Effects of Anisotropic Transmissivity on a Contaminant Plume at Nemo, South Dakota

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Key Terms: *Transmissivity, Anisotropy, Contaminant Plume, Ethylene Dibromide, Metamorphic Rocks, Black Hills*

ABSTRACT

In 1996 low concentrations of ethylene dibromide (EDB) were found in thirteen domestic water wells in Precambrian metamorphic rocks at Nemo, South Dakota. The source of the contaminant is believed to be the result of pesticides disposed at a U.S. Forest Service Work Station area in the 1970s. Monitoring wells were installed and ground water from nine of them contained EDB. Sixteen additional wells within three kilometers of Nemo were sampled but EDB was not detected. Water in two domestic wells one kilometer south-southeast of Nemo had high concentrations, 13 and 2.2 micrograms per liter of EDB. The impacted landowners were initially provided bottled water by the USFS. The USFS then drilled new wells outside of the contaminant plume which now provide water to the impacted landowners.

An equipotential map indicates that ground water should flow easterly. However the contaminant plume extends towards the south-southeast, in the direction as the foliation in the Precambrian phyllite and quartzite at Nemo. This foliation strongly influences the direction of contaminant migration. Based on an equipotential map and the known plume orientation, a graphical solution of the transmissivity anisotropy indicates that the major transmissivity is oriented N10°W and is approximately 0.73 m^2/d. The minor transmissivity is perpendicular to this and is approximately 0.13 m^2/d. A computer solution utilizing anisotropic transmissivity generated a plume which agrees with the field data.

INTRODUCTION

Nemo is a very small community located in the Black Hills, approximately 30 km northwest of Rapid City, South Dakota (Figure 1). In 1996 it was discovered that some private wells in Nemo contained ethylene dibromide (EDB). EnviroSearch International, Boise, Idaho, was hired by the U. S. Forest Service to define the extent of the contamination and to identify alternative water supplies for the impacted residences.

GEOLOGY

Figure 2 is a geologic map of the Nemo area. The bedrock is Precambrian metamorphic rock including phyllite, quartzite, marble, amphibolite, and taconite of the Boxelder Creek Formation (Redden, 1981, 1987). These meta-sedimentary rocks are nearly vertically dipping, and strike between 10 and 30 degrees west of north, averaging approximately N20°W. There are numerous folds and some cross faults. The Precambrian rocks are well exposed in some places, particularly on the ridges, but are covered by thin deposits of colluvium in many places. There is a well-developed foliation in the Precambrian metamorphic rocks that also strikes approximately the same direction as the bedding (N20°W). This foliation dips from 70°W to vertical. This prominent planar anisotropy is prevalent in the Precambrian metamorphic rocks throughout a wide area of the Black Hills (Lisenbee, 2000), extending from over 20 km north in the Lead area (DeWitt et al., 1989) to over 30 km south in the Rockerville area (Rahn, 1987). There are also numerous joints in the bedrock.

Unconformably overlying the Precambrian rock is the Deadwood Formation, a sandstone and shale. This unit crops out to the east and north of Nemo and is essentially not relevant to the focus of this paper which deals with the hydrogeology at Nemo.

Surficial deposits overlie the bedrock and include Quaternary terrace deposits and alluvium under the flood plain of Boxelder Creek and its tributaries. These Quaternary deposits are generally not more than 10 m thick. Thin colluvial deposits are also present but are not shown on Figure 2.

GROUND WATER

The average precipitation in this area is approximately 50 cm/year (Rahn and Davis, 1993). The metamorphic

