Modeling Structural Controls on Groundwater Flow and Solute Transport in Fractured Consolidated Rock Aquifers,

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Abstract

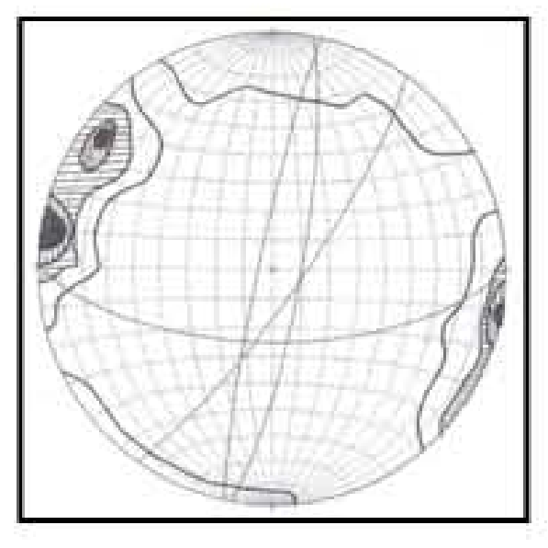
Groundwater-transmitting planar discontinuities in many bedrock formations consist primarily of non-random networks of genetically-related joints and bedding plane partings rather than the random systems of generic fractures assumed in certain fractured aquifer models. A method is presented by which groundwater flow direction and volume within each set of pervasive, sub-parallel planar discontinuities is defined by a calculated flow index, based on discontinuity orientation and spacing with respect to the average rock mass hydraulic gradient and average fracture aperture (for a simple cubic law approximation of Poiseuille hydraulic conductivity). Flow indices for principle discontinuity sets are superimposed by vector summation to obtain the direction and rate of the average flow through the fractured rock mass using only structural data for the formation. The anisotropic nature of the hydraulic conductivity tensor results in a calculated flow direction that is typically not aligned with the hydraulic gradient. The structurally based method described produces testable transport and deflection predictions without the need for costly aquifer testing to determine a priori the directional components of the hydraulic conductivity ellipse.

A case study is presented of a jointed formation in which groundwater is calculated to flow in a direction offset from that of the local hydraulic gradient; a direction confirmed with subsequent water quality monitoring. The model has been applied successfully to other sites with a variety of rock types and is currently being coded for computer based applications.

Conceptual Framework

Structural Geology Framework

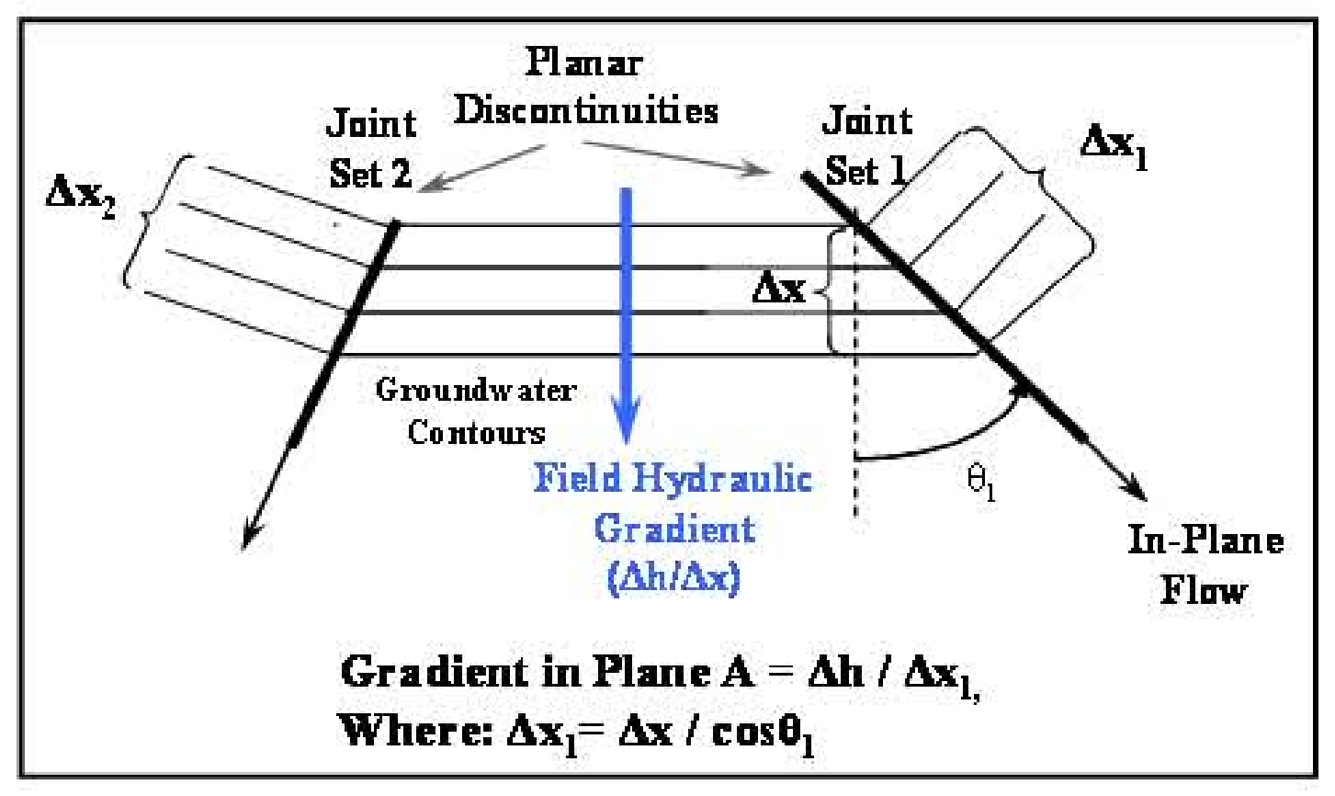
Volumetrically, groundwater-conducting planar discontinuities in rock masses tend to occur either as tectonically derived, pervasive, penetrative sets in which all discontinuities are at sub-parallel orientations and occur with statistically consistent frequency and lengths (joints) or in bedding plane partings, in the case of layered sedimentary formations. Faults tend to occur in non-penetrative systems of widely spaced zones and random, generic fractures comprise only a small percentage of discontinuities, mostly concentrated in the upper zones of formations, usually above the saturated zone. Consequently, groundwater flow is through a non-randomly distributed network of statistically regular planes.



