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Groundwater flow and groundwater-stream interaction in fractured and dipping sedimentary rocks: Insights from numerical models

Ying Fan,[1] Laura Toran,[2] and Roy W. Schlische[1]

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[1] Groundwater flow is influenced by topography, but in fractured and dipping sedimentary rocks, it is also influenced by structure. Field evidence indicates that groundwater is older on the downdip side of a stream (asymmetry) and that dip-aligned streams receive more base flow than strike-aligned streams (anisotropy). We present detailed numerical models to evaluate the effects of various factors that influence groundwater flow pathways. The models simulate a small watershed drained by headwater streams and underlain by dipping strata. Groundwater flow can be characterized by three components: down the hydraulic gradient, downdip, and along strike. The degree of anisotropy and asymmetry depends on several factors: efficiency of the weathered horizon, bedding anisotropy, and bedding dip angle. Whereas anisotropy increases linearly with dip angle, asymmetry is greatest at a threshold angle. This threshold angle is related to the mean groundwater flow direction in an equivalent homogeneous and isotropic system.

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1. Introduction

[2] The rate and direction of groundwater flow at a given location is driven by hydraulic gradient, which in turn is determined by the boundaries of the system and the location and strength of recharge and discharge. In addition to topographic control, fractures can influence groundwater flow directions in some settings. (Note that in this paper, the term fracture refers to any open fluid conduits in a consolidated geologic medium regardless of their origin.) One such case concerns the fractured sedimentary rocks of the Newark basin (Figure 1), a part of the Mesozoic rift system in eastern North America [*Olsen et al.*, 1996], where groundwater occurs in tilted, fractured beds. A simple conceptual model of the hydrogeology of the setting (Figure 2) suggests that flow is influenced by the orientation of two sets of fractures, one occurring as bedding plane partings and the other as high-angle joints that cut across the beds [e.g., *Morin et al.*, 1997, 2000]. We note that the occurrence of fractures can be highly complex due to faulting, folding, igneous intrusion and extrusion, secondary mineral precipitation and dissolution, and multiple periods of deformation [e.g., *Schlische*, 1992; *El Tabakh et al.*, 1998; *Schlische et al.*, 2003; *Herman*, 2005]. Results from several studies support the hypothesis that groundwater flow primarily occurs in the bedding plane partings; due to the low permeability across the beds and closure of fractures at greater depth, flow is forced to follow the strike until it enters a discharge zone such as streams [e.g., *Michalski and Britton*, 1997]. This hypothesis is widely accepted and it has influenced regulations on site characterization of groundwater contamination in the basin, which has numerous groundwater contamination sites.

[3] Although there seems to be a consensus that groundwater flow in dipping sedimentary rocks is primarily controlled by the orientation of bedding planes, questions remain as to the relative role of the structure versus the topography. Because the ultimate driving force of groundwater flow is hydraulic potential, which, in water table aquifers, closely mimics the topography, groundwater flow will, to some extent and at certain spatial scales, follow topography. By examining the migration patterns of a large number of contaminant plumes in the Newark basin, *Orabone* [1997] proposed that the direction of groundwater flow is controlled by a set of factors including fracture orientation, topography, and location of streams, and that fractures do not seem to dominate in all cases. Obviously, if the beds are horizontal, then they will merely create a vertical-to-horizontal anisotropy, and the flow will primarily follow topography. If the beds dip vertically, one expects to see the greatest deviation from topography. Thus the degree of structural control may depend on the dip angle of the beds.

[4] The relative role of topography versus fractures also depends on other factors. For instance, *Solomon et al.* [1992] determined that in the fractured shale terrain in Oak Ridge, Tennessee, more than 90% of the groundwater travels in the lower part of the weathered zone, discharging

[1]Department of Geological Sciences, Rutgers–State University of New Jersey, Piscataway, New Jersey, USA.
[2]Department of Geology, Temple University, Philadelphia, Pennsylvania, USA.

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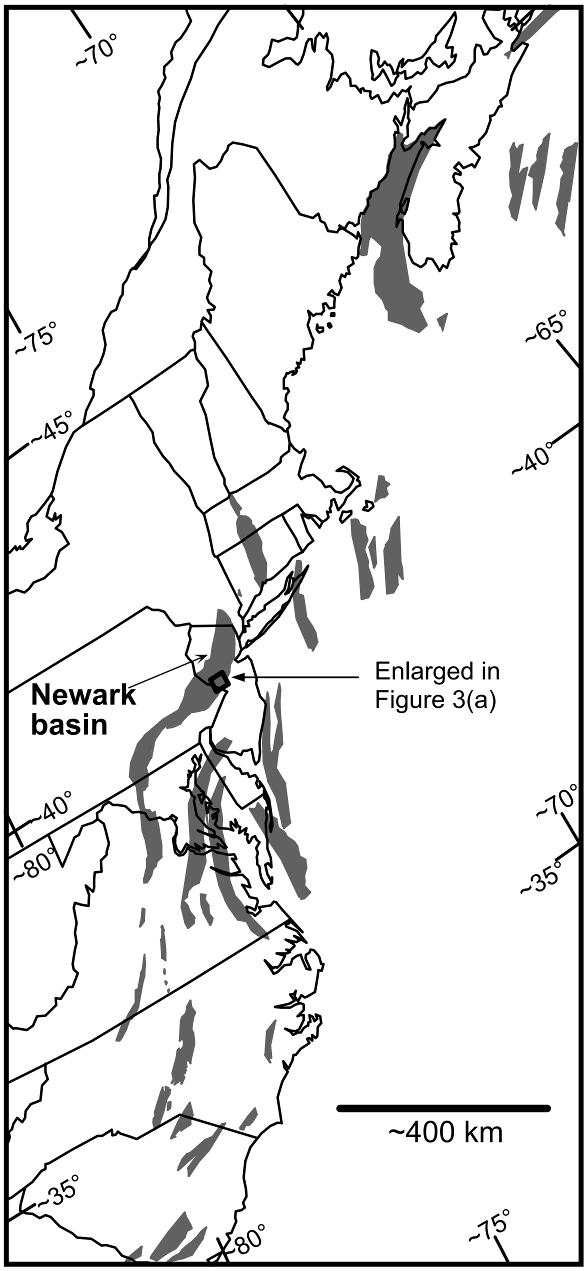

Figure 1. Triassic-Jurassic rift basins of eastern North America, including the Newark basin. Box shows location of geologic map in Figure 3a. Modified from *Schlische et al.* [2003].

into streams without ever entering the fractured rocks. In this case, topography plays a dominant role.

[5] This apparent dual topography versus structure control on groundwater flow pathways also influences its interaction with surface streams. For example, *Lewis* [1992] noted that streams aligned with the dip direction could receive more base flow than streams aligned with strike given the same contributing area. If the preferred direction of groundwater flow is along bedding planes, as hypothesized to be the case, then dip-aligned streams, cutting across the beds, are more likely to intercept groundwater flow paths. Thus the anisotropy in groundwater flow may also lead to anisotropy in groundwater-stream interaction.

[6] Observations in the dipping beds of the Valley and Ridge Province in Pennsylvania revealed another feature in groundwater-stream interaction. *Burton et al.* [2002] found that if a stream is aligned with strike, then groundwater head on the downdip side of the stream is in general higher, and its age in general older, than on the updip side. Thus there is asymmetry in groundwater residence time on the opposite sides of a stream aligned with strike.

[7] One may ask the following questions. In what end-member cases will the topography stream system dominate groundwater flow? In what cases will the fractures have the greatest effect? Are anisotropy and asymmetry in groundwater-stream interaction fundamental features in fractured and dipping sedimentary rock systems? How do these features manifest themselves over a range of structural and topographic conditions?

