and (B) borehole flow measured as a function of time after the start of pumping at a single depth station in the observation borehole.

connected into continuous networks in regions between boreholes. In practice, non-invasive surface-geophysical measurements have spatial scales such that only major fracture zones on the order of a meter or more in thickness can be identified (Long et al., 1996). Therefore, fracture connections in bedrock aquifers are most often defined by means of conventional aquifer tests with hydraulic stress applied to a single centrally located borehole and drawdown measured in a series of observation boreholes completed in specific fracture zones (Hsieh et al., 1993).

Although conventional multi-well aquifer tests can effectively define fracture connections in bedrock aquifers (Jenkins and Prentice, 1982; Tiedeman and Hsieh, 2001), there are two major problems in conducting such tests at contaminated sites: (1) there is almost no initial information about which fracture zones need to be monitored in the observation wells and (2) hydraulic stressing produces quantities of contaminated water for disposal or treatment and may mobilize contaminants in the aquifer. This paper presents an alternative approach to the conventional aquifer test for fractured-rock aquifer applications, the flowmeter pulse test. This approach is based on the observation of the propagation of short (typically 15 or 20 min) pulses of drawdown across the observation borehole array. The pulses propagate outward from the stressed borehole but do not cause much net movement of ground water, and produce relatively little water for disposal or treatment. Initial identification of which fracture zones to monitor is not necessary because the flowmeter measurements are made in the open borehole where the identities of the individual fracture connections are determined as part of the analysis. Even in those situations where definitive aquifer tests are planned, an initial series of flowmeter pulse tests can greatly increase the efficiency of such tests and improve the ability to analyze test results.

This paper presents a short overview of the flowmeter pulse theory using the aquifer modeling techniques described by Lapcevic et al. (1993) and Paillet (1998, 2000). The method is based on the identification of permeable fractures in each open borehole, followed by a series of specific pulse tests that can be used to define connections between the individual fractures detected in each borehole (Paillet, 2001). Type curves are defined for connections between boreholes based on single fracture-flow connections, and on connections between pairs of fractures. Type-curve analysis (Paillet, 1998) is used to identify the type of connection configuration, and to fit hydraulic properties (transmissivity and storage coefficient) to each such connection. The theory is applied to a series of boreholes at the Watervliet Arsenal, a fractured-shale contamination site in northeastern New York. The flowmeter pulse test approach is shown to lead to an effective characterization of the subsurface flow connections at the site that is suitable for the design of future monitoring and remediation programs.

2. The flowmeter pulse test technique

When a borehole that intersects one or more permeable fractures is stressed, the hydraulic head drawdown (in the case of pumping) or buildup (in the case of injection) extends outward along the fracture network (Fig. 1). The generally differing rates of hydraulic head drawdown propagating through individual fractures induce a time-varying flow along an adjacent observation borehole between depths where fractures intersect that borehole. The differential drawdown effect also will cause water to flow from or into wellbore storage.

Thus, if flow is measured at a depth station between or above the depth where such fractures intersect the observation borehole, the transient response to the stress can be recorded. The method can be applied in open boreholes because the number of transient flow data sets increases with the number of unknown fracture flow parameters in proportion to the number of fracture flow zones. When there is single fracture in the observation borehole, the flow can be measured anywhere above that fracture, and the measured flow compared to a flow model for a single fracture. If there are two fractures intersecting the observation borehole, flow can be measured in the interval between the two fractures and above both fractures, producing two data sets. In this way, the number of flow data sets always keeps pace with the number of fracture-zone aquifers to characterize in the analysis. The pulses of flow are repeated to provide the number of tests to allow collection of data at the required number of depth intervals.

Once the appropriate number of pulses of stress and relaxation have been run to give the data sets at the required number of depth stations appropriate for the number of fractures present, the transient flow can be compared to model type curves representative of various types of fracture connection configurations that may be present between the boreholes (Lapcevic et al., 1993; Paillet, 1993). Once a specific type curve is recognized, the hydraulic properties (transmissivity and storage coefficient) can be adjusted until the model simulation matches the measured response (Paillet, 1998; 2001). Thus, the shape of the flow response indicates the nature of the fracture connection in the region between boreholes, and the values of transmissivity and storage coefficient for the fractures are varied until the amplitude of the model curve deflection matches the measured flow data.

Although cross-hole flow tests provide a method to characterize the connections between fractures near pairs of boreholes, a given set of transient flow data cannot be uniquely interpreted; several different hydraulic connections might result in similar transient responses to a stress. The analysis can be simplified by stressing a borehole that intersects a single, permeable fracture zone to ensure that the water-level effect produced by the stress is known to affect that zone only. If the stress induces flow in the observation borehole, that borehole's fracture zone that is most directly connected to the stressed borehole will be the outflow or inflow zone. The flow from or into this zone will vary over time, depending on the connections with other fractures and by movement of water from or into wellbore storage. In the flowmeter pulse test, short pulses of stress are applied to a borehole intersecting a single fracture zone, and flow is measured at stations between and above the fractures in the observation boreholes as the pulses of stress (pumping or injection) are repeated. Flow measurements are made using either of the two available high-resolution flow measurement devices, the heat pulse flowmeter (HPFM; Hess, 1986) or the electromagnetic flowmeter (EMFM; Molz et al., 1994).

Flowmeter pulse test analysis is based on the flow model technique described by Paillet (1998). This model predicts the flow in an open borehole connecting two or more permeable zones based on the water level in the borehole and the hydraulic head in the zones in communication via the borehole. The model computes flow as a function of time after some initial condition by integrating the indicial response (Green's function integral of the slug test solution of Cooper et al., 1967) for each zone to the instantaneous difference between water level in the zone at the borehole wall and water level in the borehole. In the single-borehole case, the model predicts flow as a function of the transmissivity and hydraulic head in each zone. Paillet (2000) demonstrates that a pair of

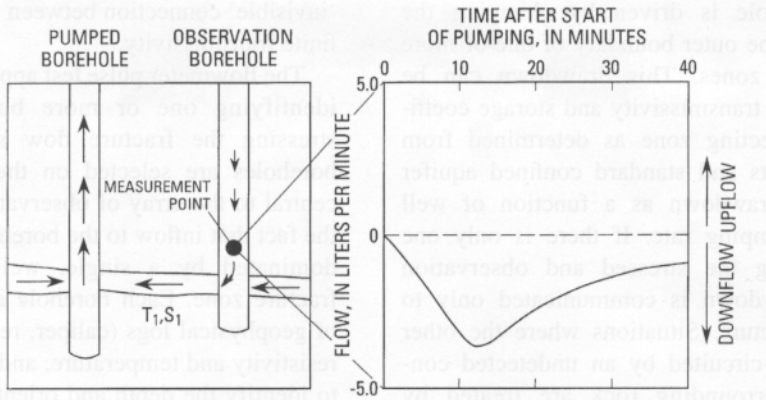

Fig. 2. Schematic illustration of type curve computed for a single fracture of transmissivity (T) and storage coefficient (S) connecting a pumped borehole with an observation borehole where flow measurements are made.

steady state flowmeter profiles (ambient and stressed) can be used to solve for the transmissivity and hydraulic head of each zone by matching predicted and measured flow values for both ambient and stressed conditions. This modeling technique specifies a storage coefficient for the computations, but the steady state flow is independent of the actual value being used. In the cross-borehole test, the flow in the

