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Regional groundwater flow in mountainous terrain: Three-dimensional simulations of topographic and hydrogeologic controls

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[1] This study uses numerical simulations to define the salient controls on regional groundwater flow in 3-D mountainous terrain by systematically varying topographic and hydrogeologic variables. Topography for idealized multiple-basin mountainous terrain is derived from geomatic data and literature values. Water table elevation, controlled by the ratio of recharge to hydraulic conductivity, largely controls the distribution of recharged water into local, regional, and perpendicular flow systems, perpendicular flow being perpendicular to the regional topographic gradient. Both the relative (%) and absolute (m^3/d) values of regional flow and perpendicular flow are examined. The relationship between regional flow and water table elevation is highly nonlinear. With lower water table elevations, relative and absolute regional flow dramatically increase and decrease, respectively, as the water table is lowered further. However, for higher water table elevations above the top of the headwater stream, changes in water table elevation have little effect on regional flow. Local flow predominates in high water table configurations, with regional and perpendicular flow <15% and <10%, respectively, of total recharge in the models tested. Both the relative and the maximum absolute regional flow are directly controlled by the degree of incision of the mountain drainage network; the elevation of mountain ridges is considerably less important. The percentage of the headwater stream with perennial streamflow is a potentially powerful indicator of regional flow in all water table configurations and may be a good indicator of the susceptibility of mountain groundwater systems to increased aridity.

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1. Introduction

[2] Regional groundwater flow between watersheds or basins is common in a wide variety of topographic and hydrogeologic settings [*Thyne et al.*, 1999; *Winter et al.*, 2003]. *Tóth* [1963] first modeled interbasinal groundwater flow and defined local, intermediate and regional groundwater systems on the basis of the length of groundwater travel between recharge and discharge locations (Figure 1a). Constraining regional groundwater flow is critical for conceptualizing groundwater systems at a variety of scales and understanding fundamental Earth processes including fluid flow in sedimentary basins, surface water-groundwater interaction, wetland hydrology, regional heat flow and geochemistry, and the role of groundwater in the formation of petroleum and mineral deposits [*Hitchon*, 1969; *Domenico and Palciauskas*, 1973; *Schwartz and Domenico*, 1973; *Winter*, 1978; *Tóth*, 1980; *Garven and Freeze*, 1984a, 1984b; *Garven*, 1989, 1995; *Person et al.*, 1996; *Hobday and Galloway*, 1999; *Winter*, 1999]. Complex interrelationships between topography, climate and geology control regional groundwater flow paths and the distribution of discharge [*Winter*, 2001]. These relationships have been examined using simplified, two-dimensional models [*Tóth*, 1963; *Freeze and Witherspoon*, 1966, 1967; *Winter*, 1978]. However, these relationships have not been systematically examined in three-dimensional, multiple-basin settings or in rugged topography where the relationships between topography and groundwater flow may be less intuitive.

[3] Mountainous terrain occupies a significant portion of Earth's land surface [*Gerrard*, 1990; *Meybeck et al.*, 2001], yet mountain groundwater systems are generally poorly understood [*Forster and Smith*, 1988]. Mountain glaciers, snowpack and groundwater are important contributors to lowland rivers and aquifers at both basin and continental scales [*Alford*, 1985; *Wohl*, 2000; *Viviroli and Weingartner*, 2004; *Wilson and Guan*, 2004; *Manning and Solomon*, 2005]. Mountain groundwater systems may become increasingly critical, especially in arid or semiarid regions, as glaciers ablate or aridity increases owing to climate change. Mountain groundwater systems are typically conceptualized and modeled as 2-D cross sections [*Jamieson and Freeze*, 1983; *Forster and Smith*, 1988], 3-D singular basins with no lateral recharge from adjacent basins [*VanderBeek*, 2003; *Kahn et al.*, 2007; *Manning and Caine*, 2007] or 3-D multiple basin systems without surface water [*Maréchal et*