[8] Several investigators have addressed the role of geological control on groundwater flow pathways and interaction with streams based on field as well as modeling studies (e.g., see a review by *Sophocleous* [2002]). Detailed monitoring has shown that discharge occurs at discrete points in both unconsolidated sediments [*Conant*, 2004] and fractured rocks [*Oxtobee and Novakowski*, 2002]. MODFLOW [*Harbaugh et al.*, 2000] modeling using particle tracking indicated that the interchange between streams and groundwater depends on both bedrock geology and variations in stream discharge [*Wroblicky et al.*, 1998]. Another MODFLOW model showed that heterogeneity in channel beds deepens the zone of mixing between groundwater and surface water [*Woessner*, 2000]. *Tiedeman et al.* [1998] found that tracking flow in fractured bedrocks beneath unconsolidated deposits was important for delineating groundwater basins; the groundwater basin in their model near Mirror Lake in New Hampshire had 1.5 times larger area than the surface water basin. *Oxtobee and Novakowski* [2003] conducted a sensitivity analysis in

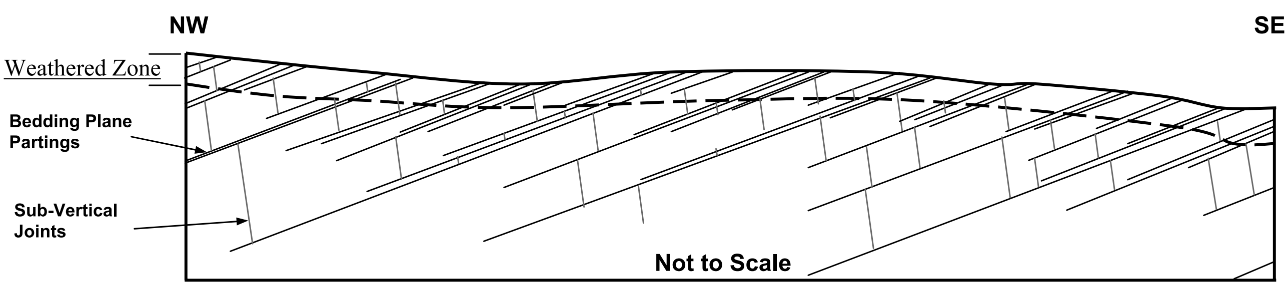

Figure 2. Conceptual model of Newark basin hydrogeology, modified from *Lewis-Brown and Jacobsen* [1995].

horizontally fractured bedrock and found stream discharge was highly dependent on the presence of vertical fractures.

[9] Many detailed and insightful field and modeling efforts have focused on the Newark basin [e.g., *Michalski*, 1990; *Lewis*, 1992; *Lewis-Brown and Jacobsen*, 1995; *Orabone*, 1997; *Michalski and Britton*, 1997; *Carleton et al.*, 1999; *Senior and Goode*, 1999; *Goode and Senior*, 2000; *Morin et al.*, 1997, 2000; *Lacombe*, 2000; *Lewis-Brown and Rice*, 2002; *Risser and Bird*, 2003; *Herman*, 2005]. *Senior and Goode* [1999] used MODFLOW to simulate pumping in a fractured rock aquifer with tilted beds in the Pennsylvania part of the basin. Their automated calibration indicated an 11:1 anisotropy as effective parameters. A smaller and finer resolution model within the same region was developed by *Goode and Senior* [2000] that incorporated tilted high-permeability zones. *Risser and Bird* [2003] used distorted layers to simulate dipping beds in a nearby area in the Newark basin. These studies have provided valuable insight into the nature of heterogeneity and anisotropy in a fractured rock environment, alternative methods for representing the dipping beds in porous media models, as well as important quantitative basis for effective model parameters to be used by others.

[10] This study attempts to continue the discussion on the relative importance of geologic structure versus surface drainage system in controlling groundwater flow pathways and interaction with streams. We make an attempt to synthesize the various site studies and to outline the most salient features of groundwater flow in a dipping sedimentary setting, by using a set of detailed, three-dimensional models of groundwater flow with explicit representation of the dipping beds. Numerical models allow us to simplify and isolate the effect of each of the factors such as stream alignment, bedding dip angle, weathered zone thickness, etc. These factors tend to operate simultaneously and in complex manners in a particular field site, making it difficult to separate the contribution of one from another. Therefore these models function as a numerical laboratory in which we can design experiments and test hypotheses. The models are specifically designed to answer the following questions:

[11] 1. What are the important features of groundwater flow and its interaction with streams in dipping strata? For example, under what circumstances do along-dip streams receive more base flow than along-strike streams as noted by *Lewis* [1992]? What physical factors lead to groundwater in the downdip side of a stream having longer residence times as observed by *Burton et al.* [2002]? In what end-member cases will the topography-stream system dominate groundwater flow? In what cases will the underlying structure have the strongest effect?

[12] 2. How are the flow directions affected by the orientation of the streams, the contrast in along-bed (via bedding plane partings) and across-bed (via high-angle joints) permeability, the efficiency of the weathered zone, and the dip angle of the beds?

[13] 3. What are the implications of the above findings to characterizing a field site? What are the implications to groundwater modeling? Can we capture these fundamental features in a numerical model without explicit representations of the dipping beds?

[14] Thus this study is motivated by the need for basic understanding of groundwater flow and groundwater-stream interaction in dipping strata, and the need to characterize such systems in the field and represent them in groundwater models. Both are useful steps toward advancing our knowledge of and our ability to quantify and predict fractured flow in complex geologic settings.

2. Model Design

[15] Figure 3a is a geologic map of part of the Newark basin, showing streams (thin black line), faults (thick black line), bedding form lines (gray) and bedrock formations (patterns). The orientation of dipping beds is characterized by two angles, the strike and the dip. Dip refers to the angle and direction of the maximum inclination of bedding, which varies from 11° to 30° toward the northwest in the study area (Figure 3a). The strike, which is perpendicular to the dip direction, is mostly northeast-southwest, subparallel to the formation contacts and bedding form lines in Figure 3a. The drainage network (Figure 3a) exhibits typical structural control; headwater streams tend to align with strike or dip, joining one another at right angles [*Ackermann*, 1997]. Figure 3a also includes the sites of several intensive field and modeling studies by the U.S. Geological Survey (USGS), notably those by *Lewis* [1992], *Lewis-Brown and Jacobsen* [1995], *Morin et al.* [1997], *Carleton et al.* [1999], *Lacombe* [2000], and *Lewis-Brown and Rice* [2002]. These studies sought to better understand groundwater flow and transport in fractured sedimentary rocks. On Figure 3a, a headwater catchment of Beden Brook is outlined and shaded, which is used to guide the formulation of our models, shown in Figure 3b. Note that the model is conceptual; it represents a small watershed underlain by dipping strata, drained by three tributaries joining at right angles at one point. The model catchment is divided into two symmetric domains (the natural asymmetry in the watershed is mainly caused by a diabase intrusion to the southwest). It idealized the real catchment to create a perfectly symmetric topography-stream system, so that any asymmetry in the modeled flow field can be attributed to the underlying structure.

[16] We use the U.S. Geological Survey (USGS) finite difference code, MODFLOW [*Harbaugh et al.*, 2000] for simulating groundwater flow and the USGS particle tracking code, MODPATH [*Pollock*, 1994] for tracing flow pathways and calculating travel times. The modeling environment is Visual MODFLOW (VMod) by Waterloo Hydrogeologic Inc. (http://www.flowpath.com/software/visual_modflow_pro), which facilitates easy editing of hydraulic conductivity (K) fields in representing the dipping beds. We chose to use an equivalent porous media model, such as MODFLOW, over a fracture network model, because we are interested in large-scale flow fields and in exploring the use of effective parameters for representing fractured environments using community models such as MODFLOW.