Frequency contours of poles to planar discontinuities with great circles of means of partial distribution (lower hemisphere, equal area projection) – hypabyssal igneous intrusive complex, New Jersey

Flow in Non-Random Planes not Oriented with Field Gradient

Groundwater flow within an individual planar discontinuity is approximately sub-parallel to strike (see adjacent figure). The lesser the angle between the strike of a water-bearing discontinuity and the azimuth of the field hydraulic gradient, the greater is the correspondence between the equipotential lines of the overall flow field and those within the discontinuity, with maximum correspondence in a plane with a strike equal to the azimuth of the hydraulic gradient and least correspondence where strike and hydraulic gradient are normal.



Gradient in Plane A = $\Delta h / \Delta x_1$,
Where: $\Delta x_1 = \Delta x / \cos\theta_1$

A particle of water at the intersection of planes of Joint Sets 1 and 2 (see adjacent figure) could flow into either discontinuity but with a greater tendency to flow into the plane with the highest gradient. The azimuth of Joint Set 1 is at a lesser angle (θ_1) to the azimuth of the field hydraulic gradient than is that of Joint Set 2 (θ_2). Comparing the in-plane hydraulic gradients for planes and keeping Δx at unity, the gradient in Joint Set 1 exceeds that in Joint Set 2 by a factor of:

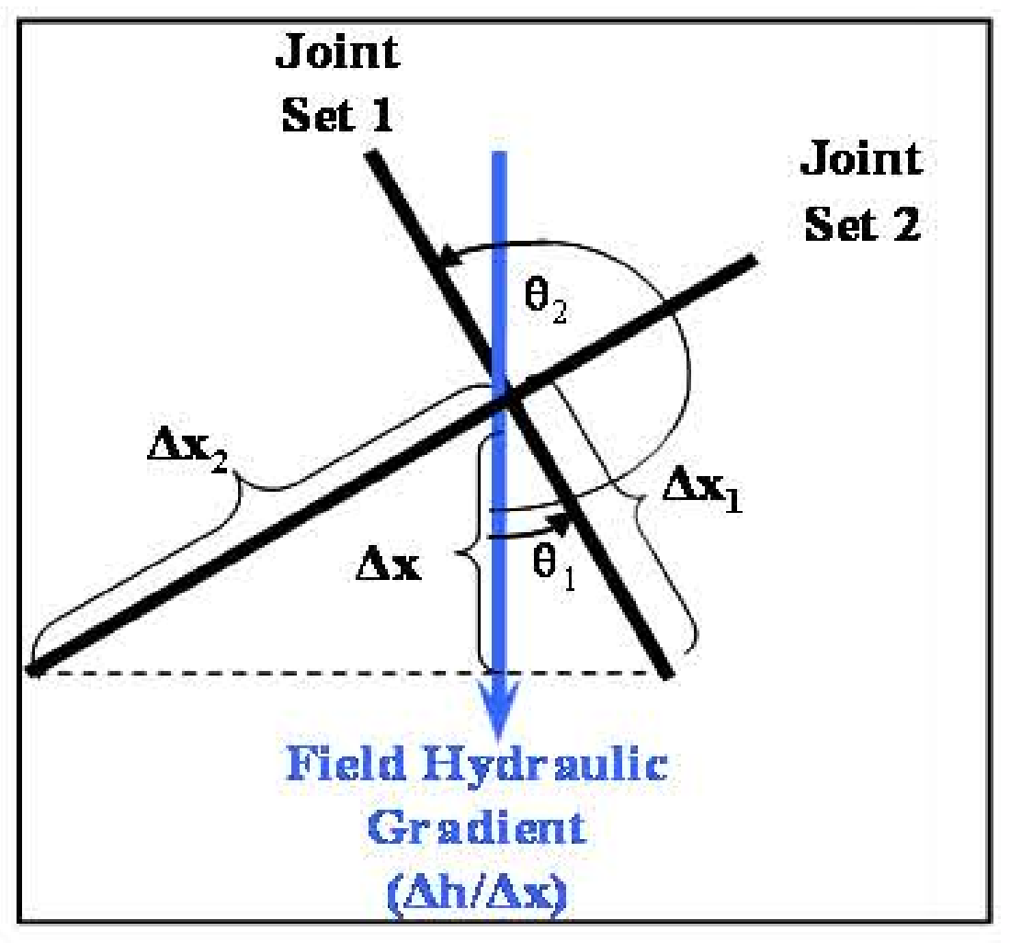
$$i_p = (\Delta h/\Delta x_1)/(\Delta h/\Delta x_2)$$

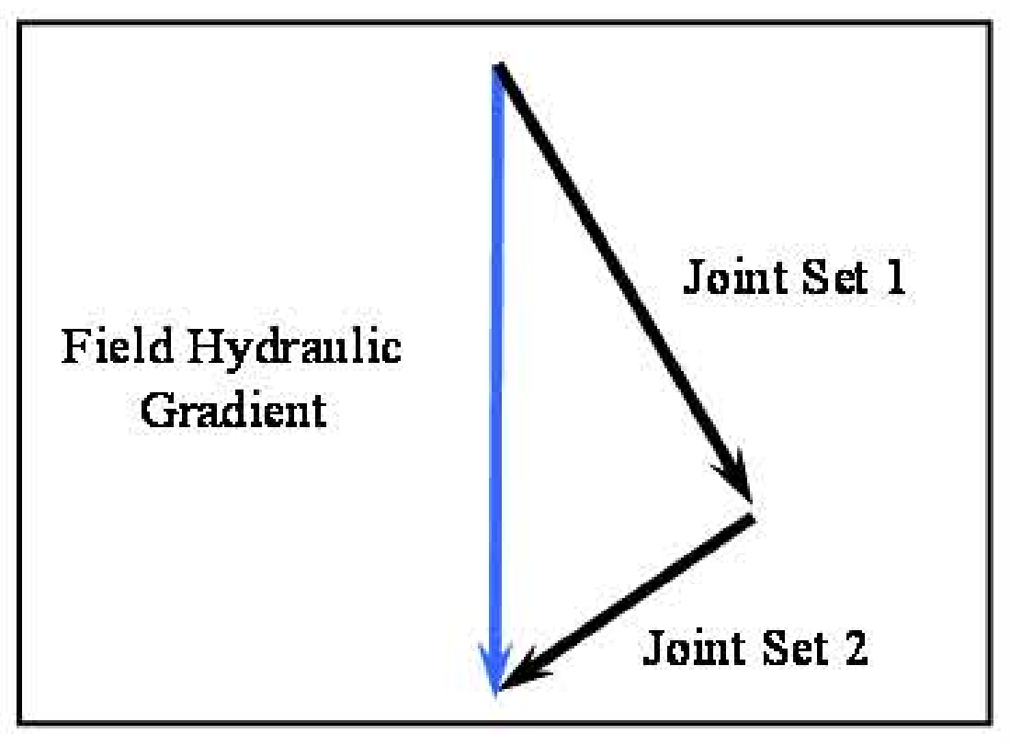
and the preferential tendency for a hypothetical particle of water to flow into Joint Set 1, expressed as a percentage, is given by:

$$\cos\theta_1/\cos(180-\theta_2)\cdot 100$$

For a hypothetical case in which $\theta_1 = 20°$ and $\theta_2 = -65°$ the flow ratio into planes in Joint Sets 1 and 2 is 2.2:1 for a 70% potential for flow into Joint Set 1 and a 30% potential for flow into Joint Set 2.