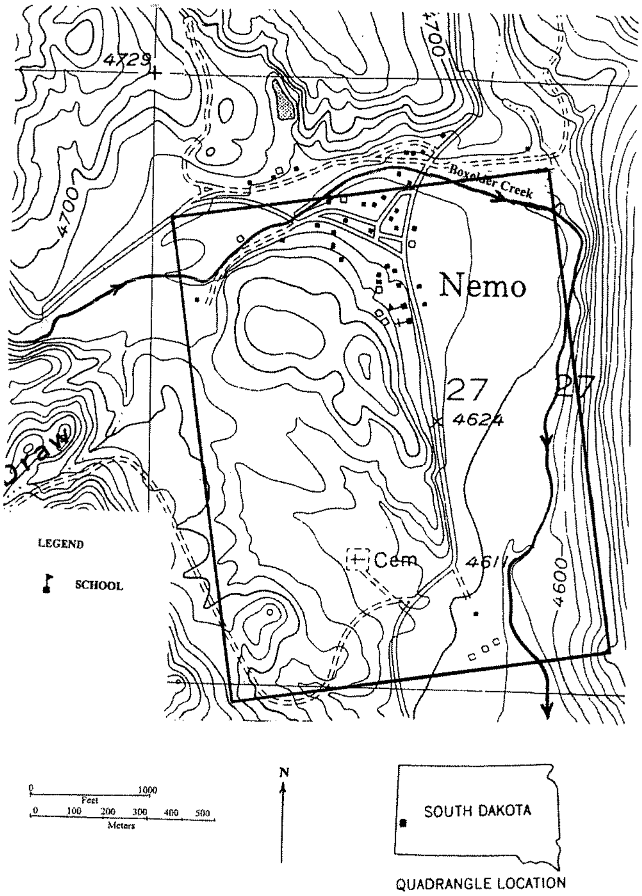

Figure 1. Topographic map of the Nemo area (from portions of the U. S. Geological Survey Nemo and Piedmont 7.5 minute quadrangles). Contour interval 20 ft. The rectangular box is the modeled study area (Figure 6).

rocks in the Black Hills generally have low permeability and most ground water available to wells in the Precambrian rocks is either obtained from overlying surficial deposits or from foliation fractures or joints in the metamorphic rocks (Rahn, 1994; Rahn and Gries, 1973; and Galloway and Strobel, 2000).

A major perennial stream, Boxelder Creek, flows through the town. In general, the water table is at the level of perennial streams such as Boxelder Creek, rising up under local positive topographic features. Water levels were obtained from numerous domestic wells near Nemo (Figure 3) and additional wells installed in 1996 by EnviroSearch. Because the surficial deposits are thin, the water table under the upland areas surrounding Nemo is within the Precambrian rocks. Using the Boxelder Creek elevation and the static level data from wells, a contour map of the water table (equipotential surface) was prepared and is shown on Figure 3. Since Boxelder Creek is an effluent (gaining) stream, the equipotential surface is drawn so that Boxelder Creek is shown to be receiving ground water from adjacent upland areas.

CONTAMINANT PLUME

The pesticide EDB was initially detected in nine domestic wells (Table 1). These local wells are completed within the bedrock and average approximately 30 m total depth. The federal drinking water "Maximum Contaminant Level" (MCL) for EDB is 0.05 ug/L (EnviroSearch, 1998). In addition to EDB, other volatile organic compounds (trihalomethanes) were detected in the Spliess and Langley wells. According to EnviroSearch (1997), "In the mid 1970s Forest Service personnel reportedly mixed and applied pesticides to trees in the Black Hills National Forest to fend off a bark beetle infestation in the area. Available information indicates containers and left over pesticides (EDB and Lindane mixed with diesel fuel and water) were disposed of at the Nemo Work Station. The exact disposal location(s) are reported to be directly west of the work station; however they have not been identified." The USFS began supplying the impacted residences with bottled water and in 1999 drilled a new water well outside of the contaminant plume and installed a water lines to these residences.

Figure 4 shows the EDB contaminant plume. The pesticide disposal point is assumed to be close to the USFS Work Station, approximately 250 m west of the school as shown in Figure 4. Of particular interest are the high concentrations of two residences (Kaberna and Weston) located 1 km south of Nemo. If one simply used the equipotential surface to determine a flow path from the disposal point it would indicate the contaminants should go roughly easterly (in a S80°E direction) from the disposal point. However, Figure 4 shows that the high EDB concentrations extend from the disposal point towards the south-southeast, trending S30°E. This direction is obviously strongly influenced by the orientation of the foliation and lithologies of the Precambrian rocks.