[17] Figure 3b gives the model dimensions, 700 m along x, 350 m along y, and 115 m along z. The horizontal dimensions are limited by computation feasibility, although small watersheds of this size are common in the hilly terrains of the region. The vertical dimension is guided by the observation that fracture-induced transmissivity

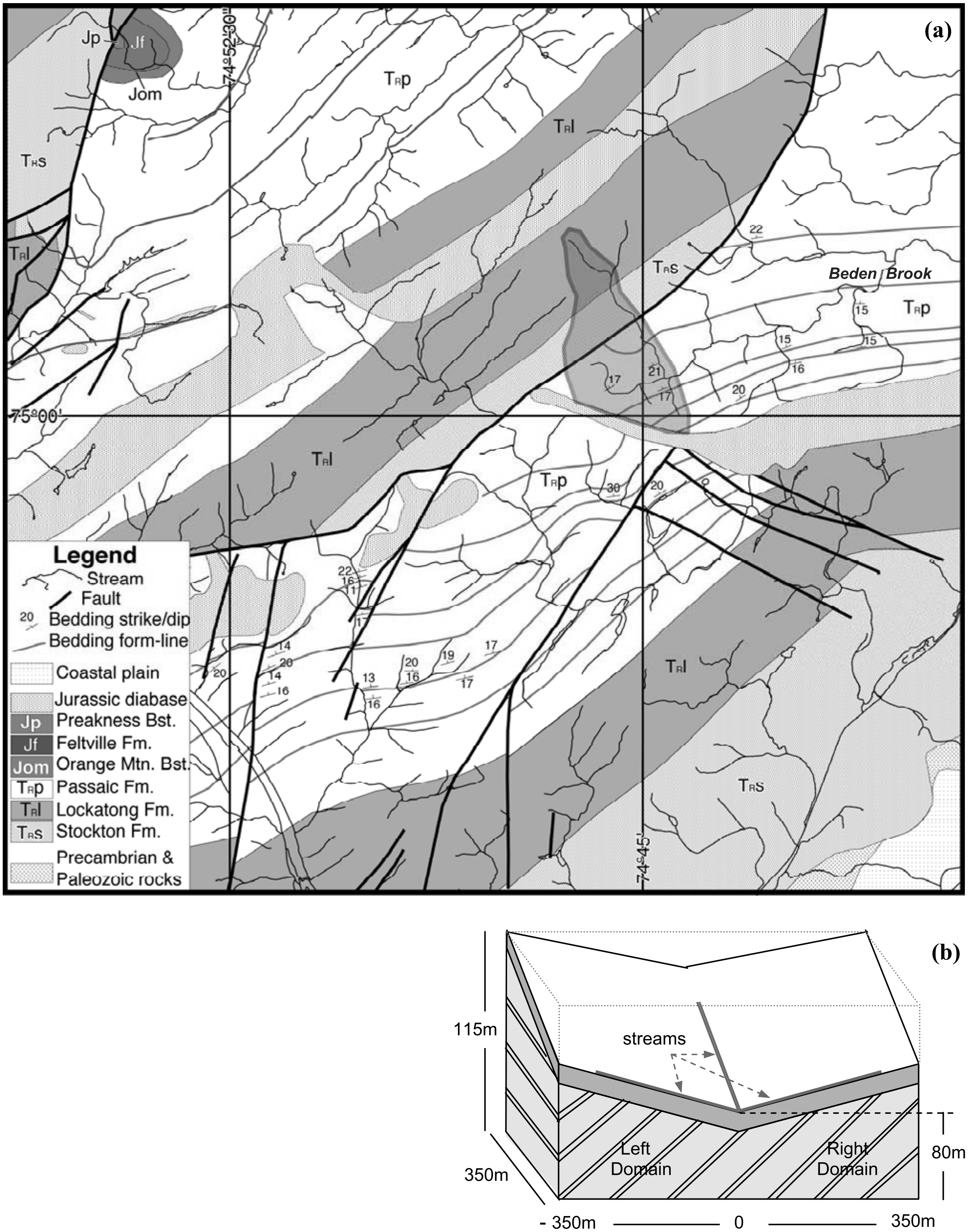

Figure 3. (a) Geologic map of part of the Newark basin (see Figure 1 for location), showing streams and the Beden Brook headwater area (shaded in gray). Stratal dip direction (direction of maximum inclination) is parallel to short lines of the strike-and-dip symbol; number gives inclination angle; strike is parallel to the long line. Modified from *Olsen et al.* [1996]. (b) Model configuration for this study (not to scale).

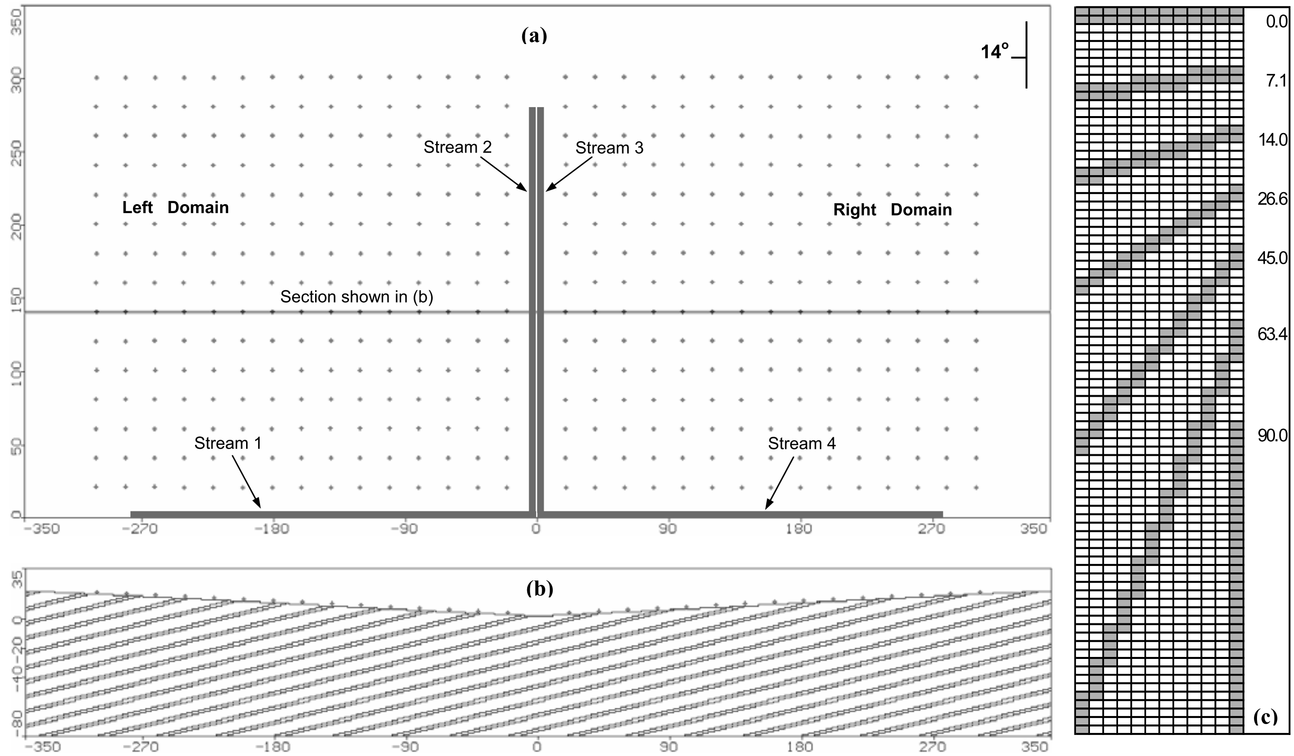

Figure 4. (a) Model plan view, showing the streams (numbered 1–4) and the 225 particles placed in each domain, (b) model cross-section view showing dipping beds, and (c) representation of dipping beds in MODFLOW at various dip angles.

decreases exponentially with depth and it is insignificant below 300 feet depth [*Morin et al.*, 1997]. The model topography is composed of two planes dipping toward the stream junction, the ultimate drainage point of the watershed. The topography slopes at 5% along the streams and 7% along the ridge (from upper corners to the stream junction), roughly following the terrain characteristics of Beden Brook. The center stream divides the model into two symmetric domains, the left and the right domain. The model has two material zones, a weathered zone, and the fractured bedrocks below. Bedding fractures are portrayed as thin zones of high permeability (K), embedded in a more solid rock matrix of low K. Regular, alternating beds of high and low K are used to represent the fractured media, which is a crude simplification of nature but sufficient for our purpose of studying general flow patterns as influenced by dipping strata. The model is aligned with the strike (in y) and dip (in x) of the beds.