The same result can be obtained by a graphical vector resolution (see adjacent figures) of the field hydraulic gradient and the two planes (see case study example in Panel 3).

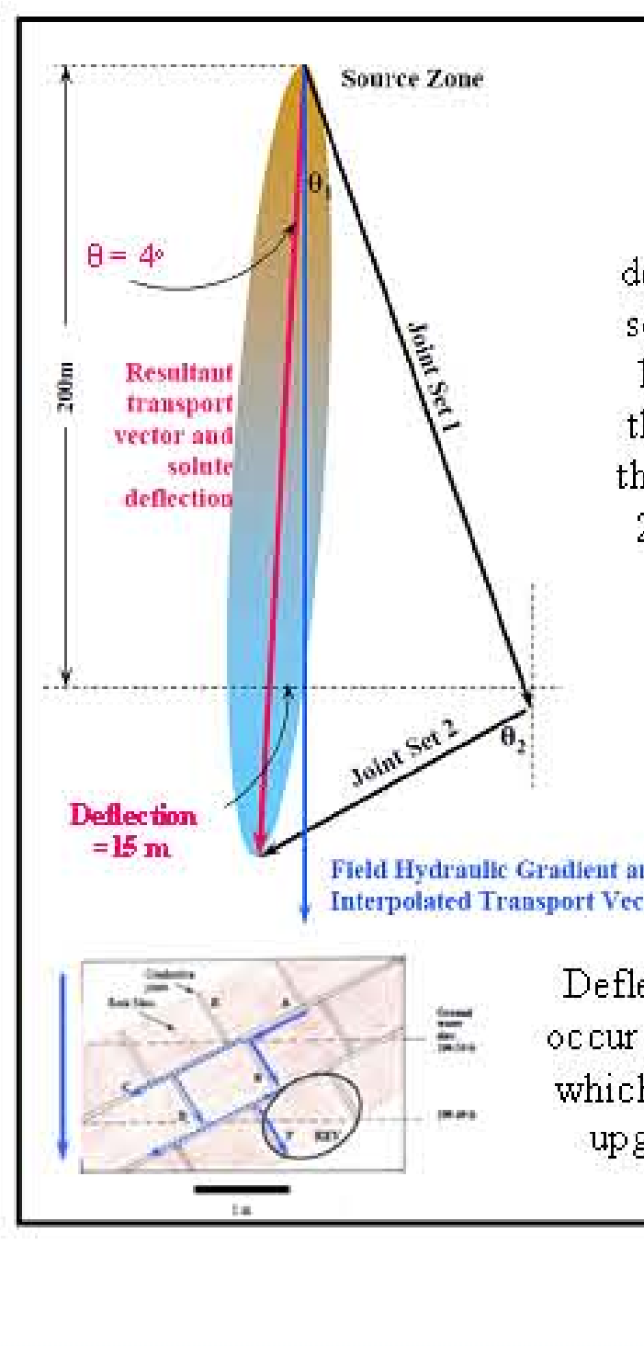




The non-random partitioning of flow into the joint sets and the differences in plane length and inter-plane spacing between systematic and non-systematic joint sets creates anisotropy on the scale of the representative elemental volume which can extend to larger scales in formations with heterogeneous distributions of non-random planes.

On a local scale (~10^2 m) the reticulated nature of joint networks typically precludes pronounced linear anisotropies but the flow partitioning into different joint sets and/or bedding planes provides for prediction of the fracture-controlled deviation of flow direction from the field hydraulic gradient and of solute deflection.

Using the 2.2:1 partitioning ratio in the example, the deflection of solutes over a hypothetical distance of 200 m would be -4° from the field gradient with solute deflection of 15 m from a linearly interpolated transport line.



In this example, deflection of a solute will be 15 m toward the west over the distance of 200 m along the field hydraulic gradient.

Deflection does not occur toward the East which would require upgradient flow.

Mathematical Model of Flow In Intersecting Joint Sets

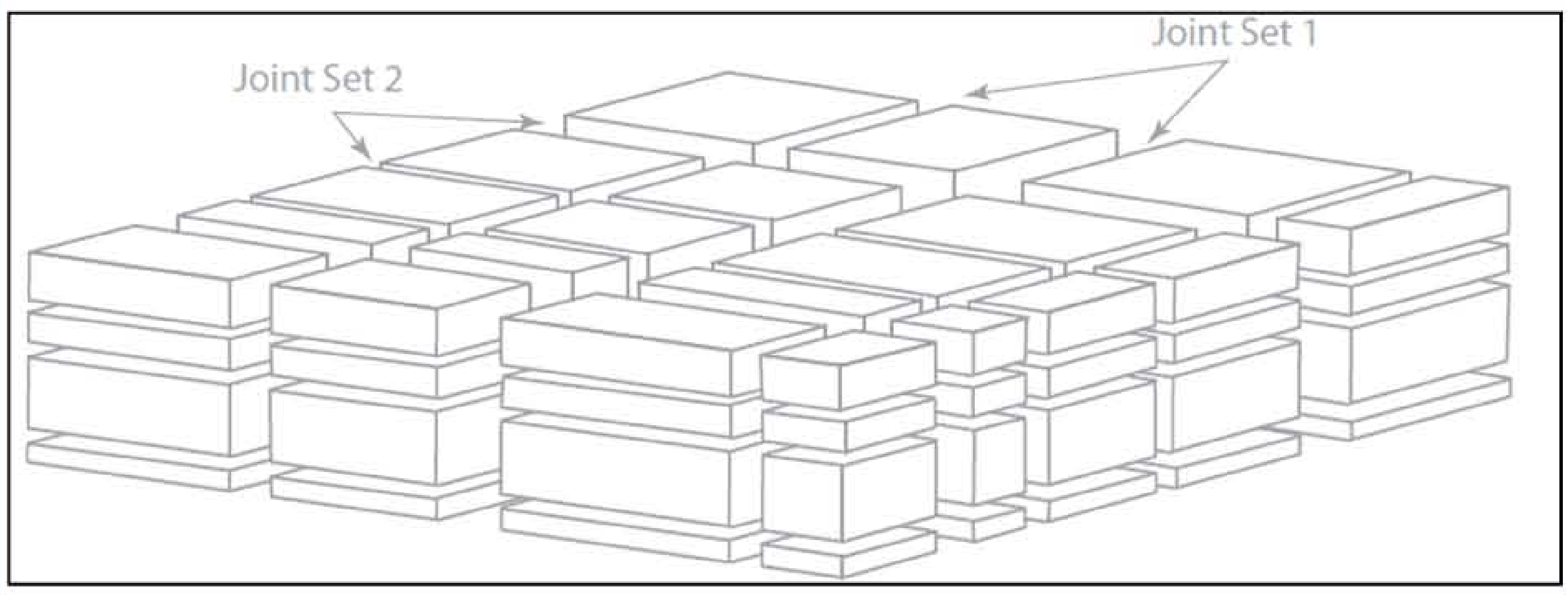
The orientation of fractures or joints in a fractured bedrock aquifer exerts control on the direction of groundwater flow. This control on contaminant plume movement is an important factor to consider in environmental groundwater contamination investigations at fractured bedrock sites.