TRANSMISSIVITY ANISOTROPY

Ethylene dibromide is a constituent of many pesticides. According to Fetter (1993), "Chlorine and bromine are components of halogenated organic compounds used for industrial solvents and pesticides...Chloride and bromide ions are not reactive. They don't precipitate in redox reactions, aren't sorbed onto mineral organic surfaces, and don't form insoluble precipitates. Chloride is sometimes used as a tracer in ground-water studies because it is conservative." The adsorption of dissolved molecular organic substances by soils and sediment has been found to be proportional to the amount of organic matter present (Langmuir, 1997). Very little organic matter would be present in the Precambrian rocks at Nemo, and hence it is reasonable to assume that very little sorption occurs. Therefore for this study it is assumed that the velocity of the contaminant plume can be used to determine the transmissivity of the metamorphic rocks.

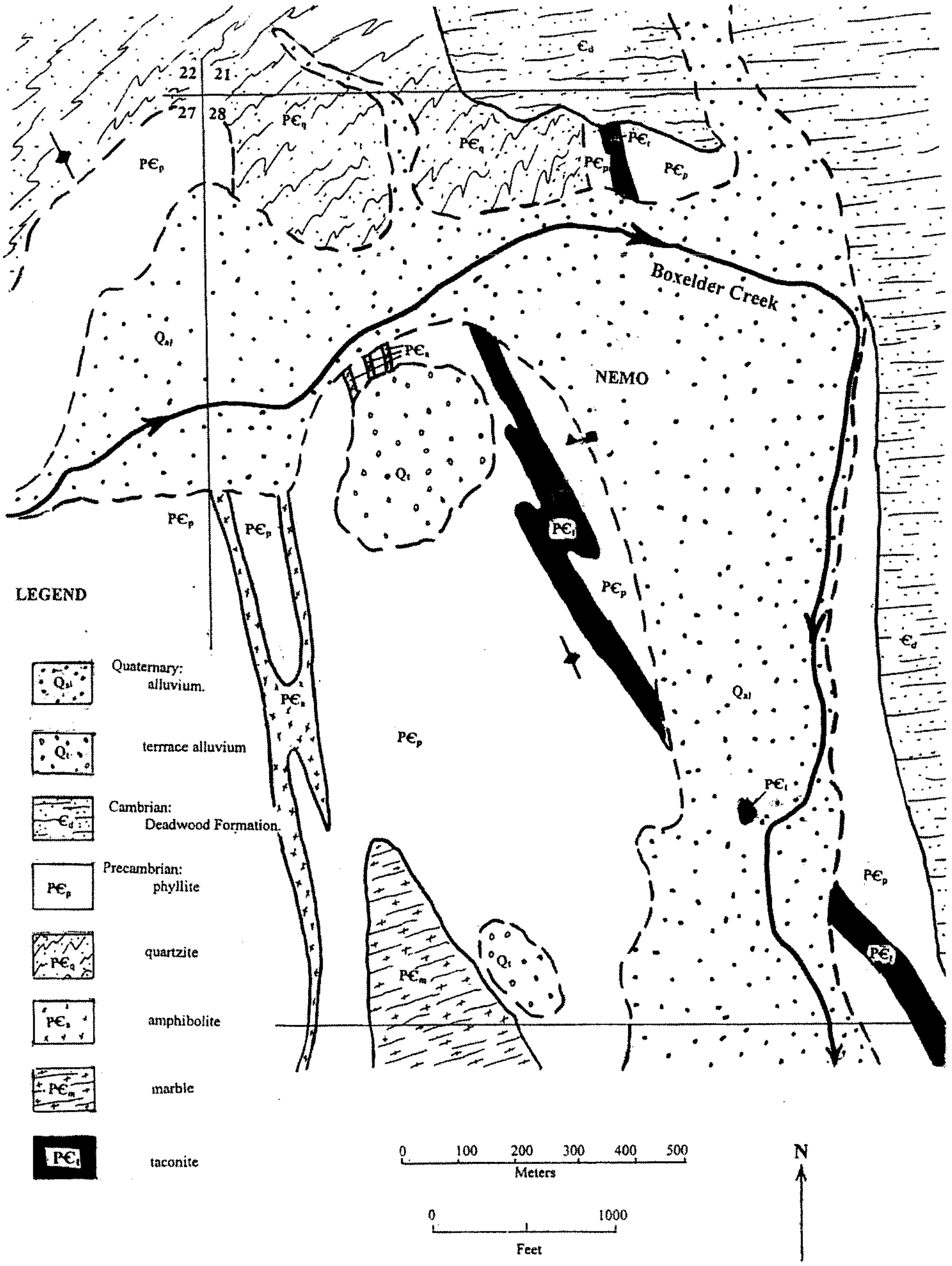

Figure 2. Geologic map of the Nemo area (modified from Redden, 1981). The Nemo school (from Figure 1) is shown as a reference point.