[18] Figure 4a gives the plan view of the model. Grid resolution is $\Delta x = \Delta y = 2$ m, yielding 350 columns (east-west) and 175 rows (north-south). Fine resolution is needed to represent thin and continuous dipping beds. The streams, numbered 1 to 4, are simulated using the Drain Package in MODFLOW, which calculates groundwater discharge into streams according to head difference and hydraulic connection between the groundwater and the stream. The center stream is represented by two lines of drain cells side by side, labeled stream 2 and stream 3, leading to perfect symmetry and isotropy in source-sink strengths in each domain. The only difference is that the left domain lies downdip of the central streams, and the right domain lies updip. This symmetry and isotropy in the topography-stream system will isolate the effect of the underlying bedding structure. A total of 450 particles (225 in each domain) are placed in the weathered zone, 1 m above the bedrock surface. The flow paths and travel times of these particles are used to assess flow patterns.

[19] Figure 4b gives a cross section of the model. Vertical resolution is $\Delta z = 1$ m. Dipping beds are represented by assigning the K field in a stair-step manner, as shown in 4c where several dip angles are illustrated. The cross section in 4b has beds dipping at 14°, which is close to the average dip of 15° in the region [e.g., *Schlische*, 1992]. We use the 14° angle as a base case in this study and later vary it to examine the effect of dip angle. No-flow boundary conditions are applied to the bottom and sides.

[20] Precipitation-derived recharge to the water table is estimated to be 254–508 mm/yr (10–20 in/yr) for the region [*New Jersey Department of Environmental Protection*, 1996]. We will use 381 mm/yr (15 in/yr) for our simulations. All simulations take place under steady state conditions.

3. Anisotropy and Asymmetry in the Flow Field

[21] The first simulation, hereafter referred to as the base case, examines the general patterns of groundwater flow in dipping strata drained by headwater streams. The model parameters are: uniform recharge of R = 381 mm/yr, uniform drain conductance (hydraulic connection between the groundwater and the stream) of 20 m^2/d per stream cell, hydraulic conductivity for the weathered zone: Kw = 0.1 m/d, for water-transmitting zones or aquifers: Ka = 1 m/d, and for confining beds: Kc = 0.01 m/d. The K values for the

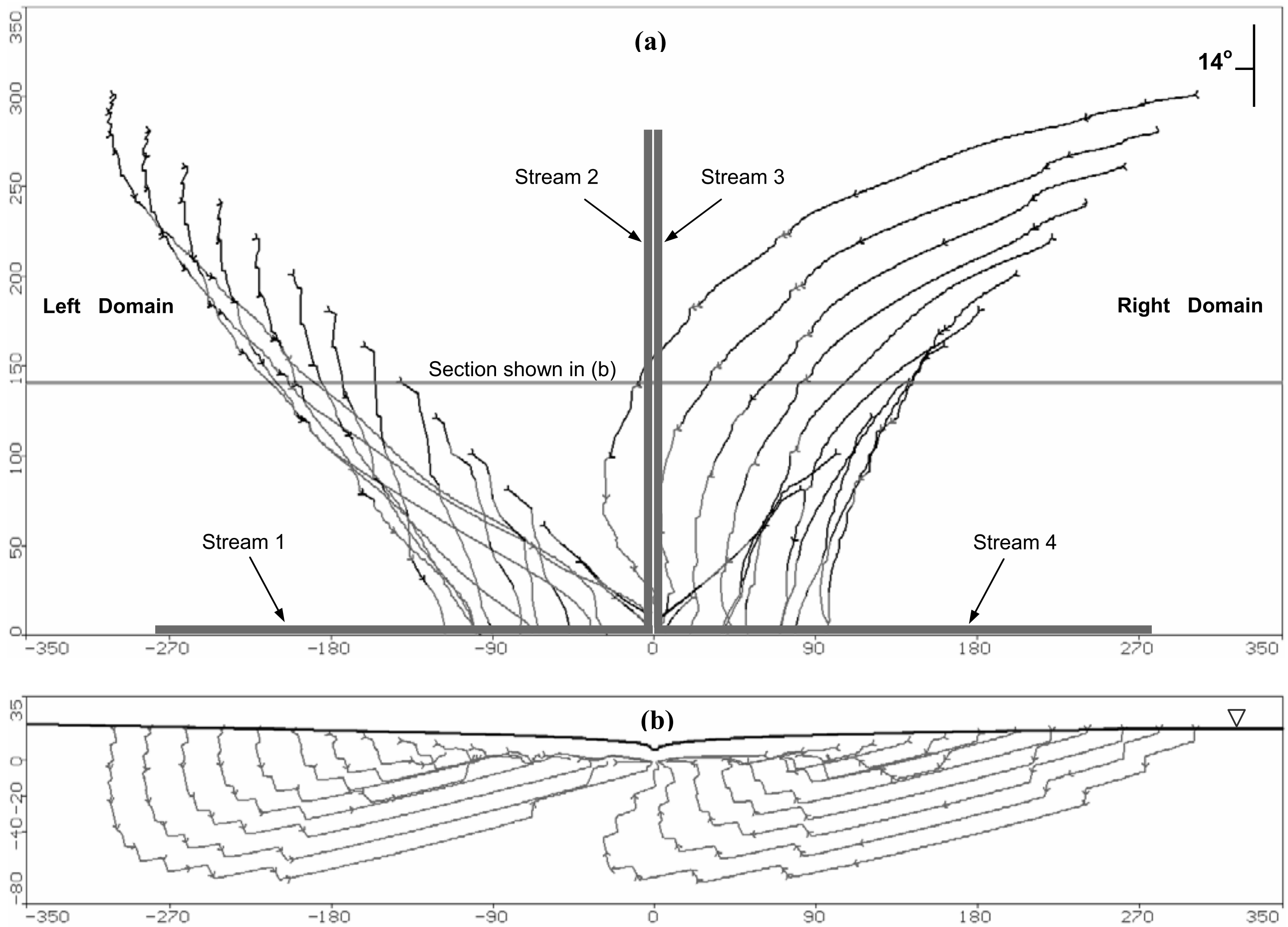

Figure 5. Simulated flow pathways for the base case, projected to (a) plan view and (b) cross-section view. Black segments are going into and gray segments are coming out of the page. Each tick mark on the pathlines indicates 10 years of travel time.

transmitting and the confining units differ by two orders of magnitude, whereas the K value for the weathered zone lies in between. These values are within the range obtained by pump and slug tests and model calibrations reported in the USGS studies cited earlier. We assume that K is isotropic within each bedding unit, that is, the anisotropy of the system is strictly a result of alternating beds of contrasting permeability.

[22] Figure 5 shows the simulated flow pathways (black is going into and gray is coming out of the page). For clarity, only the particles released on the diagonal line are shown. In plan view, the particles move in three directions: down the steepest topographic gradient toward the stream junction, down the dip, and along the strike. Each particle moves in different directions, depending on its origin. For those near the stream junction, flow paths stayed in the weathered zone, and topography is the dominant control. For those far away from streams and in the updip (right) domain, the flow path goes down the dip first, and then follows the strike toward the streams. For their downdip (left) domain counterparts, the flow path follows the strike first, and then goes up the dip toward the streams. The result is a flow distortion similar to a counterclockwise rotation. If the beds are dipping toward the right, or if the model is flipped north-south, it would be a clockwise rotation. Clearly, what controls the flow pathway of a particle or a contaminant plume depends on where it originates in this topography-stream versus dipping beds system.

[23] Results show that along-dip streams receive more base flow than along-strike streams, similar to observations by *Lewis* [1992]. Stream 1 received the most base flow, stream 4 received the second, with streams 2 and 3 receiving the least (Table 1). Along-dip streams (1 and 4) receive more than along-strike streams (2 and 3), in each domain, and as a whole (1.28 times more). The mechanism, as noted by *Lewis* [1992], is the along-strike flow component, which favors groundwater discharge into dip-aligned streams that intercept groundwater flow paths. Thus anisotropy in groundwater flow, i.e., the along-strike flow component, also produces anisotropy in groundwater-stream interaction.