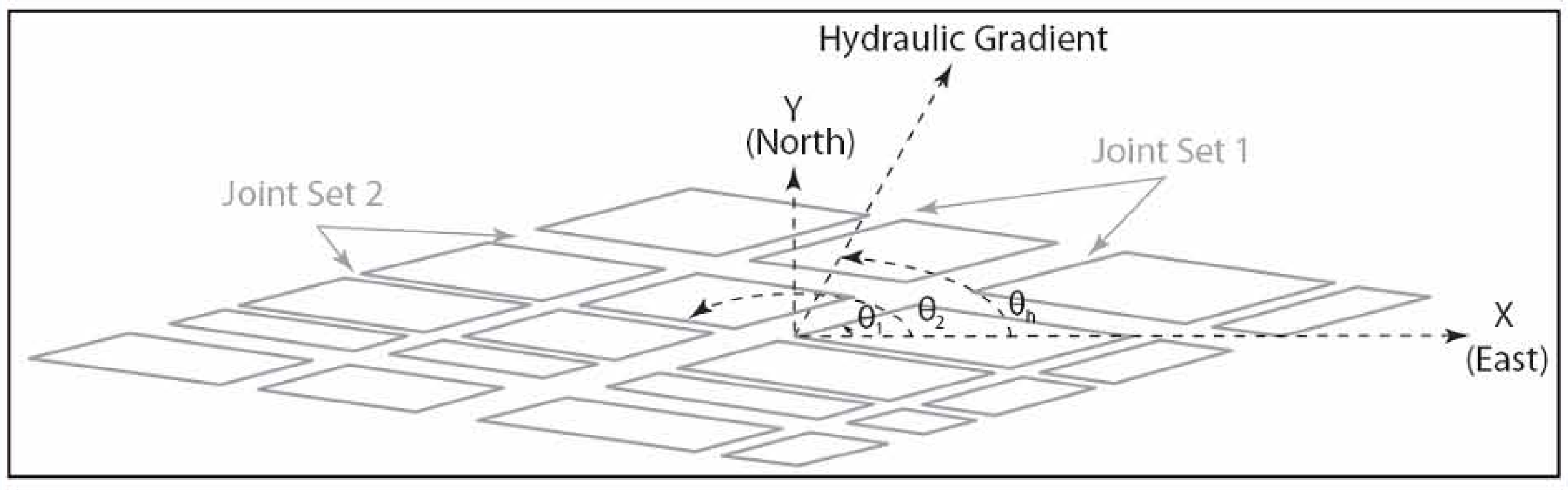
One or more regular joint sets impart a hydraulic anisotropy to a fractured bedrock aquifer such that the direction of groundwater flow often does not coincide with the direction of the hydraulic gradient in the area being studied. Thus, a plume cannot be assumed to travel perpendicular to the groundwater elevation contour lines.

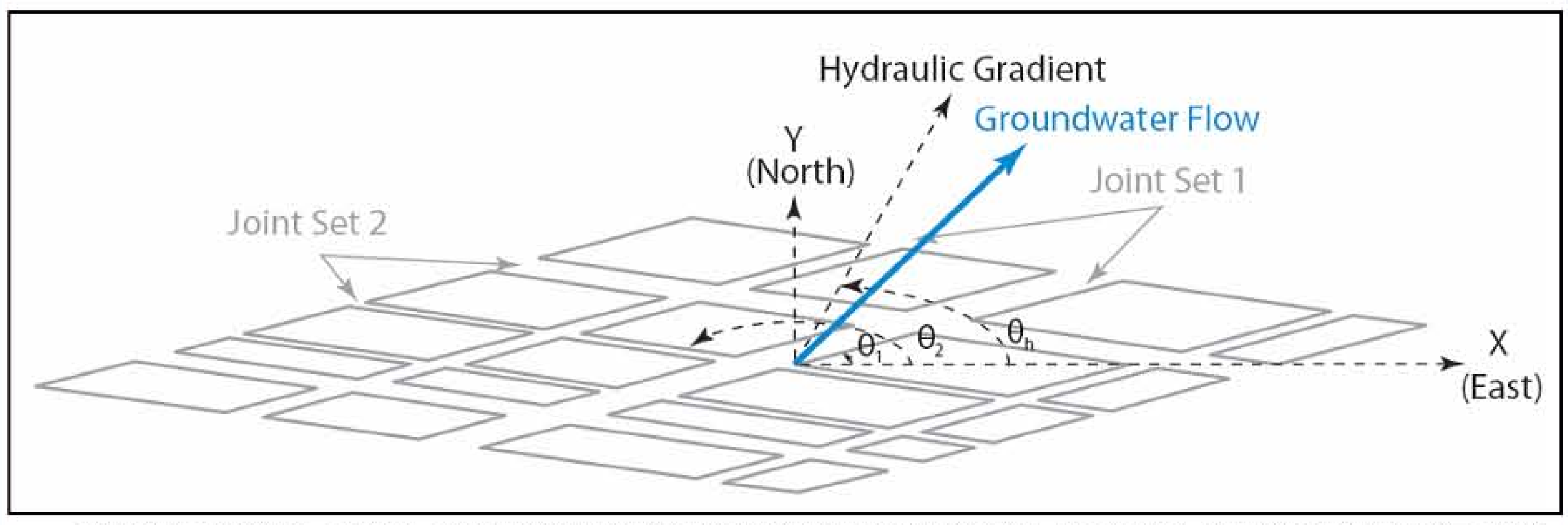
In many fractured rock systems sub-vertical fractures are important pathways for groundwater flow (see for example Dougherty et al. 2004). In these systems, bedding planes are not considered important groundwater flow pathways.