Following conventional Darcy Law equations (Freeze and Cherry, 1979; Domenico and Schwartz, 1990; and Rahn, 1996), an estimate of the transmissivity of the metamorphic rocks can be made using the contaminant velocity. If the contaminant took approximately 25 years to travel 1 km to the Kaberna residence, then the true velocity (V_t) is 40 m/yr or 0.11 m/d. Assuming an effective poro-sity (n_e) of 0.01, the Darcy velocity (V_t) can be determined:

$$V_d = V_t\ (n_e) = 0.11 \text{ m/d } (0.01) = 0.0011 \text{ m/d} \qquad \text{Eq. 1}$$

From Figure 3, the potentiometric surface slopes in the plume direction at a gradient of 0.015. Therefore, from Darcy's Law, the hydraulic conductivity (K) can be determined:

$$V_d = K\ (H/L) \qquad \text{Eq. 2}$$

Therefore:

$$K = 0.0011 \text{ m/d } /0.015 = 0.073 \text{ m/d} \qquad \text{Eq. 3}$$

Using an estimated saturated thickness of 10 m, the transmissivity (T) can be determined:

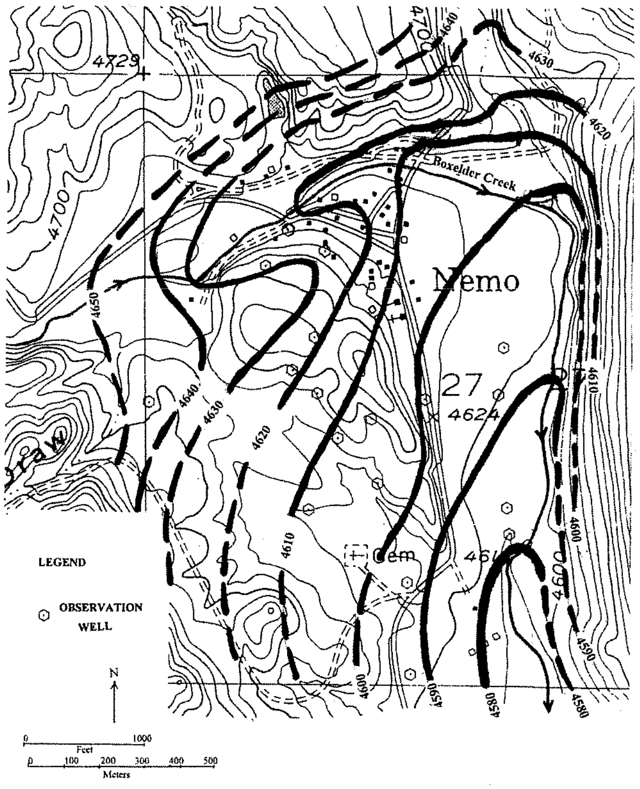

Figure 3. Potentiometric surface (feet above sea level) of the water table in the Nemo area.

$$T = K\ (b) = 0.073\ \text{m/d}\ (10\ \text{m}) = 0.73\ \text{m}^2/\text{d} \qquad \text{Eq. 4}$$

This transmissivity is nearly the same as the major transmissivity of the bedrock.

Unlike ground-water flow in isotropic media, the flow vectors in anisotropic media are not perpendicular to equipotential lines (Freeze and Cherry, 1979; Domenico and Schwartz, 1990). In fact, where very strong anisotropic transmissivity exists, flow vectors may be nearly parallel to equipotential lines. The flow direction is influenced by both the hydraulic gradient and the transmissivity anisotropy.