[24] We calculated the travel time difference between the left and right domains. In the left, 185 of the 225 particles released are below the water table and their flow paths calculated. In the right, 174 of the 225 particles are below the water table. Thus the water table is higher on the left, just as observed by *Burton et al.* [2002]. The average of the left to right travel time ratio of the 174 pairs of particles is 1.58 (Table 1); thus groundwater on the downdip side of the stream can be significantly older than its updip counterpart, also in support of the findings by *Burton et al.* [2002],

Table 1. Model Parameters and Simulation Results

Simulations	Model Parameters				Base Flow Received, m^3/d						
	R, mm/yr	Kw, m/d	Ka, m/d	Kc, m/d	Stream 1	Stream 2	Stream 3	Stream 4	Strike to Dip Ratio	Downdip to Updip Traveltime Ratio	Updip to Downdip Underflow
Permeability of the weathered zone	381	0.3	1	0.01	75.68	54.38	54.56	68.00	1.32	1.18	2.91
Effect of bedding anisotropy	381	0.1	1	0.05	67.58	59.21	59.66	65.83	1.12	1.38	0.55
Stratal dip 0°	381	0.1	1	0.01	63.06	63.06	63.06	63.06	1.00	1.00	0.00
Stratal dip 7.1°	381	0.1	1	0.01	69.20	59.35	60.59	63.32	1.10	1.59	1.82
Stratal dip 14.0°[a]	381	0.1	1	0.01	74.11	55.04	55.65	67.72	1.28	1.58	2.28
Stratal dip 26.6°	381	0.1	1	0.01	82.54	46.64	46.89	76.59	1.70	1.49	2.23
Stratal dip 45.0°	381	0.1	1	0.01	90.78	37.05	38.32	86.70	2.35	1.23	1.10
Stratal dip 63.4°	381	0.1	1	0.01	95.43	30.99	33.46	93.06	2.92	1.12	0.04
Stratal dip 90°	381	0.1	1	0.01	96.27	30.26	30.26	96.27	3.18	1.00	0.00

[a]Base case.

obtained with CFC dating of groundwater along two transects. We refer to this difference on the opposite banks of strike-aligned streams as ‘‘flow asymmetry’’ in subsequent discussions.

[25] The mechanism for flow asymmetry is the downdip flow component. We examine the flow crossing from the right to the left domain under the central streams. This flow, referred to as the ‘‘underflow,’’ is obtained with MODFLOW Zone budget which calculates the mass balance in specified regions of the model. The underflow serves as a quantification of the strength of the downdip flow component, and the result is given in Table 1 as percentage of recharge that each domain receives. It is expected that the greater the underflow, the greater the asymmetry.

4. Controlling Factors

[26] We examine three factors that may control the degree of anisotropy and asymmetry: the efficiency of the weathered zone, the contrast between along-bed and across-bed permeability, and the dip angle of the beds.

4.1. Efficiency of the Weathered Zone

[27] In the fractured shale terrain in Oak Ridge, Tennessee, more than 90% of the groundwater flow occurs in the lower part of the deeply weathered horizon, discharging into local streams without ever entering the fractured bedrock [*Solomon et al.*, 1992]. Apparently, an efficient weathered zone short circuits the flow near the surface and diminishes the role of fractures. The efficiency of the weathered zone in conducting flow is a function of the product of its thickness and permeability, or transmissivity. In this simulation, K for the weathered zone is three times higher than the base case.

[28] Results (Figure 6) show that more (14 versus 6) particles stayed in the weathered zone and followed the topographic gradient to the streams, in comparison to the base case. Thus in a situation like this, a contaminant plume entering the lower part of a watershed can appear to migrate toward the streams, showing little influence of the structure below. This is consistent with the observations of *Orabone* [1997], who examined the migration pathways of many plumes and found that topography and relation to streams played an equally important role as fractures in controlling groundwater transport.

[29] Strike to dip base flow ratio, however, is higher than the base case (1.32 versus 1.28), and so is the underflow (2.91 versus 2.28), which indicate stronger bedding influence. The reason is that a more permeable weathered zone causes the water table to drop due to faster shallow drainage. The drop is more pronounced at high elevations, causing recharge to enter the fractured system directly and the flow to follow the structure. Thus a more permeable weathered zone leads to a shallower flow depth in this zone, leaving the flow field dominated by structurally controlled flow in the deeper parts. In the lower elevations, the water table drop is less and the permeability is high, hence more particles stayed in the shallow zone and followed the topographic gradient. The smaller travel time ratio (1.18 versus 1.58 in the base case) reflects this fact, since only the low-elevation particles are below the water table and their paths are calculated, which are used for obtaining the ratio.

[30] This experiment points to the role of the amount of recharge the system receives. The balance between the recharge and the permeability in the weathered zone determines the thickness of the flow. At a given permeability, the more recharge, the thicker the weathered zone flow, which can dominate the flow fields and diminish structural control.

4.2. Degree of Bedding Anisotropy

[31] The contrast between along-bed and across-bed permeability, referred to as ‘‘bedding anisotropy’’ (in the sense that it is independent of xyz), can result from several features of the geologic media. Note that here we discuss the bulk or large-scale effective anisotropy of the fractured media only. In the base case, bedding anisotropy results from the alternating beds of different K values (two orders of magnitude). The equivalent permeability along the beds (K_1) and across the beds (K_2), following *Freeze and Cherry* [1979], for example, are,

$$K_1 = \frac{b_a K_a + b_c K_c}{b_a + b_c} = \frac{2\,\mathrm{m} \times 1\,\mathrm{m/d} + 8\,\mathrm{m} \times 0.01\,\mathrm{m/d}}{2\,\mathrm{m} + 8\,\mathrm{m}} = 0.2080\,\mathrm{m/d}$$

$$K_2 = \frac{b_a + b_c}{\frac{b_a}{K_a} + \frac{b_c}{K_c}} = \frac{2\,\mathrm{m} + 8\,\mathrm{m}}{\frac{2\,\mathrm{m}}{1\,\mathrm{m/d}} + \frac{8\,\mathrm{m}}{0.01\,\mathrm{m/d}}} = 0.01247\,\mathrm{m/d}$$

where b_a is the thickness and K_a is the permeability of the aquifer unit, and b_c is the thickness and K_c is the permeability of the confining unit. The values are those in