The earlier work of Snow (1968, 1969) has been used by several investigators to examine the anisotropy introduced by sets of parallel planar conductive features (e.g. joint sets) in regularly fractured rock masses (Oda 1985, Oda 1986, Ababou 1991, Chen et. al. 1999).

This work can be applied to develop a mathematical model for groundwater flow in sub-vertically oriented intersecting joint set systems.







For the problem of two sub-vertical joint sets where the hydraulic gradient i is within the horizontal plane, the x and y components of ground water flow are given by:

$$\begin{aligned} q_x &= (i\cos\theta_h)(K_{p1}\sin^2\theta_1 + K_{p2}\sin^2\theta_2) - (i\sin\theta_h)(K_{p1}\sin\theta_1\cos\theta_1 + K_{p2}\sin\theta_2\cos\theta_2) \\ q_y &= -(i\cos\theta_h)(K_{p1}\sin\theta_1\cos\theta_1 + K_{p2}\sin\theta_2\cos\theta_2) + (i\sin\theta_h)(K_{p1}\cos^2\theta_1 + K_{p2}\cos^2\theta_2) \end{aligned} \tag{1}$$

Where i is the scalar magnitude of the hydraulic gradient vector, q are the components of the areal flux density vector, K_{pm} is the hydraulic conductivity of the m-th joint set, θ_m is the joint dip azimuth, and θ_h is the direction of the hydraulic gradient in the horizontal plane counterclockwise from the East.

Because the flow problem is now 2-dimensional, one can easily re-orient the axes to coincide with the hydraulic gradient by subtracting θ_h from every angle.

$$\begin{aligned} q_x &= i(K_{p1}\sin^2\theta'_1 + K_{p2}\sin^2\theta'_2) \\ q_y &= -i(K_{p1}\sin\theta'_1\cos\theta'_1 + K_{p2}\sin\theta'_2\cos\theta'_2) \end{aligned} \tag{2}$$

Where $\theta_m' = \theta_m - \theta_h$, we can express strike angles relative to the hydraulic gradient, θ_m'', as

$$\begin{aligned} \theta''_1 &= \theta'_1 - \pi/2 \\ \theta''_2 &= \theta'_2 - \pi/2 \end{aligned} \tag{3}$$

The simplified form of the flow components are:

$$\begin{aligned} q_x &= i(K_{p1}\cos^2\theta''_1 + K_{p2}\cos^2\theta''_2) \\ q_y &= i(K_{p1}\sin\theta''_1\cos\theta''_1 + K_{p2}\sin\theta''_2\cos\theta''_2) \end{aligned} \tag{4}$$

Where θ_m'' is now a strike angle relative to hydraulic gradient.

The angular direction of groundwater flow is given by:

$$\theta_q = \arctan\left(\frac{q_y}{q_x}\right) \tag{5}$$

$$\theta_q = \arctan\left(\frac{-K_{p1}\sin\theta'_1\cos\theta'_1 - K_{p2}\sin\theta'_2\cos\theta'_2}{K_{p1}\sin^2\theta'_1 + K_{p2}\sin^2\theta'_2}\right) \tag{6}$$

References

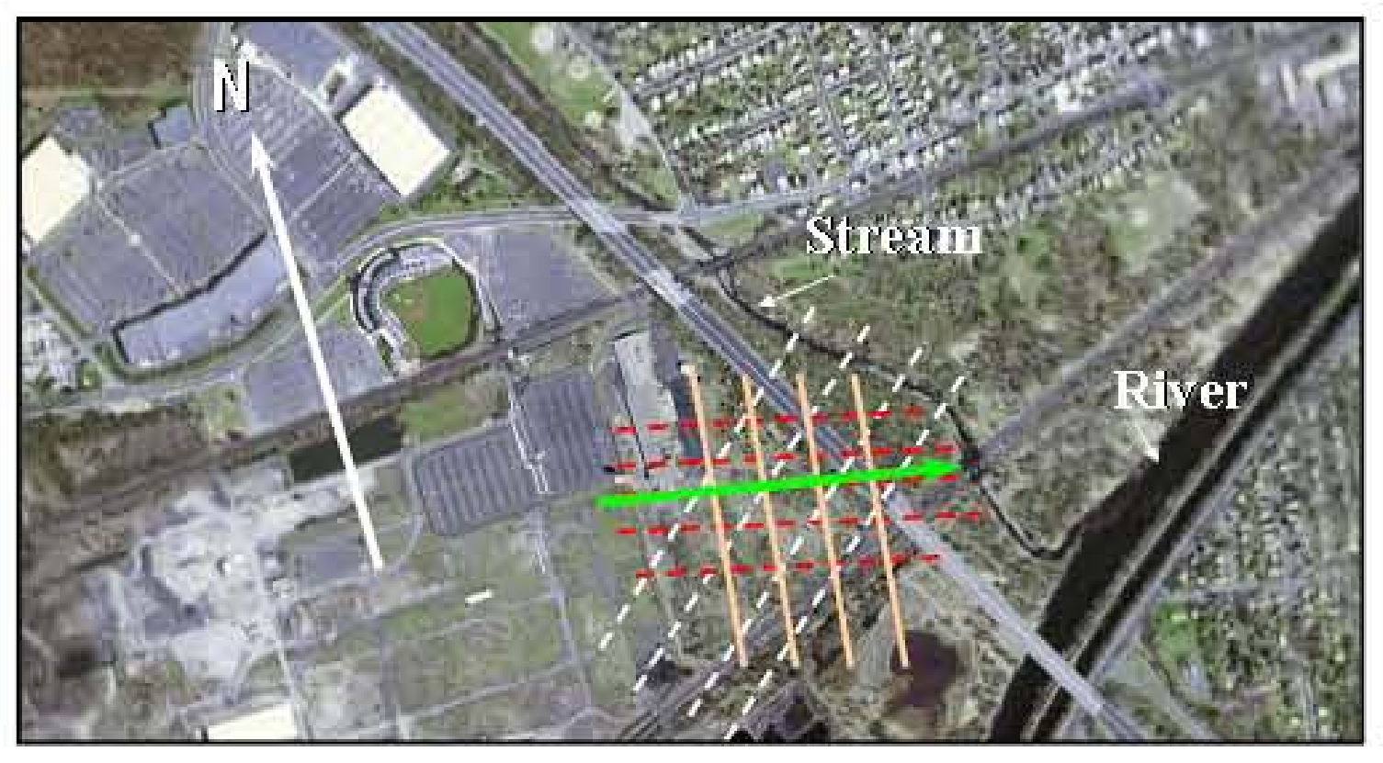
Ababou, R. 1991. Approaches to large scale unsaturated flow in heterogeneous, stratified, and fractured geological media. NUREGrCR-5743, NRC, Washington, D.C.
Chen, M., Bai, M., and Roegiers, J.-C. 1999. Permeability Tensors of Anisotropic Fracture Networks. Mathematical Geology, Vol. 31, No. 4. p. 355-369.
Dougherty, J.M., Soo, A., and Alvey, R.M. 2004. Evolving Conceptual models and Monitoring Well Reconstruction in the Passaic Formation in 2004 U.S. EPA/NGWA Fractured Rock Conference: State of the Science and Measuring Success in Remediation, September 13-15, 2004, Portland, Maine. Proceedings: National Ground Water Association, CD-ROM, p. 295-307.
Oda, M. 1985. Permeability tensor for discontinuous rock masses. Géotechnique 35, No. 4, p. 483-495.
Oda, M. 1986. An Equivalent Continuum Model for Coupled Stress and Fluid Flow Analysis in Jointed Rock Masses. Water Resources Research. Vol. 22, No. 13. p. 1845-1856.
Snow, D.T. 1968. Proceedings of the American Society of Civil Engineers. Journal of the Soil Mech. and Foundations Div. p. 73-91.
Snow, D.T. 1969. Anisotropic Permeability of Fractured Media. Water Resources Research. Vol. 5, No. 6. p. 1273-1289.