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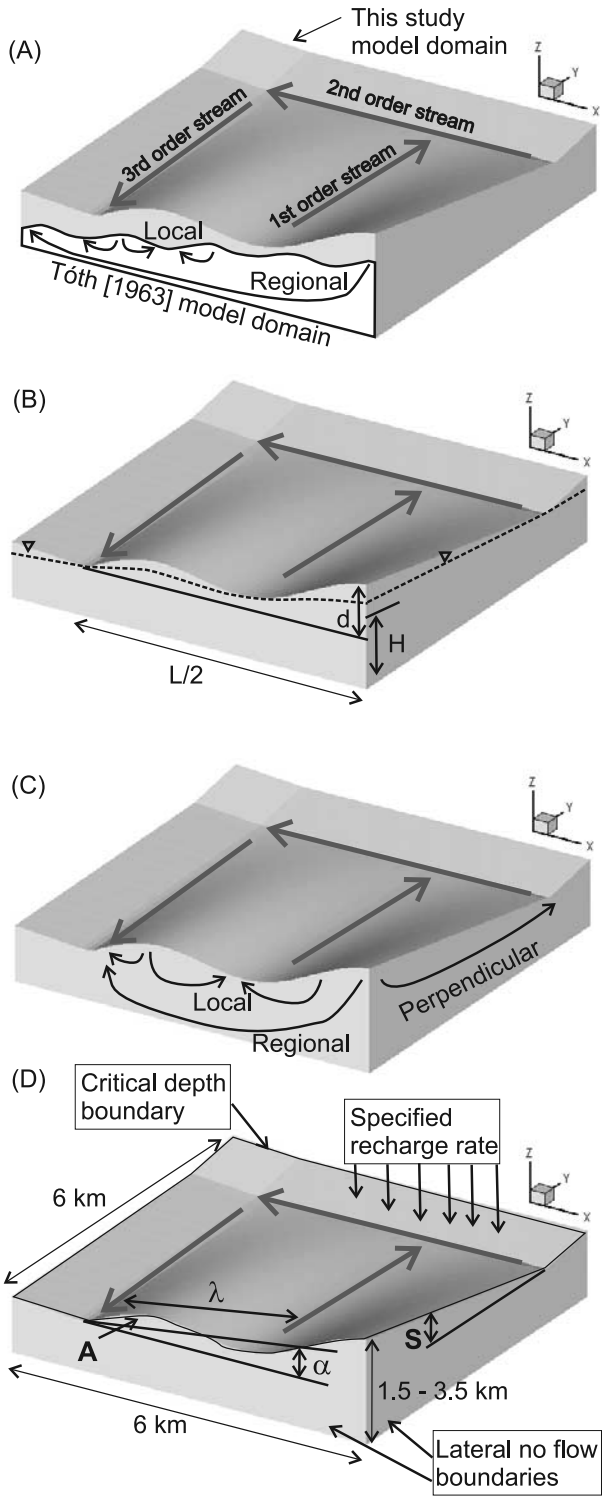

Figure 1. Development of 3-D multiple basin model domain. (a) Model domain relative to model domain of *Tóth* [1963]. (b) The geometric variables for classifying regional groundwater tables from *Haitjema and Mitchell-Bruker* [2005]. (c) Local, regional and perpendicular flow zones as defined in this study. (d) Topographic variables used to define relief and boundary conditions. See sections 2 and 3 for additional explanation of each variable.

al., 1999]. In mountainous terrain underlain by crystalline rock, a layer of higher-permeability rock hundreds of meters thick (active layer) often overlies lower-permeability rock at depth (inactive layer) [*Snow*, 1973; *Maréchal and Etcheverry*, 2003; *Manning and Caine*, 2007]. In crystalline and other lower-permeability regions, existing data (though limited) suggest that water tables are often relatively close to the land surface, even below high ridges [*Robinson et al.*, 1974; *Tiedeman et al.*, 1998; *Bossong et al.*, 2003; *Caine et al.*, 2006]. High-relief and high-water table elevations suggest that significant gravity-driven regional flow could be present in mountainous terrain. However, regional flow may be limited by other factors such as the incision of mountain valleys and very low permeability at depth within the mountain mass.