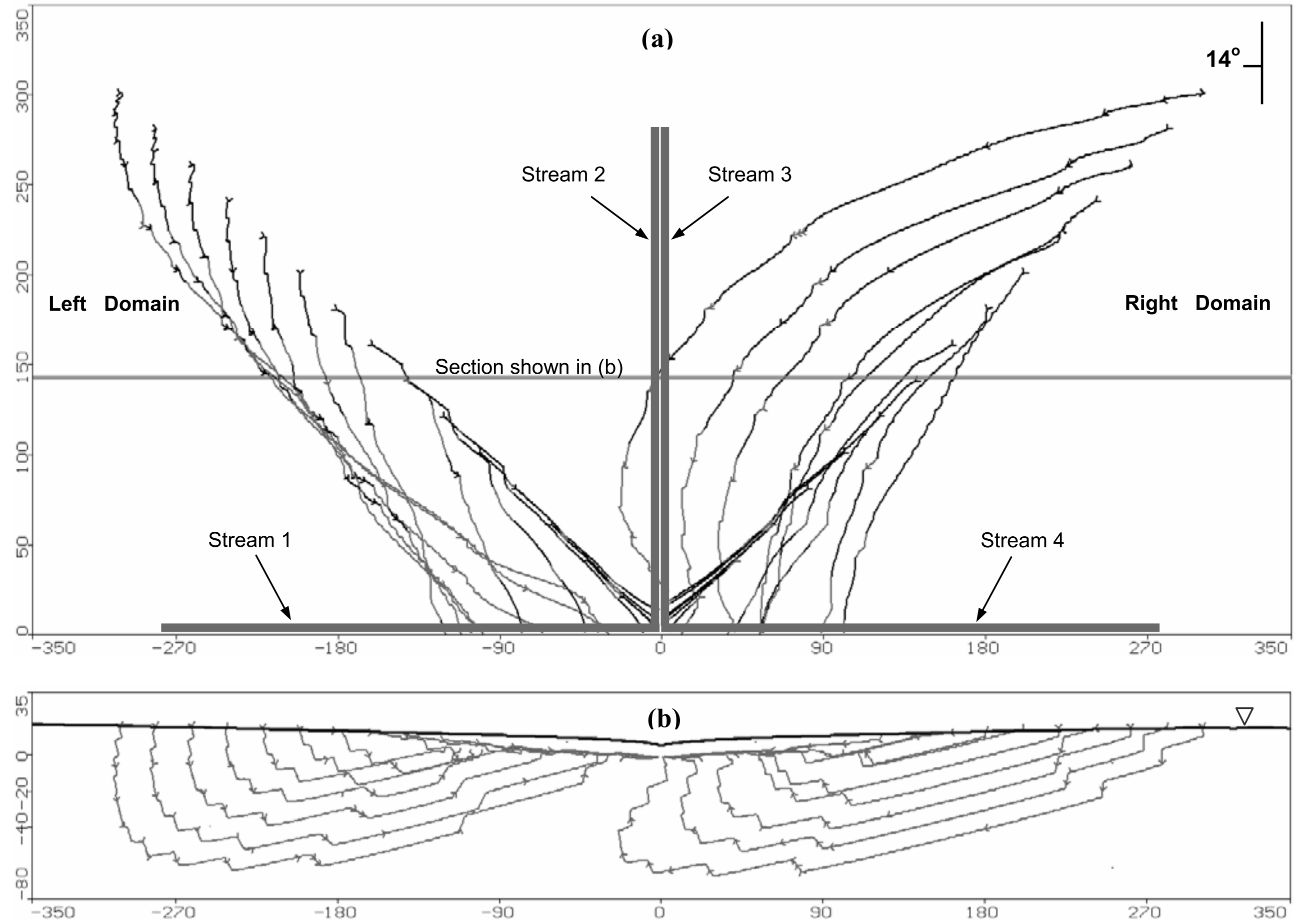

Figure 6. Simulated flow pathways for a more permeable weathered zone, projected to (a) plan view and (b) cross-section view. Black segments are going into and gray segments are coming out of the page. Each tick mark on the path lines indicates 10 years of travel time.

the base case (section 3 and Table 1). The resulting anisotropy ratio is $K_1/K_2 = 16.7$. Thus the model medium is about 17 times more permeable along the beds than across the beds. This is not very different from the anisotropy ratio of 11 found by *Lewis-Brown and Jacobsen* [1995] and *Senior and Goode* [1999] by calibration to pumping test results.

[32] Bedding anisotropy is influenced by many factors in nature. It can result from small-scale anisotropy within a geologic unit with platy or flaky mineral structure. It can also result from large-scale heterogeneity. In the Newark basin, *Morin et al.* [1997] reported the frequent presence of high-angle joints (fractures) that cut across the beds (Figure 2). Provided that they are not sealed by secondary minerals, these open subvertical fractures can be important flow conduits, connecting bedding plane partings and allowing flow across the beds. Bedding anisotropy can also be influenced by the late stage, subhorizontal fractures reported by *El Tabakh et al.* [1998], which cut across the bedding planes as well as the high-angle joints. The effect of these across-bed fractures is to reduce the bedding anisotropy and hence flow distortion. To simulate a situation with significant across-bed flow, we increase the permeability of the confining units by five times, resulting in an anisotropy ratio of $K_1/K_2 = 3.9$. That is, permeability along the beds is only 4 times higher than across the beds.

[33] Results (Figure 7) show a reduced flow distortion compared to the base case, with a much stronger topographic-driven flow component. The strike to dip base flow ratio (Table 1) is reduced (1.12 versus1.28), as well as the left to right travel time ratio (1.38 versus 1.58). Thus frequent occurrence of across-bed fractures significantly reduces flow anisotropy and asymmetry.

4.3. Stratal Dip Angle

[34] The stratal dip angle may have a strong influence on the degree of flow distortion. For flow anisotropy, if the beds are horizontal, there will be no anisotropy in the x-y plane; the bedding structure only creates a horizontal to vertical anisotropy. If the beds are vertical, the flow field will exhibit the maximum anisotropy in the x-y plane. The question is: what happens in between? Does anisotropy increase with dip angle linearly or nonlinearly?

[35] For flow asymmetry, the end-members are harder to define. If the beds are horizontal, there will be no asymmetry. If the beds are vertical, there will be no asymmetry either. The question is: at what dip angle does the flow exhibit the greatest asymmetry?

[36] To answer these questions, we constructed six more models with different dip angles. These, together with the base case at 14°, give us seven scenarios with the following dip angles: 0°, 7.1°, 14.0°, 26.6°, 45.0°, 63.4° and 90.0°.

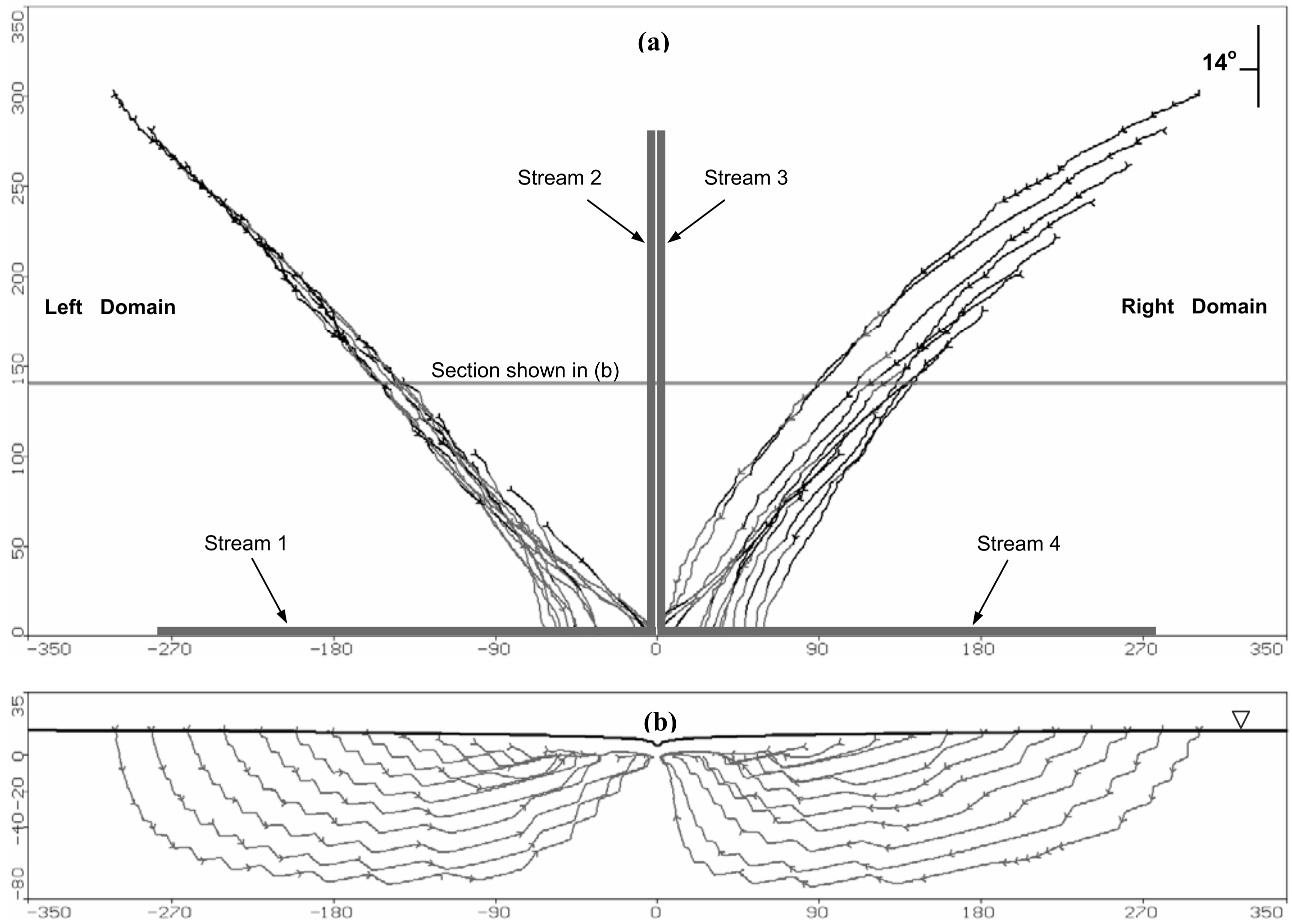

Figure 7. Simulated flow pathways for weaker bedding anisotropy, projected to (a) plan view and (b) cross-section view. Black segments are going into and gray segments are coming out of the page. Each tick mark on the path lines indicates 10 years of travel time.