Case Study

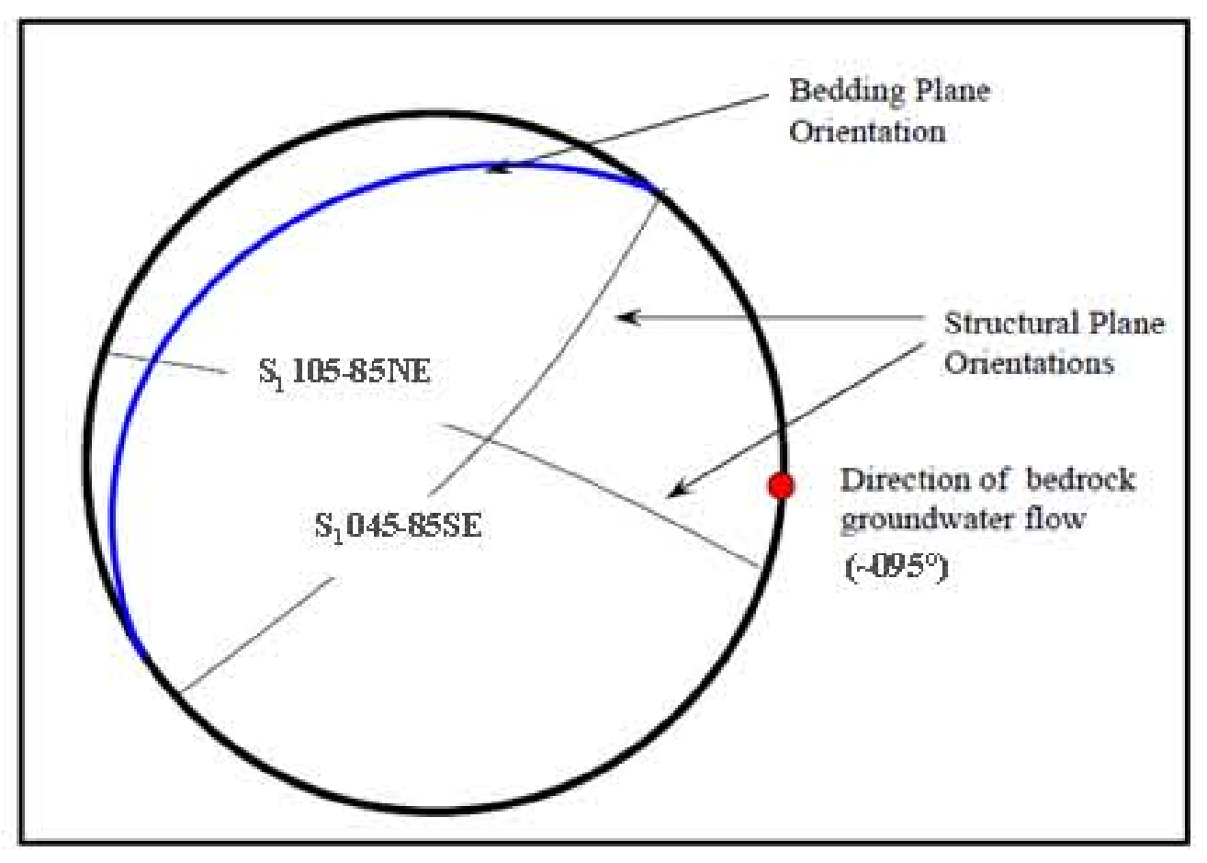
Groundwater flow and solute transport in a gently dipping, thinly-bedded, jointed shale formation with discharge to a second-order tributary

Dissolved load in shallow (30 m) confined groundwater was suspected to underflow a shallow tributary and discharge to the nearby regional groundwater discharging in a major river. Hydrologic data confirmed the discharge to the tributary and a detailed stream assessment showed no adverse impacts to ecological receptors or water quality, but the regulatory agency required remediation at the stream for the widespread, diffuse upgradient source mass.