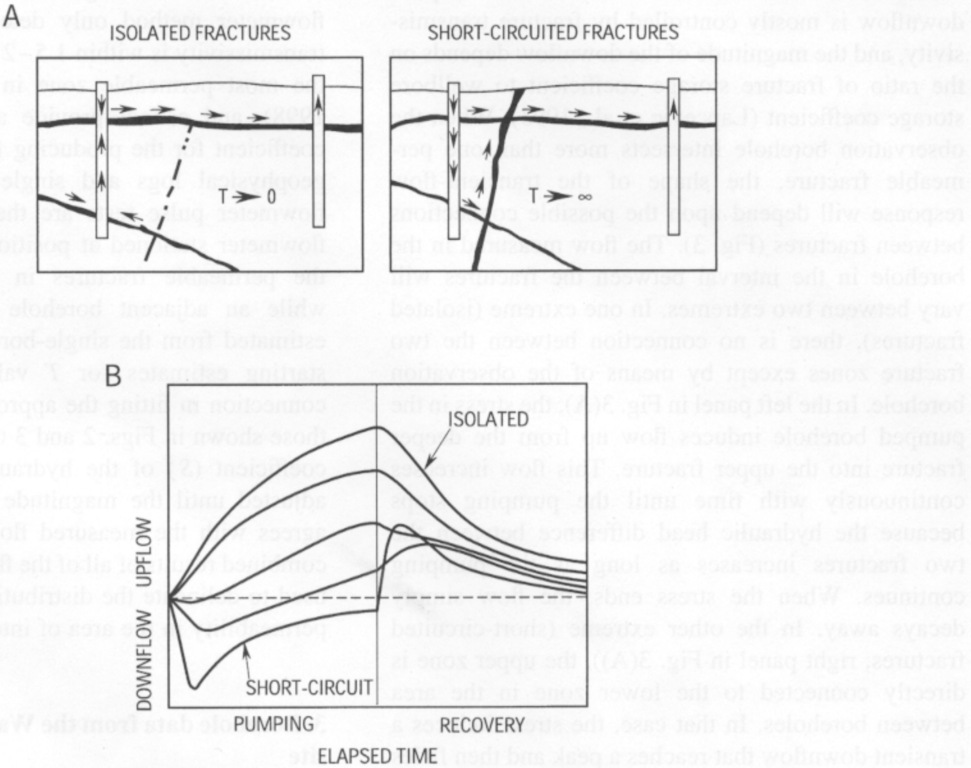

Fig. 3. Type curves computed for a situation where (A) a single fracture connects pumped and observation boreholes, and the observation borehole intersects a deeper fracture of approximately the same transmissivity and (B) type curves vary in direction and magnitude of flow according to the transmissivity of a third fracture in the surrounding formation.

observation borehole is driven by changing the hydraulic head at the outer boundary of one or more of the producing zones. This drawdown can be predicted using the transmissivity and storage coefficient of the connecting zone as determined from single-borehole tests and standard confined aquifer solutions giving drawdown as a function of well separation and pumping rate. If there is only one fracture connecting the stressed and observation borehole, the drawdown is communicated only to that individual fracture. Situations where the other fractures are short-circuited by an undetected connection in the surrounding rock are treated by communicating the drawdown to those fractures in the same way.

The transient-flow type curve for the simplest configuration—where the stressed and observation boreholes are connected by a single fracture and flow in the observation borehole is from wellbore storage—is shown in Fig. 2. The response to pumping consists of a variable downflow. The time of the peak downflow is mostly controlled by fracture transmissivity, and the magnitude of the downflow depends on the ratio of fracture storage coefficient to wellbore storage coefficient (Lapcevic et al., 1993). When the observation borehole intersects more than one permeable fracture, the shape of the transient-flow response will depend upon the possible connections between fractures (Fig. 3). The flow measured in the borehole in the interval between the fractures will vary between two extremes. In one extreme (isolated fractures), there is no connection between the two fracture zones except by means of the observation borehole. In the left panel in Fig. 3(A), the stress in the pumped borehole induces flow up from the deeper fracture into the upper fracture. This flow increases continuously with time until the pumping stops because the hydraulic head difference between the two fractures increases as long as the pumping continues. When the stress ends, the flow simply decays away. In the other extreme (short-circuited fractures; right panel in Fig. 3(A)), the upper zone is directly connected to the lower zone in the area between boreholes. In that case, the stress induces a transient downflow that reaches a peak and then fades away with time. The recovery induces a similar upflow response. In general, the flow response will lie somewhere between the two extremes, where the 'invisible' connection between the two fractures has a finite transmissivity.

The flowmeter pulse test application is designed by identifying one or more boreholes suitable for stressing the fracture flow system. The stressed boreholes are selected on the basis of a location central to the array of observation boreholes, and by the fact that inflow to the borehole during pumping is dominated by a single, well-defined fracture or fracture zone. Each borehole is logged with a suite of geophysical logs (caliper, resistivity, fluid column resistivity and temperature, and borehole-image logs) to identify the depth and orientation of fractures and bedding planes intersecting the borehole. HPFM or EMFM flow logs are then run under ambient and stressed conditions to identify permeable fractures, and to provide estimates of the transmissivity (T) and hydraulic head of each such fracture. This is the single-borehole flow log analysis described in detail by Paillet (1998), where flow measurements are made in the borehole being stressed. The single-borehole flowmeter method only detects flow zones whose transmissivity is within 1.5–2 orders of magnitude of the most permeable zone in the borehole (Paillet, 1998), and cannot provide an estimate of storage coefficient for the producing fractures. Based on the geophysical logs and single-hole flowmeter tests, flowmeter pulse tests are then conducted with the flowmeter stationed at positions between and above the permeable fractures in observation boreholes while an adjacent borehole is stressed. T values estimated from the single-borehole tests are used as starting estimates for T values of the hydraulic connection in fitting the appropriate type curve from those shown in Figs. 2 and 3 to the data. The storage coefficient (S) of the hydraulic connection is then adjusted until the magnitude of the predicted flow agrees with the measured flow. In a final step, the combined results of all of the flowmeter pulse tests are used to delineate the distribution of fracture-network permeability in the area of interest.

3. Borehole data from the Watervliet Arsenal study site

The Watervliet Arsenal study site is in northeastern New York State (Fig. 4). Information on