At Nemo, the foliation in the Precambrian rocks causes the ground-water flow direction to depart from the direction of the hydraulic gradient as deduced from the equipotential lines. Using a graphical analysis as shown in Freeze and Cherry (1979), it is possible to calculate the transmissivity anisotropy in the Precambrian rocks. This graphical analysis is similar to those used for seismic ray vectors in anisotropic media (Slawinski et al., 2000). The direction of the hydraulic gradient in this area is S80°E (Figure 3); this vector is drawn through the origin of a yet-to-be-defined ellipse (Figure 5). The S30°E flow contaminant vector (as shown by the contaminant movement from Figure 4) is also plotted through the origin of a yet-to-be-defined ellipse, and a perpendicular line is extended to the hydraulic gradient vector (point "A" on Figure 5). A complete ellipse is then constructed so that point "A" defines a point of tangency to the ellipse. Mathematically an ellipse constructed in this manner is not unique (Rahn and Opp, in preparation). Actually a family of ellipses can be constructed, and their long axes would be oriented roughly in an east-west direction. Specifically their strike would range from N80°W to N60°E. Therefore the minor axes of these ellipses (hence the T_{max} orientation) would be roughly in a north-south direction, ranging from a strike of N10°E to N30°W. The mid-value of T_{max} would be oriented N10°W. The shape and orientation of this ellipse is shown in Figure 5. The minor axis of this ellipse is the direction of the major transmissivity (T_{max}); the minor transmissivity (T_{min}) is perpendicular to T_{max}. The major transmissivity tensor direction agrees closely with the strike of the foliation and lithologic units in the Precambrian rocks.

The relative lengths of the ellipse axes can be used to solve for the relative values of the transmissivity anisotropy as follows:

$$\text{The minor } (b) \text{ axis} = 1/(T_{max})^{0.5} \qquad \text{Eq. 5}$$

$$\text{and the major } (a) \text{ axis} = 1/(T_{min})^{0.5} \qquad \text{Eq. 6}$$

In this case the ellipse has a minor axis 2.34 times as long as the major axis. Therefore the ratio of the transmissivities is:

$$T_{max}/T_{min} = (1/a\ \text{axis})^2/(1/b\ \text{axis})^2 = (1/1)^2/(1/2.34)^2 = 5.48 \qquad \text{Eq. 7}$$

Thus the major transmissivity is approximately 5.5 times as great as the minor transmissivity. Using the transmissivity derived from the contaminant travel time (from above), reasonable estimates of the anisotropic transmissivities are:

$$T_{max} = 0.73\ \text{m}^2/\text{d} \qquad \text{Eq. 8}$$
$$T_{min} = 0.13\ \text{m}^2/\text{d} \qquad \text{Eq. 9}$$

COMPUTER MODEL

Within the Nemo area, a study area was selected and modeled using Visual MODFLOW (Konikow et al., 1996; Guiguer and Franz, 1997). Initially the study area was modeled assuming isotropic conditions. The model grid was established using a north-south orientation. The geologic map was used to create various conductivity zones; these zones were adjusted to simulate the potentiometic map (Figure 3). Various transmissivity zones were created using the geologic map. The zones varied from 0.1 to 10 m/d. The grid was set up so that the outermost boundary of the potentiometric map would

Table 1. *Water quality from selected wells (ug/L). From EnviroSearch International (1998).*