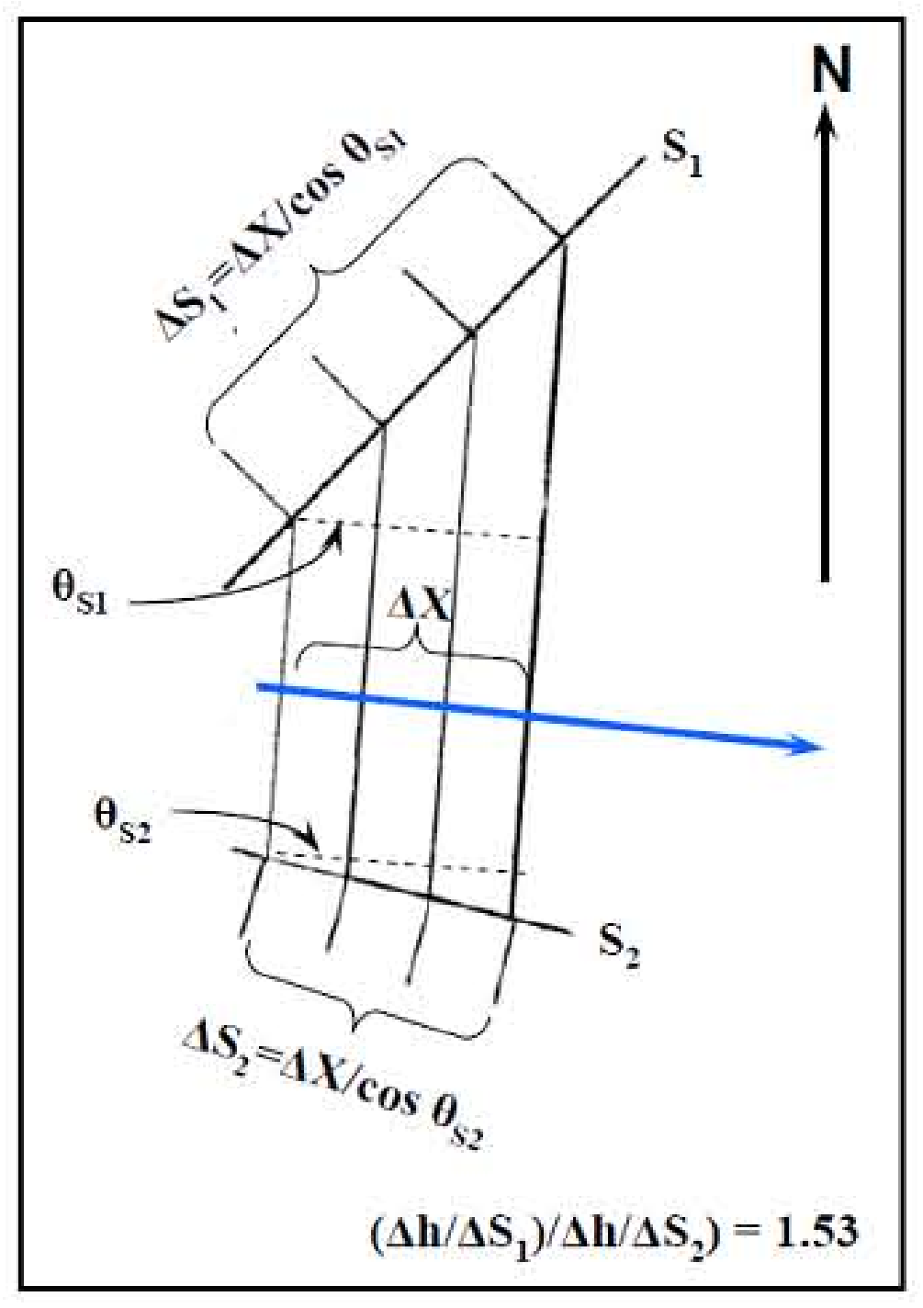
The flow and transport model presented herein was used to narrow the predicted width of the solute transport zone, and to select plume definition monitoring wells. Model confirmation provided for elimination of further delineation, and focused the remediation on a target area in the tributary rather than over a broad area.



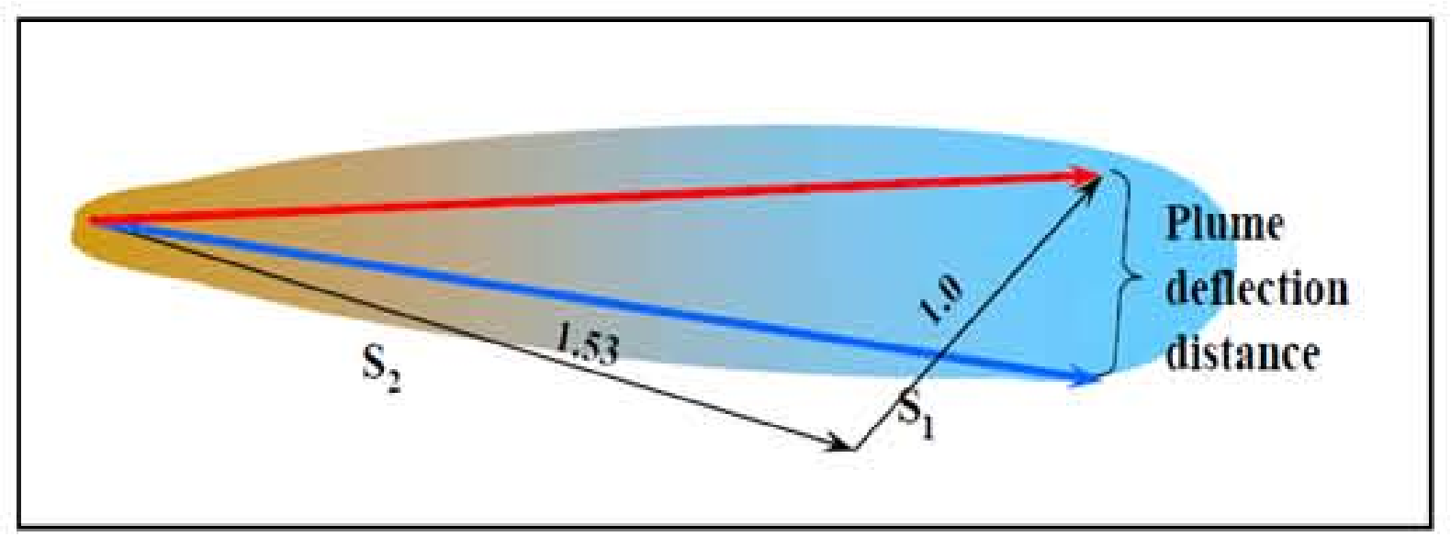
Field Hydraulic Gradient (Green arrow: azimuth ~095°) superimposed on principal bedrock groundwater-transmitting structural fabric elements. White lines: S_1 joints (045°-90) - strike is approximately coincident with bedding plane strike but bedding dips NW; Red lines: S_2 joints (105°-85NE); Buff lines: generalized groundwater elevation contours.