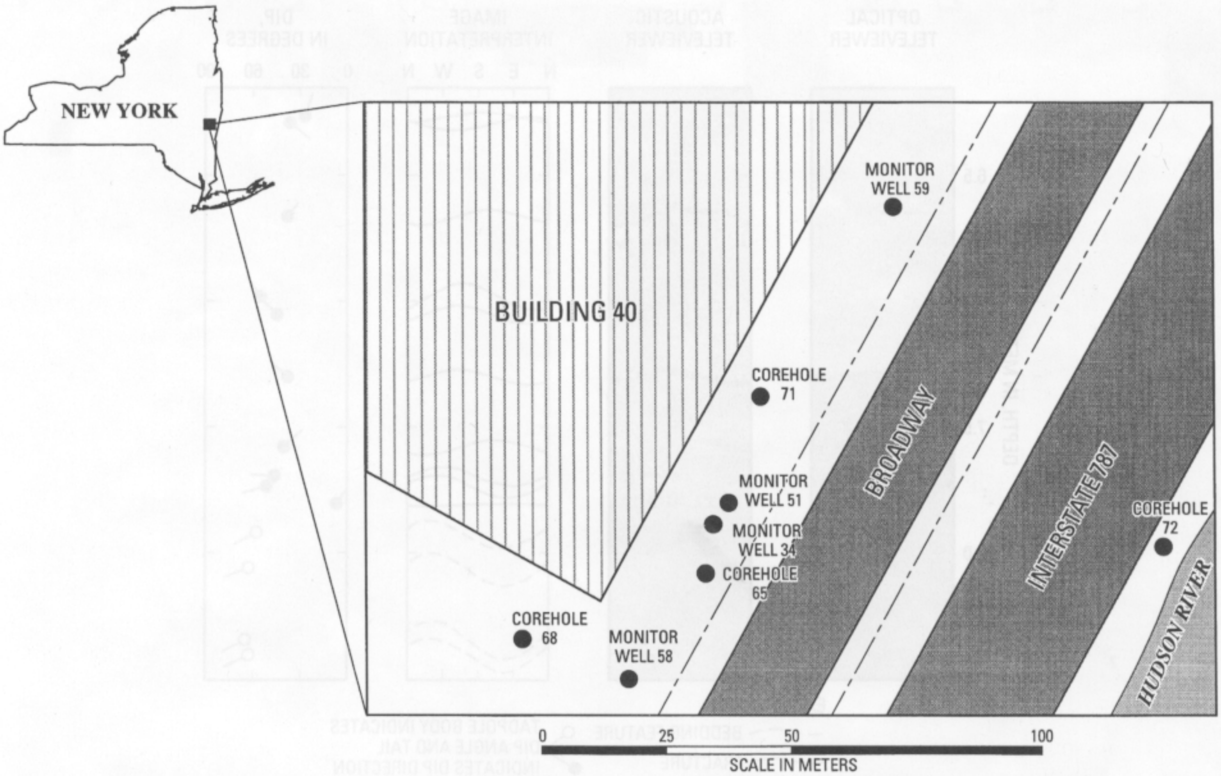

Fig. 4. Location of the coreholes and monitoring wells at the Watervliet site.

the fracture-flow network at the site was needed to design an effective ground-water monitoring system, estimate migration of contaminants offsite, and evaluate potential containment and remedial actions. The Ordovician-age shale at the site is overlain by 3–5 m of artificial fill, alluvium and glacial-drift deposits. The general direction of ground-water flow is toward the adjacent Hudson River, a regional discharge area.

Four recently drilled coreholes and four older monitoring wells were available for geophysical and flowmeter logging in and near the contaminant plume (Table 1). Acoustic-televiewer logs were collected in the open intervals of the

Table 1
Summary of boreholes at the Watervliet site

Borehole number (USGS county number)	Land-surface elevation above sea level (m)	Hole depth below land surface (m)	Casing depth below land surface (m)	Water-level elevation above sea level (m)
MW34 (A656)	5.66	9.6	5.0	2.74
MW51 (A657)	5.70	21.6	16.0	2.73
MW58 (A654)	6.26	25.0	19.5	2.91
MW59 (A659)	6.15	29.3	22.9	2.79
CH65 (A655)	6.70	50.3	6.4	2.74
CH68 (A652)	6.53	22.9	5.3	3.82
CH71 (A658)	6.31	32.0	6.4	2.75
CH72 (A660)	5.25	38.1	6.7	1.90

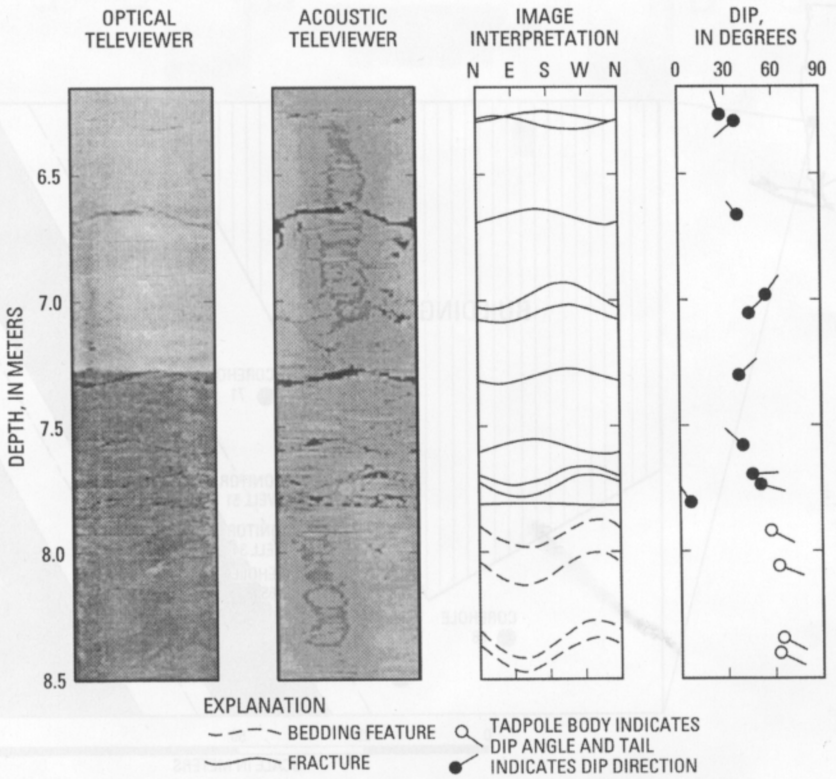

Fig. 5. Interpretation of fractures and bedding plane features in monitoring well 34 using optical and acoustic televiewer logs.

monitoring wells and coreholes. Optical-televiewer logs were collected in monitoring well 34 (Fig. 5), the upper part of corehole 65, and corehole 68. Borehole flow profiles under ambient and stressed conditions (single-borehole flowmeter tests) were collected with either the HPFM or the EMFM. Single-hole flowmeter tests entailed short-term injection of about 15 l/min into each monitoring well or corehole, except for corehole 72, which was pumped at about 8 l/min. In general, the HPFM was used for ambient flow measurements because of the better low-flow detection capability of that flowmeter. A representative composite of the geophysical log data obtained from corehole 71 is shown in Fig. 6. Although numerous fractures were detected by the televiewer in this corehole, single-hole flowmeter logs and fluid column log analysis indicates two permeable fracture zones (Molz et al., 1989; Paillet, 2000). Flow-log modeling was used to estimate the transmissivity of these two fracture zones (Paillet, 1998; Paillet et al., 2000), and to define an approximately 3 cm hydraulic-head difference between the two zones where they are intersected by the corehole. Estimated transmissivity values for permeable fractures in the eight boreholes varied from 0.01 to 24 m^2/d (Table 2). Ambient flow was detected in the three coreholes (65, 68, and 71) that intersected more than a single permeable fracture zone, and indicated hydraulic-head differences from a few cm to about 20 cm.

Possible connections between the permeable fractures intersected by individual boreholes are indicated by comparing the depths where such fractures intersect individual monitoring wells or coreholes (Fig. 7). This information was combined with fracture strike and dip determined form the televiewer logs to project discrete fractures into the area surrounding boreholes (Fig. 8). Although the subsurface projection of detected features is a standard analysis technique in the study of fractured-rock aquifers, there is no specific information to show

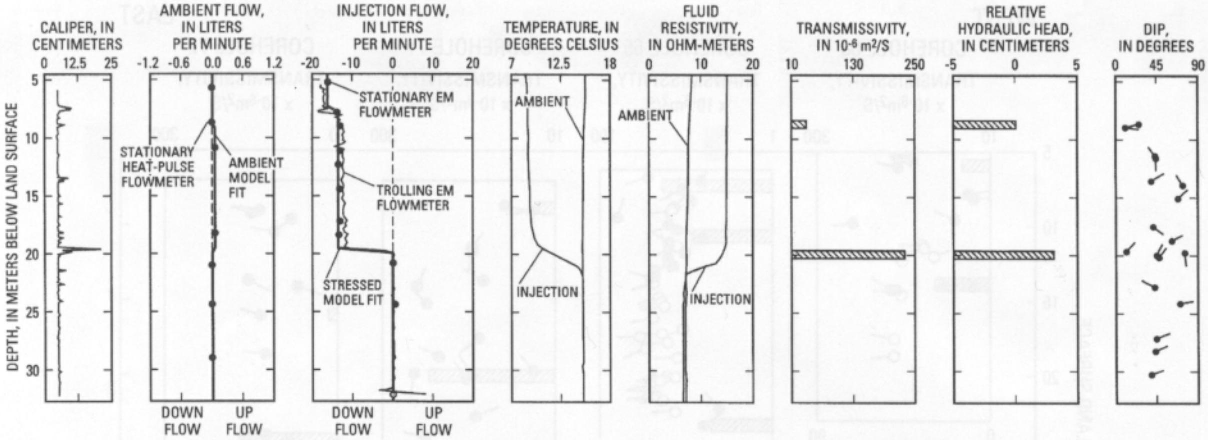

Fig. 6. Interpretation of HPFM and EMFM logs to provide estimates of the transmissivity and relative hydraulic head of fractures indicated by caliper and televiewer logs; head and tail of the tadpoles on fracture dip panel indicate dip angle and dip azimuth of fractures shown on acoustic and optical televiewer images.

that the fractures shown in Fig. 8 actually form continuous subsurface flow paths in the aquifer at the study site. Specific information about how individual fractures are connected to form a continuous network is required before the possible fracture connections implied by Fig. 8 can be accepted as a reliable model for ground-water flow at the Watervliet Arsenal site. This information could only be provided by cross-borehole tests as described later.