Sampling Location	Date of Laboratory Submittal	EDB	Benzene	Toluene	Ethyl-benzene	Total Xylenes	Naphtha-lene	1,2,3-Trichloro-benzene	Isopropyl-benzene (Cumene)	Trichloro-ethene	Bromo-dichloro-methane	Bromo-form	Chloro-form	Dibromo-chloro-methane
Adams Elton	10/08/96	0.92–0.93	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/16/96	0.86	<0.20	<0.20	<0.20	<0.20	<0.50	<0.50	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
	05/27/97	0.73	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Atkinson	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Church	10/08/96	1.3–1.8	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/16/96	1.4	<0.20	<0.20	<0.20	<0.40	<0.50	<0.50	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
	05/27/97	0.29	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Cooper Derrall	10/08/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Deverman #1	10/08/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	05/27/97	<0.020	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Deverman #2	10/08/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	05/27/97	<0.020	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Eggers	07/01/97	<0.020	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Fieron	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Fieron 2nd House	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Flak	03/28/97	<0.020	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
	05/19/97	0.018	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Flak Seep	05/19/97	0.069	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Ford	10/16/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Ford Shirley	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Hageman KC	10/08/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Kaberna	10/22/96	13	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/29/96	10	<0.20	<0.20	<0.20	<0.20	<0.50	<0.50	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
	03/25/97	9.4	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
	05/19/97	12	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Krahn	10/08/96	0.17	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/16/96	0.13	<0.20	<0.20	<0.20	<0.40	<0.50	<0.50	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
	07/01/97	0.045	<0.50	<0.50	<0.50	<1.00	<0.50	0.52	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Langley	10/16/96	<0.010	<0.20	<0.20	<0.20	<0.40	<0.50	<0.50	<0.20	<0.20	<0.20	<0.20	0.69	<0.20
	03/31/97	<0.020	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Martin	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Federal Drinking Water MCL		0.05	5	1,000	700	10,000	NA	NA	NA	5.0	NA	NA	NA	NA
RBC		0.00075	0.36	750	1300	1400	1500	NA	1500	1.6	0.17	2.4	0.15	NA
Post Office/Fire Dept	10/08/96	0.062	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/16/96	0.045	<0.20	<0.20	<0.20	<0.40	<0.50	<0.50	<0.20	0.27	<0.20	<0.20	<0.20	<0.20
	10/29/96	0.053	<0.20	<0.20	<0.20	<0.20	<0.50	<0.50	<0.20	0.22	<0.20	<0.20	<0.20	<0.20
	05/27/97	0.023	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
School	10/08/96	1.12	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/16/96	0.82	<0.20	<0.20	<0.20	<0.40	<0.50	<0.50	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
	06/25/97	1.1	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Smith	07/01/97	<0.020	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Spleiss House	10/08/96	0.47	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/16/97	1.0	<0.20	<0.20	<0.20	<0.40	<0.50	<0.50	<0.20	<0.20	0.28	2.8	0.85	0.96
	10/22/96	1.0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
TS–INF/Spleiss	05/22/97	3.6	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	1.20	<0.50	<0.50	<0.50	<0.50	<0.50
TS–EFF/Spleiss	05/22/97	<0.020	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Troxell / Keough	10/08/96	4.7–5.4	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/16/96	3.6	<0.20	<0.20	<0.20	<0.40	<0.50	<0.50	<0.20	<0.20	<0.20	<0.20	<0.20	<0.20
	05/27/97	5.4	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Troxell Lilian	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Troxell Buck	10/29/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Tungland	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Weston	10/22/96	2.2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	10/29/96	1.7	<0.20	<0.20	<0.20	<0.20	<0.50	<0.50	<0.50	<0.20	<0.20	<0.20	<0.20	<0.20
	05/19/97	0.28	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Witcap	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Zopp Donna	10/22/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Creek E & W of Nemo	10/08/96	<0.010	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
4 T Old	03/19/97	0.053	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Mine	03/19/97	<0.020	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Unknown well south of Hooper	03/19/97	<0.02	<0.50	<0.50	<0.50	<1.00	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50	<0.50
Federal Drinking Water MCL		0.05	5	1,000	700	10,000	NA	NA	NA	5.0	NA	NA	NA	NA
RBC		0.00075	0.36	750	1300	1400	1500	NA	1500	1.6	0.17	2.4	0.15	NA

NOTES:

NA – Not Analyzed or Not Applicable
TS – INF/Spleiss – Treatment System Influent
MCL – Maximum Contaminant Level
tr – trace; detected below the quantification limit
TS – EFF/Spleiss – Treatment System Effluent
RBC – Risk Based Concentrations from EPA Region III Table. Concentrations assume residential exposure by tap water ingestion.

become constant heads along the boundaries of the model. The contaminant plume was simulated at transient conditions for a period of 20 years. After this model was run it was found that the direction of the contaminant plume could not be matched to the true contaminant plume direction.

A new model was then set up so that anisotropic transmissivity conditions could be utilized over the entire modeled area. The study area was established so that the major transmissivity tensor direction is N10°W, as determined above from the above graphical analysis. It was therefore necessary for the entire study area grid to be oriented N10°W (Figure 6).