Construction of K fields at these angles is illustrated in Figure 4c. Similar bed thickness, measured across the beds, was maintained for all seven models to the extent possible. The bed thickness for the transmitting zones is, 2.000, 1.985, 1.940, 1.789, 2.121, 2.236, and 2.000 m, respectively, for the seven dip angles. The confining zones are four times thicker in each case. This variation in bed thickness will not affect the flow since bedding anisotropy (see section 4.2) is the same as long as the transmitting and confining units are proportionally varied, as is the case here.

[37] Figure 8 shows the simulated particle pathways for the seven dip angles, together with a homogeneous and isotropic case discussed later. For each angle, the top plot gives the plan view of the pathways, and the bottom plot gives the cross section. The plan views show an increasing along-strike flow component with increasing dip angle, best reflected by the pathways in the left domain (the southward swing). The dip to strike base flow ratio (Table 1) increases with dip angle, from 1.00 at horizontal to 3.18 at vertical beds. As shown in Figure 9a, the increase in anisotropy is gradual at low dip angles, is slightly steeper as the angle increases, and becomes gradual again. The trend is slightly nonlinear.

[38] The plan views in Figure 8, particularly the pathways in the right domain, show an increasing downdip flow, best reflected by the pathways in the right domain (the westward swing), from horizontal to beds dipping at 14°. At higher angles, it decreases with increasing dip angle until there is no downdip flow at all where the beds are vertical. The left to right travel time ratio (Table 1) also reflects this pattern.

[39] Because groundwater travel time depends on the effective porosity (n_e) of the media, the choice of this parameter will affect the travel time ratio. Results shown in Table 1 are obtained with the same n_e value (0.15) for both the transmitting and confining beds, as well as the weathered zone. For unconsolidated material, the effective porosity is not different from the total porosity for flow of water. For fractured media, the effective porosity for transmitting flow is primarily in the open and connected fractures, not the matrix due to the extremely low matrix porosity. Because the water-transmitting zones are associated with abundant and connected fractures, it can have a higher n_e than the confining beds. However, the subvertical joints that cut across the beds are equally or more frequent than the bedding fractures in some cases [*Morin et al.*, 1997]. Because groundwater flow tends to cross (versus parallel) the low-permeability units, these across-bedding joints can significantly enhance the effective porosity. Hence it is not clear which unit may have a higher n_e. To incorporate this uncertainty, we simulate the travel times with three sets of n_e values, 0.20 for the high-K and 0.10 for the low-K unit, 0.15 for both (reported in Table 1), and 0.10

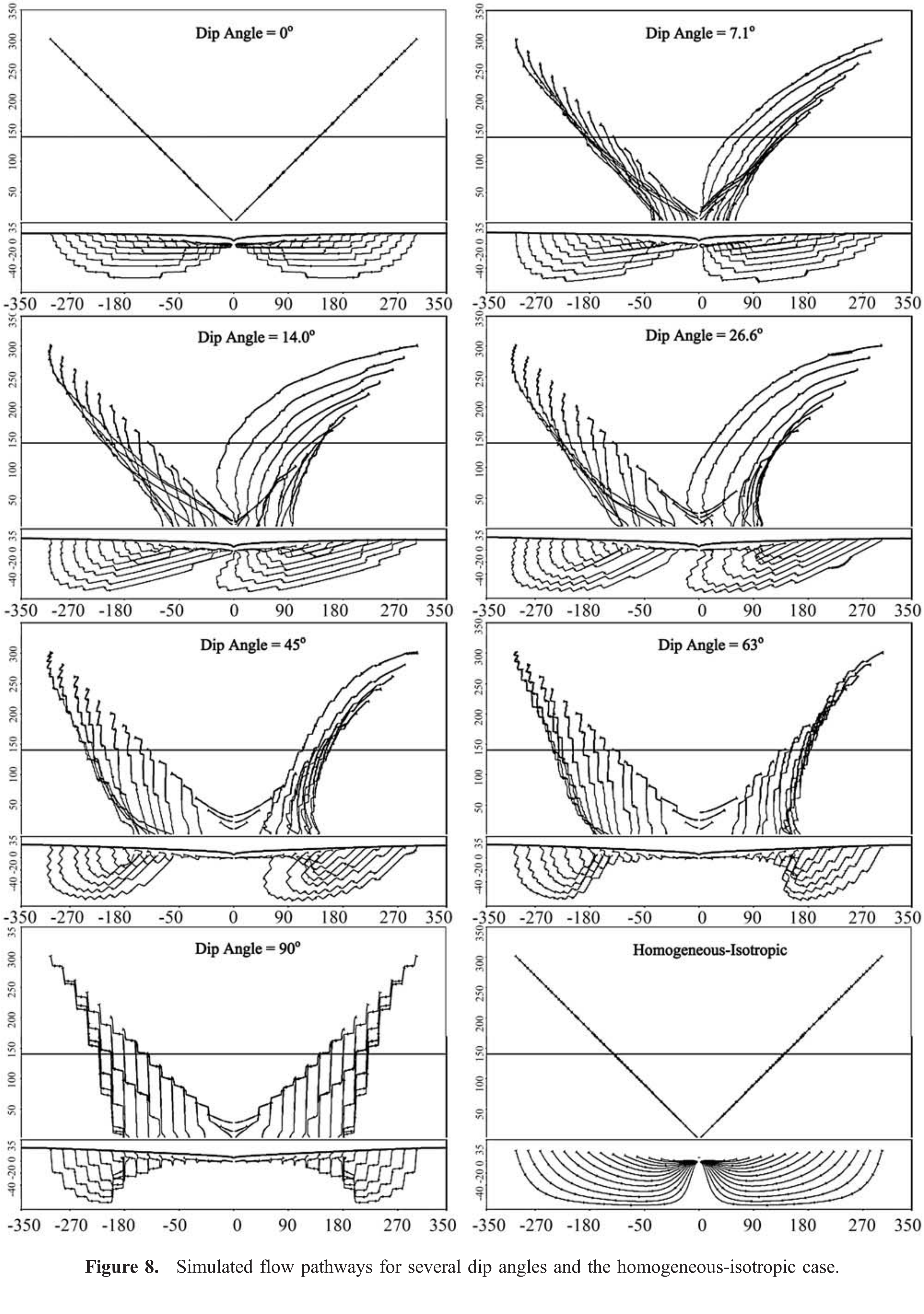

Figure 8. Simulated flow pathways for several dip angles and the homogeneous-isotropic case.