4. Flowmeter pulse tests at the Watervliet Arsenal site

Flowmeter pulse tests at the Watervliet Arsenal site were designed using the information about permeable fractures listed in Table 2. Two boreholes, monitoring well 34 and monitoring well 59, were initially selected for application of stress because those boreholes intersected a single, permeable fracture zone. The

Table 2

Summary of permeable fracture zones detected in the Watervliet boreholes; estimates of fracture zone transmissivity were estimated using single-borehole flow log analysis suing the model technique given by Paillet (1998)

Borehole number	Depth of fracture zone below land surface (m)	Transmissivity (m^2/d)	Hydraulic-head elevation above sea level (m)
MW34	7.3	24	2.74
MW51		No permeable zones detected	
MW58	23.0	0.01	2.91
MW59	27.9	21	2.79
CH65	6.7	6.0	2.73
	10.5	4.4	2.73
	23.2	3.4	2.77
	26.3	0.28	2.77
	33.5	0.28	2.77
CH68	5.8	5.4	3.68
	13.0	10	3.89
CH71	7.0	3.7	2.72
	19.8	21	2.75
CH72	14.9	2.1	2.0
	22.9	5.5	2.0

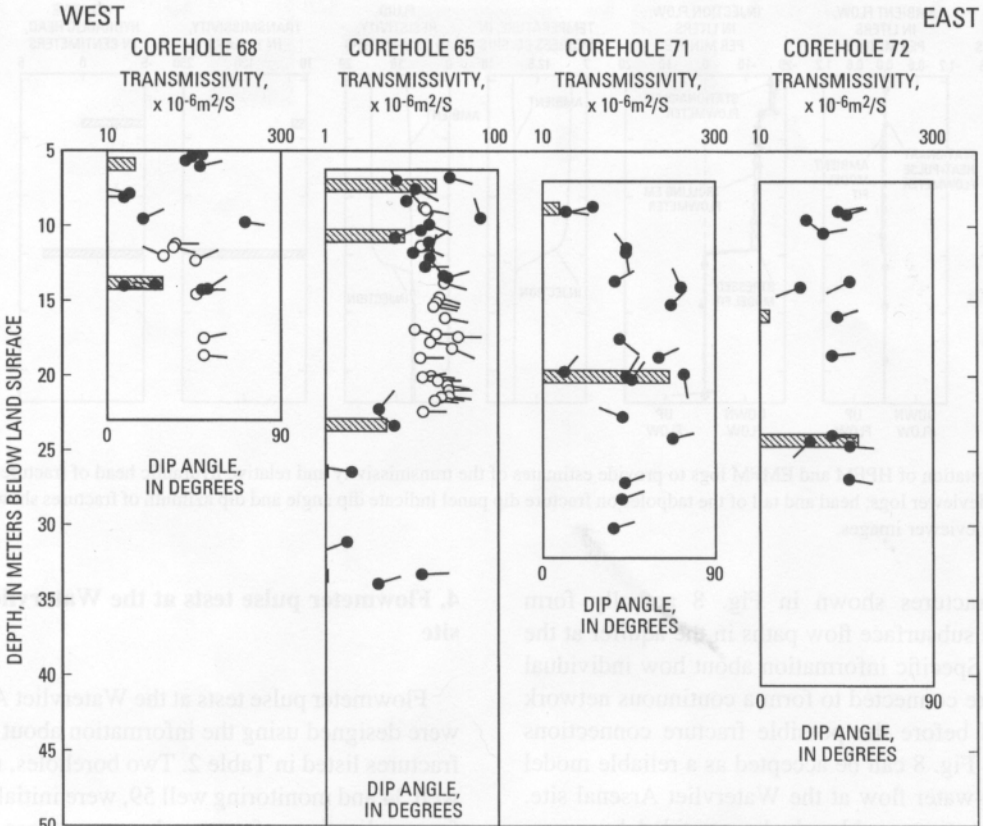

Fig. 7. Flowmeter and televiewer log interpretations for coreholes 65, 68, 71, and 72 arranged along an east–west section to indicate possible connections among fractures in the subsurface; strike and dip of individual fractures and bedding planes are given by tadpoles with heads represented by solid and open circles.

hydraulic stress was provided by injecting water at a rate of about 10 l/min for periods up to 20 min. Tests were repeated enough times to insure that as many flow data sets were obtained as needed to characterize the number of water-producing fractures intersecting each borehole. Test periods of at most 20 min were required to capture the characteristic shape (peak amplitude or curvature) of the response, and intervals of about 1 h were needed between tests to insure sufficient recovery from periods of stressing. Flow was measured in adjacent observation boreholes using the HPFM because that flowmeter was needed for maximum low-flow sensitivity. Flowmeter responses to pulses of injection measured at stations between permeable fractures in observation boreholes were expected to match one of the type curves shown in Fig. 9. The shape of the response of the measured flow is clearly sensitive to the presence of otherwise undetected connections between the fractures. The type-curve response is most sensitive in configurations where the fracture connecting the two boreholes is above a 'secondary' fracture only present in the observation borehole. The solid curves were computed using similar values of T (9.3 m^2/d) for both fractures and a typical fracture $S(1 \times 10^{-5})$. When the secondary fracture T value is made smaller (0.93 m^2/d) for the isolated fracture case, the magnitude of flow is greatly reduced when the primary fracture is shallow, while wellbore storage effects become significant when the 'primary' fracture is deep. However, all of the different type curve responses shown in Fig. 9 appear different enough from each other that the different kinds of response would be recognized in the flowmeter pulse test