Lower hemisphere projection of planar fabric elements depicting the orientation of the field hydraulic gradient (red circle) in relation to measured structural fabric elements. Bedding plane partings (blue) strike 50° from the field gradient, dip in the opposite direction and, consequently, exert little to no control on groundwater flow direction. Planar element intersections are not aligned with measured groundwater flow, plunging 80° toward 075° (joints) and 5° toward 300° (joints w/bedding). The S_2 joint set is the pervasive fabric element with a strike azimuth nearest that of the field hydraulic gradient.

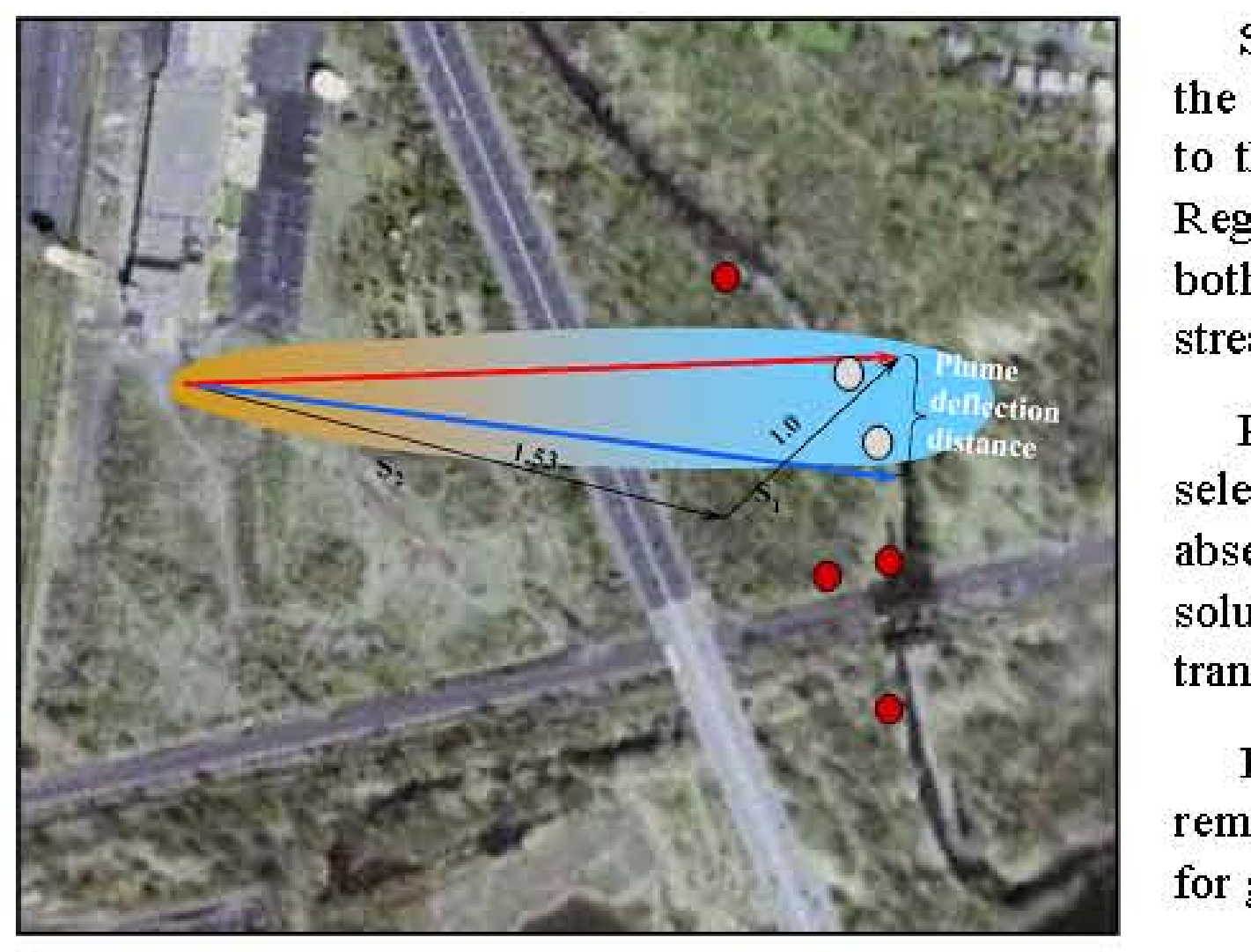


$$(\Delta h/\Delta S_1)/\Delta h/\Delta S_2) = 1.53$$



Resolution of in-plane hydraulic gradients in S_1 and S_2 joints (bedding plane has similar strike to S_1 – dip direction and angle are not relevant to the model solution). Geometric resolution results in a preferential tendency for groundwater and solutes to flow into S_2 joint planes with a pathway ratio ($S_2 : S_1$) of 1.53:1.

Model prediction is that solute deflection will be toward the north 65 m for every 100 m of transport along the field gradient, or a distance of approximately 300 m over the 450 m study area distance to the stream discharge.



Superimposed on an aerial photograph of the site, the model predicted that solutes should be discharging to the stream only in the shaded zone shown at left. Regulatory review had required monitoring wells both east and west banks along the entire length of the stream near the site (see adjacent figure).

Red circles are locations of monitoring wells selected with the current model in which solutes were absent. The wells in the shaded plume area contained solutes at predicted concentrations based on fate and transport calculations.

Based on stream monitoring, the focus of remediation is now on source removal with no plans for groundwater remediation.

Conclusions

Non-Random planar fabric elements in consolidated rock formations are structurally dependent, occur in sets with statistically consistent preferential orientations and form the majority of water-bearing planes. The differences of mean plane lengths, frequencies and spacings between the planar elements impart strong anisotropy to groundwater flow on the scale of the Representative Elemental Volume of the planar network, which tend to be defined on the scale of 10^0 to 10^1 m. On the scale of most flow and solute transport investigations (10^1 to 10^2 m) the reticulated nature of systematic and non-systematic joint sets with or without bedding plane partings, tend to preclude development of strong aquifer anisotropy on the scale of the observations being made.

The REV-imposed anisotropy is manifest on the scale of most study areas, however, in the deflection from the field hydraulic gradient of mean groundwater flow direction and solute transport. Testable predictions of the angle and distance of deflection at compliance points based on this model can be used to select monitoring locations for plume delineation and monitoring.

The method described herein provides a field verifiable model based on the geometric relationships between water-bearing planes and the field gradient in the absence of considerations of plane aperture widths or wall roughness. The model premises and construction are, however, consistent with and supported by mathematical constructs of aquifer hydraulic anisotropy tensors which have been modified herein to coincide with the geologic data.

Expansion of the model to include multiple discontinuity sets will provide for inclusion of bedding plane partings, additional joint sets and/or fault system effects on groundwater flow and solute transport.