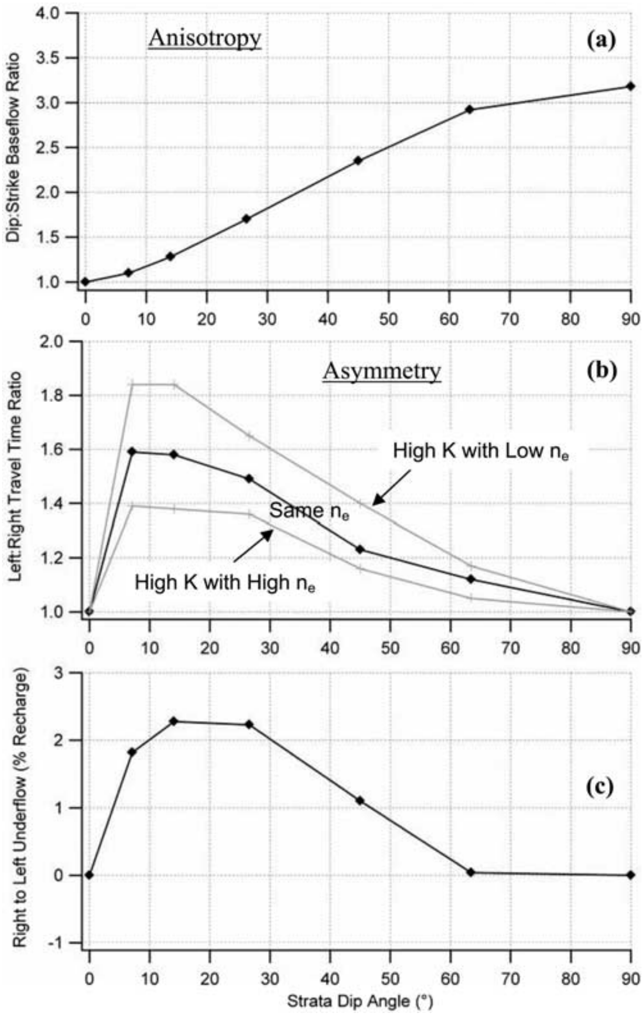

Figure 9. Effect of strata dip angle: (a) dip:strike ratio in base flow, a measure of flow anisotropy, (b) left:right ratio in particle travel time, a measure of flow asymmetry, and (c) groundwater flow under the central streams from the right to the left domain, as percent recharge.

for the high-K and 0.20 for the low-K unit. This gives a range of plausible travel time ratios, as plotted in Figure 9b in gray lines. Because the right domain is dominated by along-bed flow and the left domain by across-bed flow, the 0.20–0.10 case slows down the flow in the right and gives a lower travel time ratio, and the 0.10–0.20 case gives a higher ratio.

[40] Despite the range of uncertainty, flow asymmetry, as measured by the travel time ratio, appears the greatest where the beds are dipping at an angle near 14°, as shown in Figure 9b. Thus the results suggest that there is a threshold angle at which the flow field exhibits the greatest asymmetry.

[41] Why does the system have a threshold angle? Does this angle reflect some intrinsic flow properties of the system? We propose the following as a possible explanation. Flow asymmetry occurs when flow on one side is facilitated and flow on the other side suppressed. When the threshold angle coincides with preferential flow pathways of the same system but without the dipping structure, the asymmetry may be enhanced. To test the idea, we examined the flow pathways in an equivalent homogeneous and isotropic system, where groundwater flow is solely controlled by the topography-stream system, without structural control. The simplest way to do so is by looking at the system aspect ratio, the ratio of the vertical dimension of the flow domain to the horizontal dimension. If recharge enters the flow domain at the water table, and if discharge is a gaining stream down the topographic gradient, then for a particle originating at the water table near the divide, it will descend the entire vertical flow depth (H) and traverse a horizontal distance L from source to sink. Therefore the flow domain aspect ratio, H/L, may control the groundwater flow pathways to some extent. This ratio, converted to an angle, may reflect the mean direction of groundwater flow.

[42] To assess the water table height near the divide in an equivalent homogeneous and isotropic system, we performed a simulation using uniform K values (0.1 m/d, the geometric mean of the three K zones). The resulting water table height, measured from the base of the system, is H = 96.4 m under the upper corners of the model. As shown by the pathways in Figure 8 for the homogeneous-isotropic case, a particle originating at the upper corner of the model will travel toward the stream junction. The travel distance is hence $L = 350\sqrt{2}$ m, which yields an aspect ratio of $H/L = 0.1948$ and an angle $\beta = \tan^{-1}(0.1948) = 11.02°$. Thus, without structural control, groundwater prefers to travel at this angle on the average. This value is close to the threshold in Figure 9b of the greatest flow asymmetry. Thus it is likely that a given flow system, without structural control, may favor a flow pathway at a certain angle, and when the dipping beds are introduced, the effect is to assist flow in the updip domain. If the beds happen to be dipping at a similar angle, then the beds further enhance the flow in the updip domain and increase asymmetry. Note that for a different topography-stream-aquifer system, modeled or natural, the aspect ratio will vary, leading to a different threshold angle of greatest asymmetry. The shallower the flow system, the smaller this threshold will be.

[43] Because the mechanism for flow asymmetry is the downdip flow component, we also plot the underflow as a function of the dip angle in Figure 9c. As expected, the angle of the greatest underflow corresponds to that of the greatest asymmetry.

5. Summary and Discussion

[44] Groundwater flow is influenced by topography, but in dipping strata, it is also influenced by the underlying structure. Field evidence indicates that flow pathways follow the direction of the strike in some cases, but follow the topography toward local streams in others. Field evidence also indicates that groundwater is older on the downdip side of a strike-aligned stream, and model simulations suggest that dip-aligned streams receive more base flow than strike-aligned streams. The goal of this study was to help understand these observations, using a set of numerical models designed to assess the effect of both topography and structure.

[45] Groundwater flow in this setting is characterized by three flow components: down the topographic gradient, down the dip, and along the strike. The along-strike flow creates a flow anisotropy, expressed as deflection of flow

pathways in the strike direction as well as disparity in stream discharge between along-strike and along-dip streams. The downdip flow creates a flow asymmetry, expressed as deflection of flow pathways in the downdip direction as well as disparity in groundwater residence times on the opposite sides of a strike-aligned stream.

[46] The degree of anisotropy and asymmetry depends on several factors: the higher the transmissivity in the weathered horizon, the less important the fracture control; the greater the contrast between across-bed and along-bed permeability, the greater the flow anisotropy and asymmetry; and, the larger the bed dip angle, the greater the anisotropy but not asymmetry. Asymmetry reaches a maximum at a threshold angle, and this angle is related to the mean groundwater flow direction in an equivalent homogeneous and isotropic system.

[47] One practical implication of the results is that there is a greater hydraulic connection between surface water and groundwater if the streams are aligned with the dip, which may have relevance to water quantity and quality issues. It may also have theoretical implications for stream network morphology. For example, if the streams are primarily fed by groundwater, as they are in humid climate, and if dip-aligned streams receive more inflow than strike-aligned streams, it may be possible to see wider and shorter channels along the dip.

[48] The results may also have implications to groundwater modeling using effective parameters. The particles in Figure 5b follow the bedding planes while maintaining their course toward the streams. In doing so, the particles on the left are forced to penetrate the beds, and the particles on the right mostly travel along the beds. This gives rise to a higher overall flow resistance on the left. This asymmetry in the apparent resistance may suggest one way to simulate the observed older age on the downdip side, without explicit use of dipping beds, by using an ‘‘effective’’ resistance. Employing an anisotropy ratio in the x-y plane can enhance the along-strike flow component and generate the right degree of flow anisotropy. However, anisotropy in K will not generate flow asymmetry. Because flow asymmetry is induced by the downdip flow component, perhaps there is a way to enhance this flow component with another effective parameter.

[49] In conclusion, what controls the flow pathway of a particle or a contaminant plume in dipping strata depends on where it originates in the topography-stream versus dipping beds system. This may help explain the observation of *Orabone* [1997] that no single factor seems to control the migration of the large number of plumes he studied. The relative importance of topographic versus structural control on groundwater flow pathways will vary greatly from site to site. The complexity of natural sites means that it may not be possible to use a single conceptual model, but models must be based on the hydrostratigraphy of each site. The modeling study here suggests the important features to consider.

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Y. Fan and R. W. Schlische, Department of Geological Sciences, Rutgers–State University of New Jersey, Wright Labs, 610 Taylor Road, Piscataway, NJ 08854-8066, USA. (yingfan@rci.rutgers.edu; schlisch@rci.rutgers.edu)

L. Toran, Department of Geology, Temple University, 1901 North 13th Street, Philadelphia, PA 19122, USA. (ltoran@temple.edu)