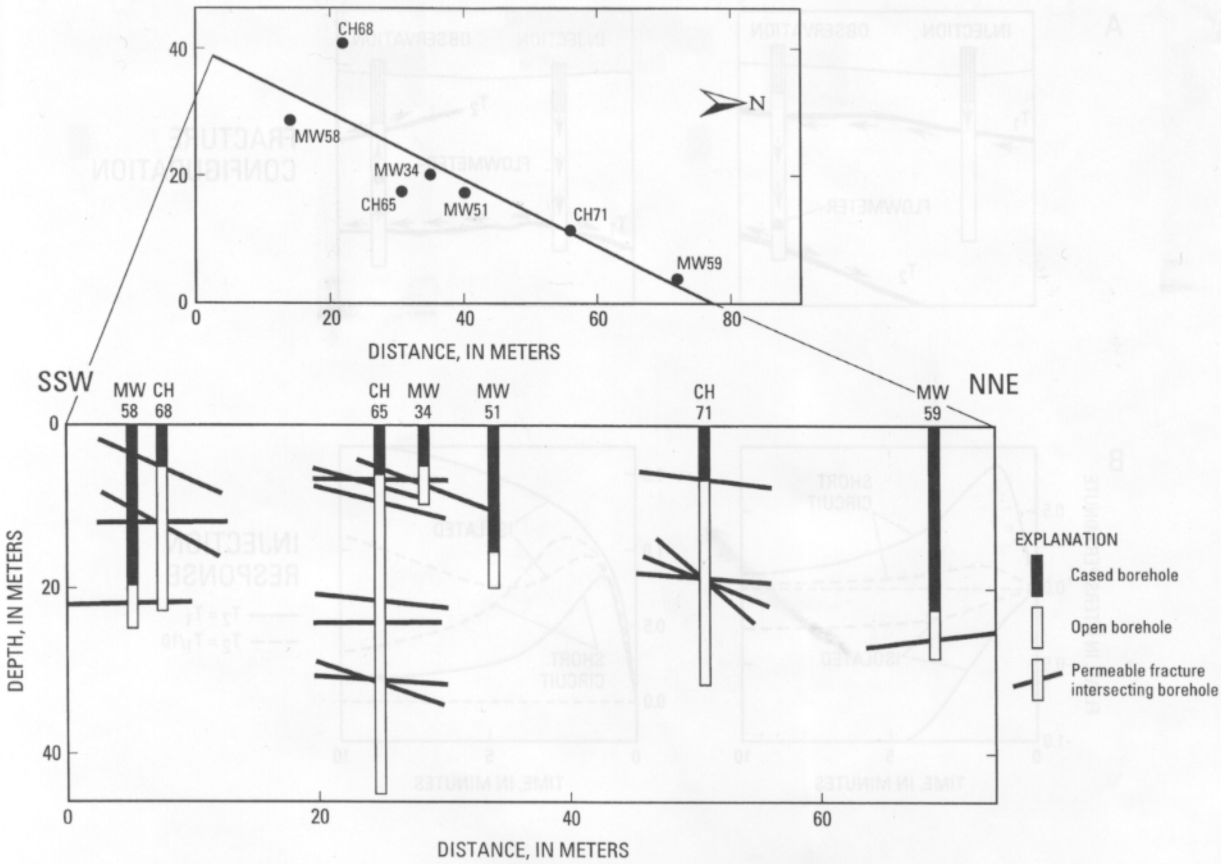

Fig. 8. Cross-section through the study site showing the projection of transmissive fractures identified in individual boreholes projected into the region between boreholes to indicate possible fracture flow paths.

results. Therefore, the flowmeter pulse tests are capable of indicating where connections exist between fractures in adjacent boreholes, and whether there are undetected cross-connections between sets of fractures in the surrounding area.

The analysis of the Watervliet cross-borehole pulse tests consisted of matching model predictions to the series of flow measurements made as a function of the time after the beginning or end of injecting. Injection rate, borehole separation, and wellbore storage are fixed quantities, while transmissivity and storage coefficient values can be varied until the mean-square difference between model prediction and measured data point approaches a minimum. However, the preceding single-borehole tests have already given estimates for transmissivity for each water-producing fracture in the stressed and observation boreholes. Therefore, the T values for the cross-borehole tests are constrained to these values. The analysis consists of using these T estimates in the model, and adjusting fracture storage coefficients to minimize the difference between model prediction and data. The fact that the general shape of the model response agrees with the distribution of measured data points adds further confidence in the interpretation. Then, the T estimates used in the model can be adjusted to further improve the agreement between model and data. This additional adjustment in T values can be made on the grounds that the cross-borehole test samples a somewhat different and generally larger region of the otherwise heterogeneous distribution of fracture permeability in the region connecting stressed and observation boreholes (Paillet, 2001).

The results of the cross-borehole flow experiments at the Watervliet Arsenal site are summarized in Table 3. These results are based on matching computed type

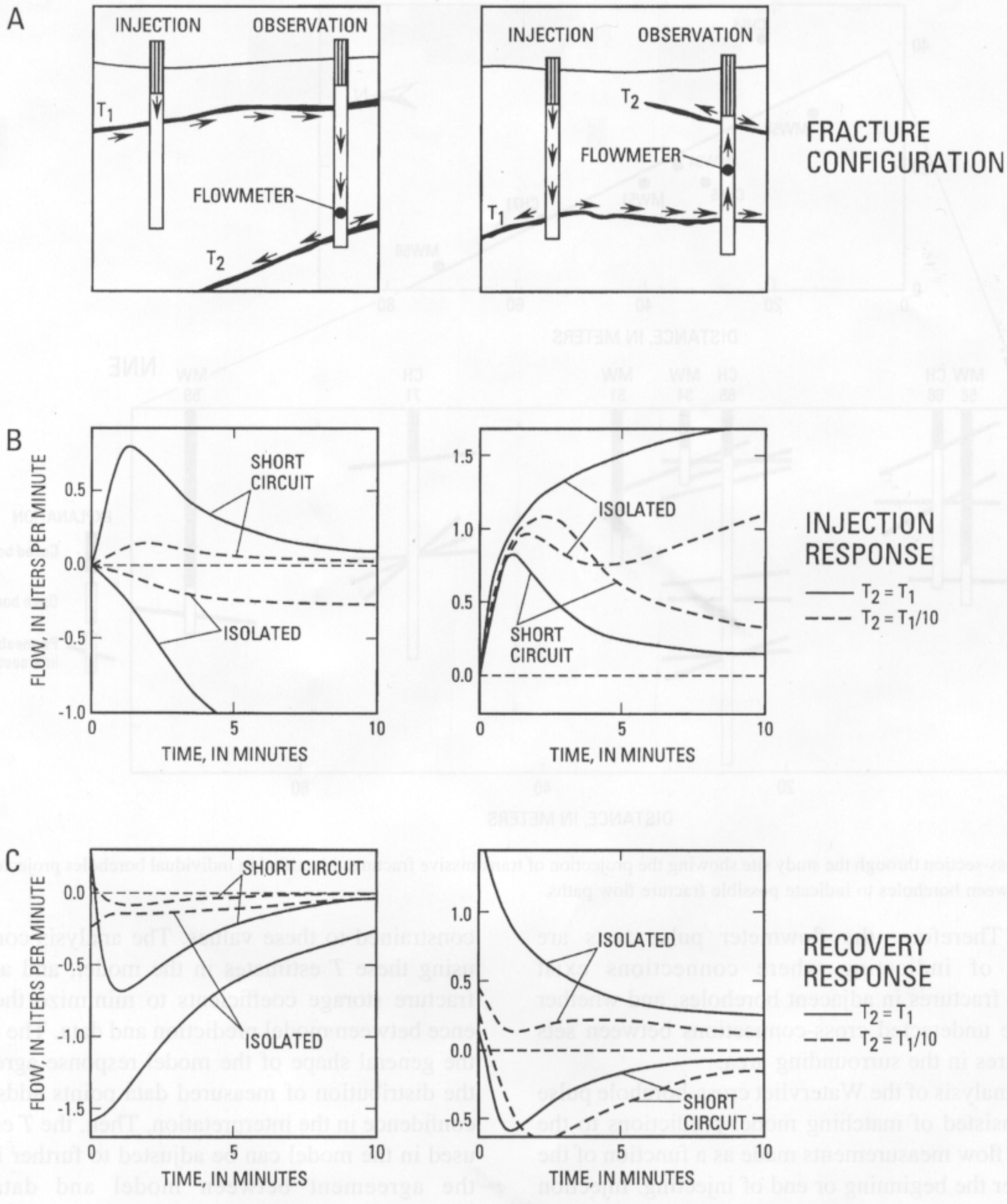

Fig. 9. Schematic illustration of fracture connections and type curves for flow transient response during cross-flow injection tests where fracture pairs are either isolated or short circuited: (A) possible facture connections with either shallow primary fracture connection inducing flow to a deep secondary fracture in the observation borehole, or deep primary fracture connection inducing flow to a shallow fracture in the observation borehole; (B) response to injection in the stressed borehole; and (C) response during recovery after injection ceases. Type curves are computed for cases where all fracture S values are 10^{-5}, the primary fracture transmissivity (T_1) is 100×10^{-6} m^2/s, and the secondary fracture transmissivity (T_2) is equal to that of the primary fracture (solid curves) or one tenth of that of the primary fracture (dashed curves).