The elevation of the potentiometric surface (from Figure 3) was used to set constant heads along the borders of the grid. Because Boxelder Creek has hydraulic connection to this potentiometric surface, the water-surface elevations of Boxelder Creek were also used as constant

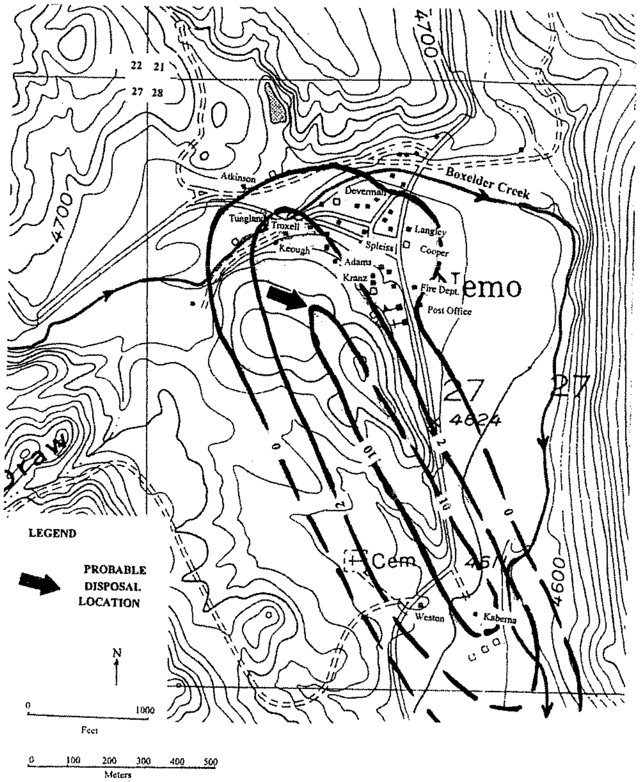

Figure 4. Map showing EDB plume (ug/L) in the Nemo area (modified from EnviroSearch International, 1998).

heads. Through computer simulations, the complete potentiometric surface was generated using anisotropic tensors. A good correlation was achieved between this generated potentiometric surface (Figure 6) and the actual potentiometric surface (Figure 3).

A contaminant plume was then generated by Visual MODFLOW using MT3D (Zheng, C. and Papadopulos, S. S. & Associates, Inc, 1990) assuming adsorption and chemical reactions are negligible. Using this anisotropic model, the modeled contaminant plume (Figure 6) is similar to the actual plume (Figure 4). The modeled plun trends S26°E, very close to the actual plume which tren S30°E.

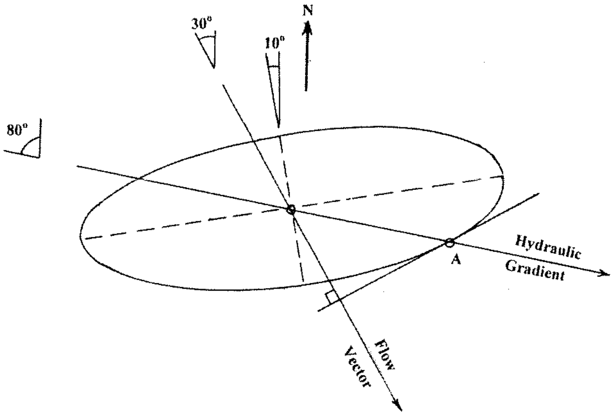

Figure 5. Graphical solution showing relationship of ground-water flow direction to hydraulic gradient and transmissivity anisotropy. See text for explanation.

SUMMARY AND CONCLUSIONS

Foliation, fractures, and other structural features i bedrock can have a profound effect on the movement c ground water. Anisotropic transmissivity can influenc the shape of the cone of depression around a pumpin well. For example, a pumping test in the Madison Limestone in Rapid City, SD, showed an elliptical cone c depression (Greene and Rahn, 1995); this directio coincides with the jointing and prominent passagewa orientation in nearby caves.

Structural anisotropy of the bedrock can also affec the direction of movement of contaminant plumes. In th Nemo case, the EDB plume did not trend directl downgradient in relation to the equipotential surface Rather, the flow was controlled by the foliation in th phyllite. The plume was strongly influenced by a transmissivity anisotropy and resulted in the contamination o domestic wells over a kilometer away.