[4] The objective of this study is to define the salient controls on regional groundwater flow in three-dimensional mountainous terrain by systematically exploring the relationship between topographic and hydrogeologic variables and regional groundwater flow. Long-term regional groundwater flow and discharge patterns are examined in idealized mountainous terrain using a numerical model describing fully integrated subsurface and surface flow. The idealized mountainous terrain comprises first-, second-, and third-order drainage basins with topography defined by sinusoidal functions and stream gradients. Typical values for stream gradient, valley wavelength, amplitude, flank slope, hydraulic conductivity, and recharge are derived from hydrologic and geomatic literature. Three distinct types of mountainous terrain are modeled: high relief (e.g., Himalaya), moderate relief (e.g., Rocky Mountains), and low relief (e.g., Appalachians). Additionally, using the moderate relief as a base case, we examine the sensitivity of regional groundwater flow to different topographic and hydrogeologic variables. By determining the controls on regional groundwater flow in mountainous terrain, we develop a framework for hydrogeologists and managers to evaluate, understand and predict the potential importance of regional groundwater flow in a variety of topographic and hydrogeologic settings.

2. Problem Description

[5] This study uses numerical simulations to evaluate the role of topographic and hydrogeologic variables in controlling long-term, deep groundwater systems in mountainous terrain. Long-term patterns are examined by focusing on steady state solutions. Numerical simulations, rather than analytical solutions, are used because analytical solutions are limited to simple and specific topographic configurations and hydrogeologic parameters. A model domain is designed to represent a typical network of three mountain drainage basins of increasing magnitude with first-, second-, and third-order streams in each drainage basin (Figure 1a). The first- and second-order streams are a headwater and secondary stream, respectively, which may or may not have perennial flow for their entire length depending on the water table configuration. The third-order stream is a tertiary river with perennial flow. The physical dimensions of the model are limited to a typical mountain basin network, with a depth restricted to 1 km below the lowest point in the topography. A wide variety of topographic settings are modeled but every simulation has typical mountain river

gradients [*Wohl*, 2000] and is consistent with accepted definitions of mountain topography [*Gerrard*, 1990].

[6] The configuration of the water table in relation to surface topography is critical for determining groundwater flow and discharge patterns. Water tables can be categorized into recharge controlled or topography controlled [*Sanford*, 2002; *Haitjema and Mitchell-Bruker*, 2005]. Topography-controlled water tables are common in humid, subdued or low-permeability terrain where actual recharge rates exceed the potential infiltration capacity and water tables are a subdued replica of topography. Recharge-controlled water tables are common in arid, rugged, or high-permeability terrain where actual recharge rates are less than the potential infiltration capacity. *Haitjema and Mitchell-Bruker* [2005] use the Dupuit-Forchhemier approximation to suggest that recharge-controlled and topography-controlled water tables can be differentiated using the following dimensionless criterion:

$$\frac{RL^2}{mKHd} \rangle 1 \text{ for topography controlled water table}$$

$$\frac{RL^2}{mKHd} \langle 1 \text{ for recharge controlled water table}$$

where R (m/a) is the areal recharge rate which is constant across the domain, K (m/d) is the hydraulic conductivity, L (m) is the distance between significant (i.e., third-order) streams [*Haitjema and Mitchell-Bruker*, 2005]. L is equivalent to double the distance between the regional groundwater divide and the third-order stream in Figure 1; the model domain is conceptualized as having a mirror image to the right. The average aquifer thickness is H (m), d (m) is the maximum terrain rise, and m (unitless) is either 8 or 16, depending on the flow problem being one-dimensional or radially symmetric, respectively (Figure 1b; see also *Haitjema and Mitchell-Bruker* [2005]). For recharge-controlled water tables, a larger proportion of flow is regional [*Haitjema and Mitchell-Bruker*, 2005]. However, the validity of the above criterion for distinguishing recharge-controlled from topography-controlled water tables in more complex and rugged 3-D topography has not been tested. We examine the critical transition from topography-controlled to recharge-controlled in the three different types of mountain relief, compare this transition to that predicted by the above criterion, and test how water table configuration affects regional groundwater flow.