Table 3
Summary of fracture connections in the Watervliet boreholes determined from flowmeter pulse tests

Stressed borehole number	Stressed interval below land surface (m)	Observation borehole number	Response interval below land surface (m)	Hydraulic transmissivity (m^2/d)	Connection storage coefficient
MW34	7.3	CH71	19.8	14	5×10^{-5}
MW34	7.3	CH65	6.0–12.0	9.3	5×10^{-5}
MW59	27.9	CH71	19.8	21	5×10^{-5}
MW59	27.9	CH65	6.0–12.0	23	1×10^{-5}
CH65	6.0–12.0	CH71	19.8	9.3	5×10^{-5}
CH65	20.0–35.0	CH71	19.8	7.4	1×10^{-4}
CH65	20.0–35.0	MW58	23.0	–[a]	–[a]

[a] Flow too small to detect with flowmeter, but connection verified by measured changes in water level in MW58 during pumping of CH65 from interval below packer.

curves to measured flow data for appropriate type curves based on known injection rates and borehole spacing (Fig. 10). The measured responses in various observation boreholes during the pulsed injection experiments indicate that there is a continuous fracture zone connecting coreholes 65 and 71 and monitoring wells 34, 58, and 59. For example, the flow in corehole 71 at a depth station between the two permeable fractures in that borehole matches the type curve for a direct fracture connection between the stressed borehole, monitoring well 34, and the observation borehole. The response can be modeled as a single fracture connecting the two boreholes, or as a case where both fractures in corehole 71 are connected to the fracture in monitoring well 34 (Fig. 10(A)). The single fracture type curve response is computed as the limiting case where the transmissivity of the second fracture is reduced to zero. The results clearly show that the connection is directly through the deeper fracture zone in corehole 71, and not through the upper fracture alone (the isolated fracture case). In these experiments, coreholes 68 and 72 did not have any measurable connection with any of the other boreholes. This lack of connection is indicated by the absence of induced flow by the stressing of monitoring wells 34 and 59, and by water level measurements that would have shown the existence of hydraulic connections too small to be detected with the flowmeter.

The flow induced at stations between the two upper permeable fractures and the three lower permeable fractures in corehole 65 when water is injected in monitoring well 34 shows an initial response close to the isolated fracture type curve. However, the measured flow levels off after about 3 min of pumping. The response to recovery also 'overshoots' the expected simple relaxation of the flow. Both of these results are taken to indicate that the elevated hydraulic head induced by the injection has found an indirect path to the deeper fractures in corehole 65. Although none of the detected water-producing fractures shown in Fig. 8 indicate such a connection, the flowmeter pulse test in Fig. 10(B) shows that this connection does exist.

A similar result was obtained during pulsed injection in monitoring well 59, with flow measurement in coreholes 65 and 71. The flow measured at a station between the two permeable fractures in corehole 71 falls midway between type curves for isolated and short circuited cases, where the primary connection is through the deeper fracture (Fig. 10(C)). The flow measured at a station between the upper and lower sets of fractures in corehole 65 also indicates a connection between the upper and lower fracture sets that is not otherwise indicated by the geophysical data (Fig. 10(D)). The flow response again shows an abrupt departure from the type curve, and an overshoot of flow during the recovery part of the transient. Thus, the flowmeter pulse flow data consistently indicate that there are permeable cross-connections between the major water-producing fractures identified in the single-borehole measurements.

The overall flowmeter interpretation indicates a single highly permeable fracture zone connecting

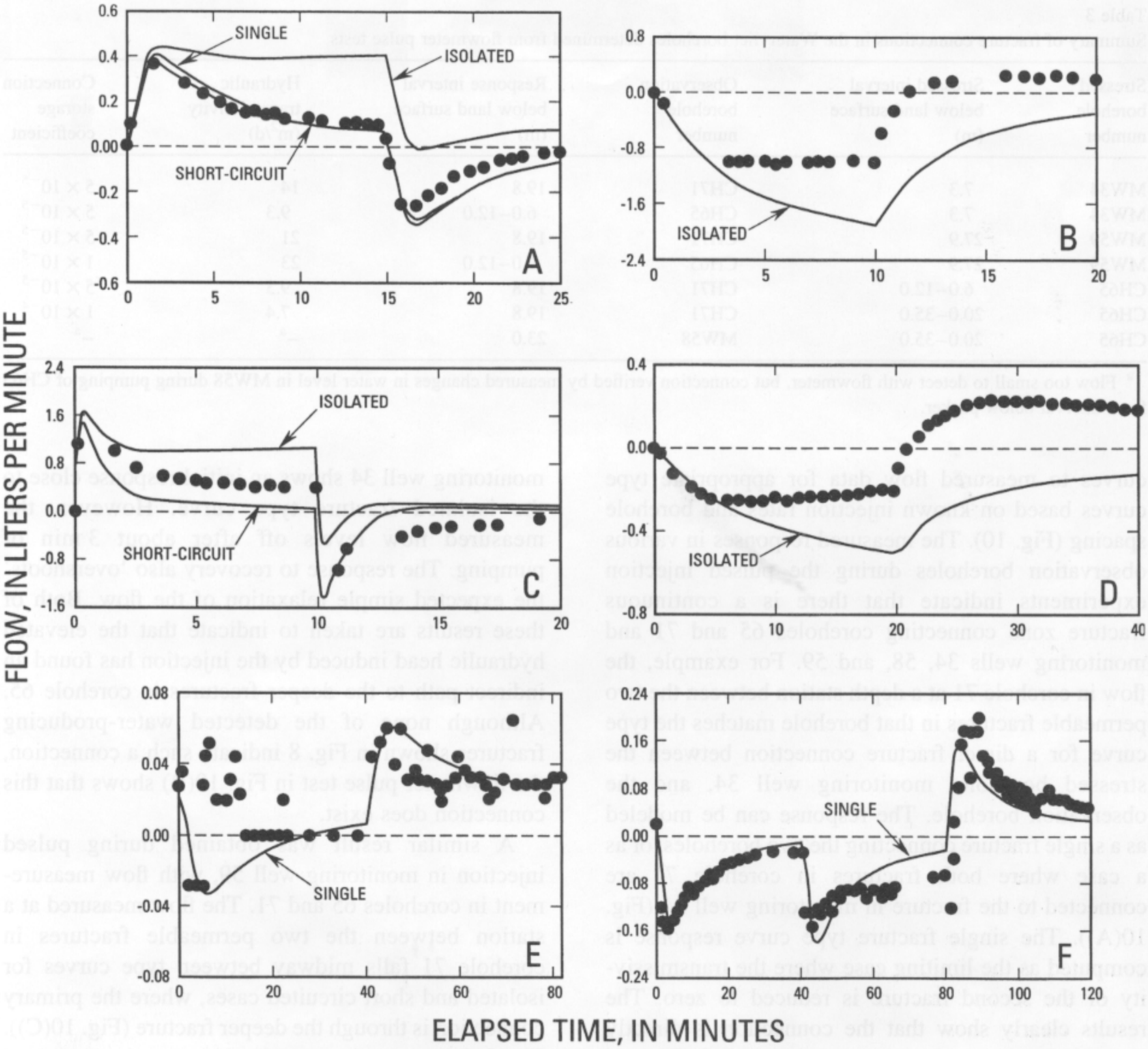

Fig. 10. Cross-flow experiments at the Watervliet site: (A) injection in monitoring well 34 and flow measured at 15 m in corehole 71; (B) injection in monitoring well 34 and flow measured at 15 m in corehole 65; (C) injection in monitoring well 59 and flow measured at 15 m in corehole 71; (D) injection in monitoring well 59 and flow measured at 15 m in corehole 65; (E) pumping from below a packer set at 20 m in corehole 65 and flow measured at a depth of 15 m in corehole 71; and (F) pumping from above a packer set at 15 m in corehole 65 and flow measured at a depth of 15 m in corehole 71.

coreholes 65 and 71 and monitoring wells 34 and 59. This zone is embedded in network of less permeable fractures. The hydraulic-head differences for individual fractures estimated from single-hole flowmeter log analysis indicate an upward hydraulic-head difference of about 20 cm in the upper 15 m of the shale bedrock, corresponding to an upward-directed vertical head gradient of about 0.015. The smaller head gradients inferred from the single-hole flow tests in coreholes 65 and 71 probably result from the existence of hydraulic connections between the apparently isolated fractures intersected by those coreholes.