This study shows that the geology must be carefully studied in order to assess the direction of movement of contaminants in ground water. Hydrogeologic models are only as good as the geologic input to them. Ground-water flow models should be utilized after thorough field mapping. In metamorphic terrain such as this, foliation should be carefully mapped, and factored into the model. If a tracer or contaminant plume is known, the transmissivity anisotropy can be determined; then the T_{max}/T_{min} ratio and orientation can be used to model other ground water flow situations in this terrain.

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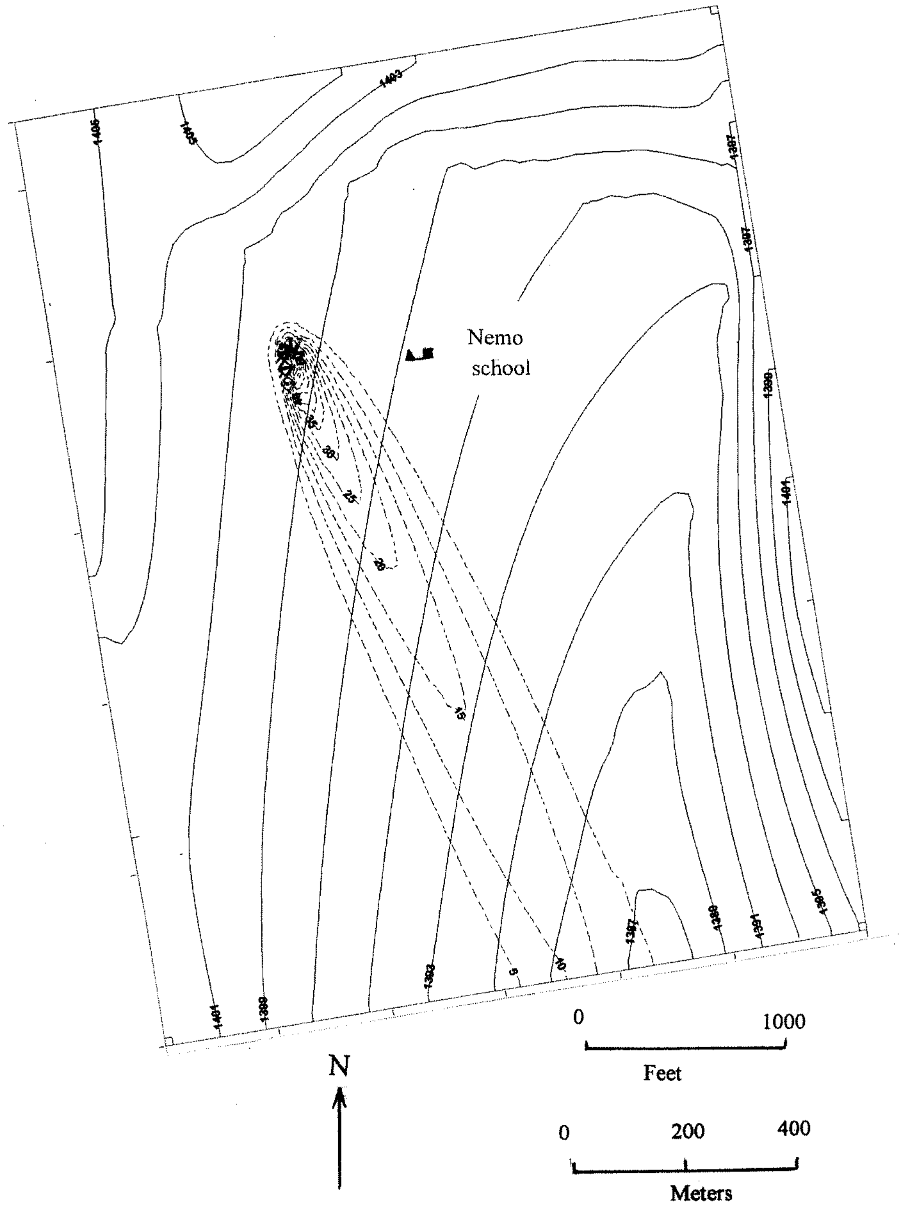

Figure 6. Map of study area using anisotropic model showing generated potentiometric surface (meters above sea level) and plume concentration (ug/L). The Nemo school is shown.

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