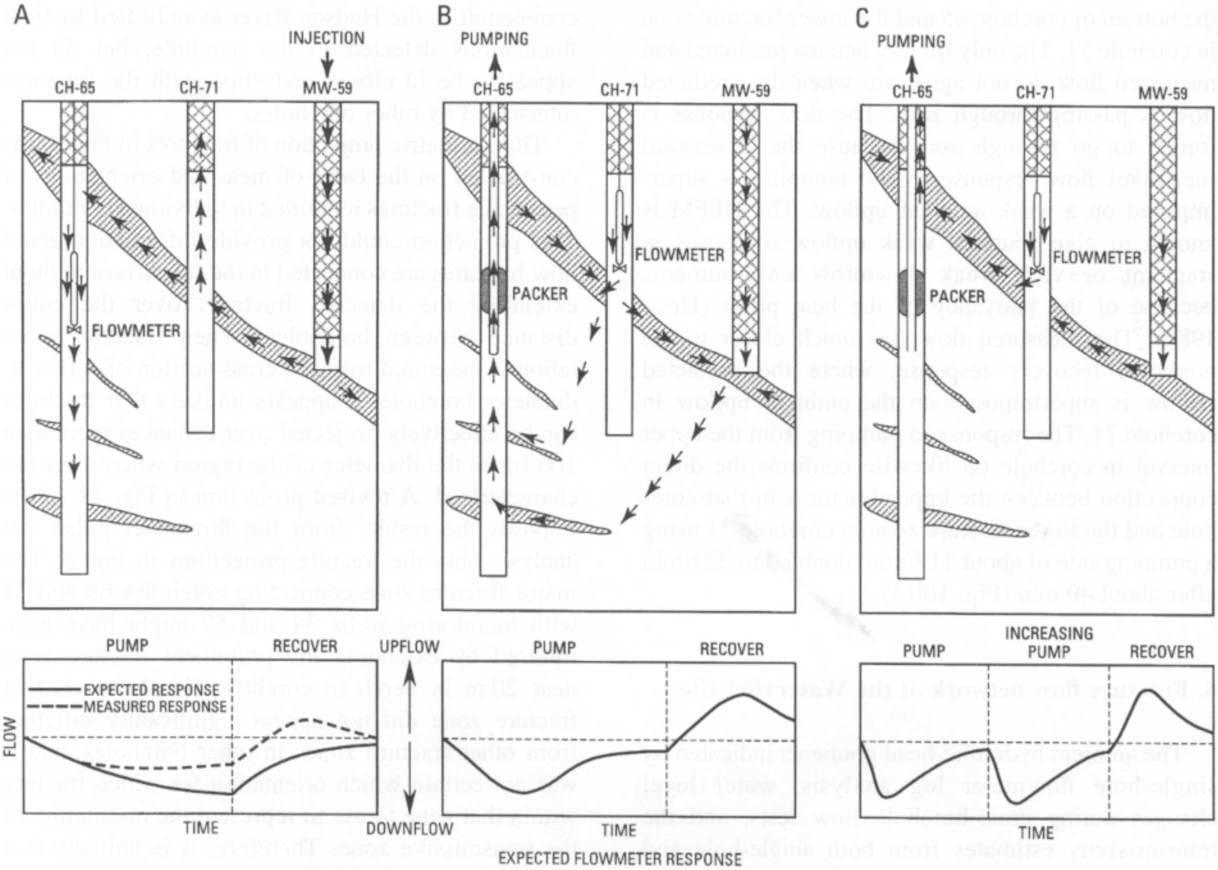

Fig. 11. Verification of hidden fracture connections in the vicinity of corehole 65, showing expected borehole flow and flowmeter measurements for (A) original open-borehole experiment; (B) pumping from below the packer in corehole 65; and (C) pumping from above the packer in corehole 65.

5. Verification of hidden fracture connections

The conclusion that the discrete fractures listed in Table 2 have additional cross-connections in the surrounding rock mass was tested by conducting additional flowmeter pulse tests. Previous tests indicated a hidden connection between the upper and lower fractures in corehole 65 (Fig. 11(A)). The cross-borehole flowmeter tests were repeated, with pumping applied sequentially to the zones in corehole 65 above (Fig. 11(B)) and below (Fig. 11(C)) a packer set at 15 m in depth. The inflated packer would prevent any communication between corehole 71 and the lower interval in corehole 65 via the direct fracture connection in the upper part of corehole 65. Therefore, any flow induced in corehole 71 by pumping from below the packer in corehole 65 would indicate the hidden flow path inferred from previous flowmeter pulse tests.

The predicted flow connection between the zone below the packer in corehole 65 and the lower fracture zone in corehole 71 was clearly verified (Fig. 10(E)). The pumping was restricted to about 4 l/min by the low transmissivity of the fractures in the lower part of corehole 65. The low pumping rate caused the induced flow in corehole 71 to fall close to the nominal 0.05 l/min detection limit of the HPFM, inducing relatively large scatter in the flowmeter data. The flow response in corehole 71 matches the expected type curve for a direct connection between the bottom of corehole 65 and the lower fracture zone in corehole 71. The only times when the predicted and measured flow do not agree are when the predicted flow is passing through zero. The flow response is forced to go through zero because the downward (negative) flow response to the pumping is superimposed on a weak ambient upflow. The HPFM is known to give spurious weak upflow responses in stagnant or very weak downflow environments because of the buoyancy of the heat pulse (Hess, 1986). The measured flow lies much closer to the predicted recovery response, where the predicted upflow is superimposed on the ambient upflow in corehole 71. The response to pumping from the upper interval in corehole 65 likewise confirms the direct connection between the upper fractures in that corehole and the lower fracture zone in corehole 71 using a pumping rate of about 11 l/min, doubled to 22 l/min after about 40 min (Fig. 10(F)).

6. Fracture flow network at the Watervliet site

The ambient hydraulic-head gradients indicated by single-hole flowmeter log analysis, water level changes during cross-borehole flow tests, and the transmissivity estimates from both single-hole and cross-borehole test provide a consistent picture of the hydrology of the fracture network intersected by the monitoring wells and coreholes at the Watervliet Arsenal site. The fracture network includes a highly transmissive zone of well-connected fractures that is intersected at 7.5 and 28 m in monitoring wells 34 and 59, and at 7.5–10.5 and 20 m in coreholes 65 and 71, respectively. The hydraulic connections between the fractures in monitoring well 59 and corehole 71 appears to be the most direct of this well-connected zone, even though the borehole image logs show that this is not a single large fracture connecting the two boreholes. The major fracture zone, which extends for more than 60 m across the site, is less directly but still well-connected to fractures below 24 m in corehole 65. The transmissive fractures at 6 and 14 m in corehole 68 appear weakly connected to the fractures intersected by the other boreholes, and they are vertically less connected to each other than the upper and lower fractures in coreholes 65 and 71. The transmissive fractures in corehole 72 are in hydraulic connection to the Hudson River as indicated by tidal fluctuations detected in the borehole, but do not appear to be in close connection with the fractures intersected by other boreholes.

The geometric projection of fractures in Fig. 8 was constructed on the basis of measured orientations of permeable fractures identified in individual boreholes. This projection could not provide information about how fractures are connected in the subsurface without extending the detected fractures over the entire distance between boreholes. When fracture orientation is measured over the cross-section of a 10-cm-diameter borehole, it appears unlikely that fractures can be effectively projected over distances more than 100 times the diameter of the region where they are characterized. A revised projection in Fig. 12 superimposes the results from the flowmeter pulse test analysis onto the fracture projections in Fig. 8. The major fracture zone connecting coreholes 65 and 71 with monitoring wells 34 and 59 might have been inferred by extending the prominent fracture zone near 20 m in depth in corehole 71. However, that fracture zone did not appear significantly different from other fracture zones in other boreholes, and it was not certain which orientation for which fracture within that zone to use to represent the orientation of the transmissive zone. Therefore, it is unlikely that this projection would have been made without the direct and unambiguous demonstration that a strong hydraulic connection exists given by the cross-borehole flowmeter pulse tests.

The cross-borehole flowmeter tests also demonstrate that there is a significant upward-directed hydraulic-head gradient at the Watervliet site. In the one borehole, corehole 68, where water level measurements during aquifer pulse testing demonstrate that there are two fracture zones isolated from each other and from other fractures in the system, there is about 20 cm of head decrease over 15 m of depth. Upward flow was detected in two other boreholes, coreholes 65 and 71, and was associated with head differences of at most a few centimeters. However, cross-borehole experiments indicate that the apparently isolated fractures in these boreholes are connected by other undetected fractures. If there is an upward hydraulic-head gradient, and if these fractures are connected into a network, then the head differences along the borehole are being

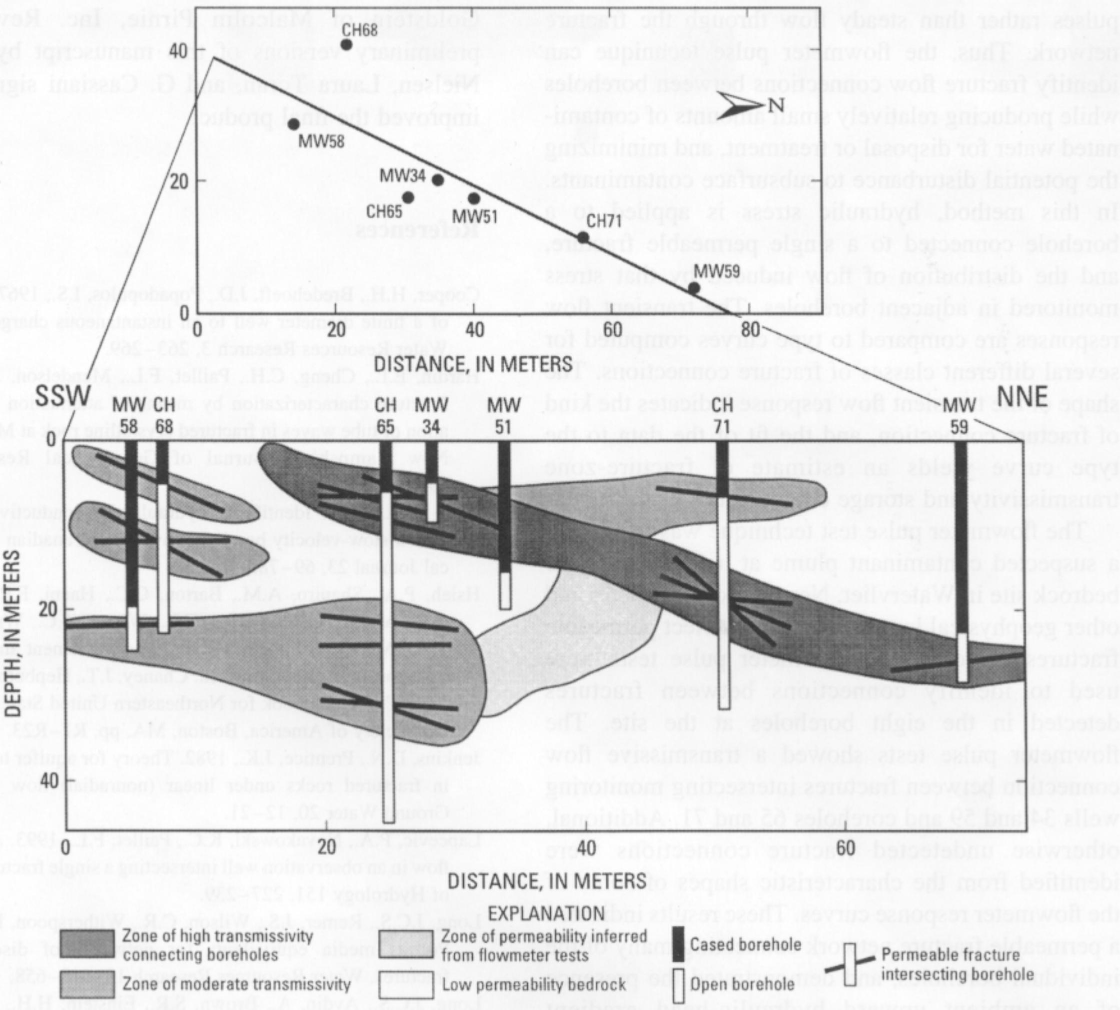

Fig. 12. Cross-section through the study site showing the connections between transmissive fractures identified in individual boreholes determined from the cross-borehole flowmeter experiments at the Watervliet site.

short-circuited by the background flow, and are not a true representation of the regional hydraulic-head gradient. That is, if the fractures are hydraulically connected and there is a hydraulic head gradient within the fracture network, then Darcy's law indicates that the head differences are driving ambient flow through the fracture system. According to these arguments, there is ongoing upward circulation of ground water through the suspected plume region at the Watervliet study site, driven by an upward gradient of about 0.015.

7. Summary

Conventional aquifer tests may not be possible at contaminated sites where such tests produce large amounts of water for disposal or treatment, or where pumping may otherwise disturb a poorly defined plume. Flowmeter pulse tests define subsurface connections between discrete fractures using short periods of pumping to monitor the propagation of the pulse through the fracture flow system. The method is based on the concept of monitoring the propagation of pulses rather than steady flow through the fracture network. Thus, the flowmeter pulse technique can identify fracture flow connections between boreholes while producing relatively small amounts of contaminated water for disposal or treatment, and minimizing the potential disturbance to subsurface contaminants. In this method, hydraulic stress is applied to a borehole connected to a single permeable fracture, and the distribution of flow induced by that stress monitored in adjacent boreholes. The transient flow responses are compared to type curves computed for several different classes of fracture connections. The shape of the transient flow response indicates the kind of fracture connection, and the fit of the data to the type curve yields an estimate of fracture-zone transmissivity and storage coefficient.

The flowmeter pulse test technique was applied to a suspected contaminant plume at a fractured shale bedrock site in Watervliet, New York. Flowmeter and other geophysical logs were used to detect permeable fractures in boreholes. Flowmeter pulse tests were used to identify connections between fractures detected in the eight boreholes at the site. The flowmeter pulse tests showed a transmissive flow connection between fractures intersecting monitoring wells 34 and 59 and coreholes 65 and 71. Additional, otherwise undetected fracture connections were identified from the characteristic shapes of some of the flowmeter response curves. These results indicated a permeable fracture network connecting many of the individual boreholes, and demonstrated the presence of an ambient upward hydraulic-head gradient throughout the site. All of this was accomplished without producing large quantities of contaminated water for disposal or treatment, and with minimal disturbance to the contaminant plume known to exist at the Watervliet site.

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