[7] *Tóth* [1963] differentiated local, intermediate and regional groundwater systems on the basis of the length of groundwater travel between recharge and discharge locations (Figure 1a). In local systems, groundwater recharges and discharges in the same drainage basin whereas in intermediate systems groundwater discharges in a drainage basin down-gradient from that in which it recharged. In regional systems, groundwater recharges in the uppermost basin and discharges in the lowermost basin [*Tóth*, 1963]. Therefore in the domain illustrated in Figure 1, regional flow is recharged in the first- or second-order drainage basin and discharged in the third-order drainage basin (Figure 1c). Similarly, a new type of flow system is introduced, namely perpendicular flow, which can be defined as flow recharged in the first-order drainage basin and discharged in the second-order drainage basin. Since the recharge rate is constant across the domain, all discharge in a basin in excess of the recharge rate is directly attributable to interbasinal flow. Therefore the regional and perpendicular flows can be calculated as:

$$Q_{\text{regional}} = Q_{\text{discharge third}} - Q_{\text{recharge third}}$$

$$Q_{\text{perpendicular}} = Q_{\text{discharge second}} - Q_{\text{recharge second}}$$

where Q (m^3/d) is a flow rate either between basins (regional and perpendicular) or across the ground surface (discharge third, recharge third, discharge second and recharge second). $Q_{recharge}$ for a basin of interest is calculated by multiplying the recharge rate by the area of the basin. $Q_{discharge}$ is the summed steady state discharge for all the surficial nodes in the basin. Both the relative (%) and absolute (m^3/d) values of regional flow ($Q_{regional}$) and perpendicular flow ($Q_{perpendicular}$) are examined. The 2-D model described in the work of *Tóth* [1963] has five subbasins which makes it difficult to quantify the different flow systems (Figure 1a). Therefore an important contribution of this study is quantifying the components of local, regional, and perpendicular flow (Figure 1c) for the first time.

3. Numerical Methods

[8] Numerical modeling and finite element grid building are completed in *HydroGeoSphere* and *GridBuilder*, respectively [*McLaren*, 2005; *Therrien et al.*, 2006]. *HydroGeoSphere* is a three-dimensional, finite element, fully integrated subsurface and surface flow model, which is an extension of the original subsurface model of *Therrien and Sudicky* [1996]. *HydroGeoSphere* is used because it is a robust simulator of variably saturated conditions and surface water - groundwater interactions which has proven accurate for a variety of spatial and temporal scales [*Cey et al.*, 2006; *Li et al.*, 2008]. A modified form of the Richards' equation describes transient subsurface flow in a variably saturated porous media and areal surface flow is represented in the diffusion-wave approximation of the Saint Venant equation [*Therrien et al.*, 2006]. The model uses a dual node approach to couple surface and subsurface domains where a Darcy flux is computed between surface and subsurface domains. The two domains are assumed to be separated by a thin layer of porous media. This approach is generally more robust than the common node approach, also available in *HydroGeoSphere*, which assumes a continuity of head between the two domains. Details concerning the theory and numerical solution techniques of *HydroGeoSphere* are given in the work of *Therrien et al.* [2006]. *GridBuilder*, a flexible triangular mesh generator, is used because a new finite element grid is necessary for each topographic modification.

[9] The domain represents a three dimensional network of mountain basins measuring 6 km wide by 6 km long with a depth of 1 km below the lowest point in the topography (Figure 1d). The maximum height of the topography varies with the type of relief, as described below. The domain is

discretized into 100 m elements in each direction laterally, and 100 m elements vertically. The mesh is refined near the surface to 25 m elements where the main hydraulic head and water flux dynamics occur. This results in a domain of 54 000 nodes and 104 430 elements. Transient simulations from saturated initial conditions are executed until steady state conditions are derived in all simulations. Steady state, where discharge equals recharge (±0.1%), is typically attained after 30–100 years of model time. The robustness of the flow solution is tested by separate simulations where the nodal density is doubled and time steps are refined by a factor of ten. The elevation of the water table and discharge flows are consistent ±1 m and ±0.5%, respectively. Therefore the solution is considered insensitive to discretization and time step control.

[10] All lateral boundaries and the bottom of the domain are assigned no-flow boundaries (Figure 1d), like previous regional 2-D models [*Tóth*, 1963; *Freeze and Witherspoon*, 1966; *Garven and Freeze*, 1984a; *Forster and Smith*, 1988]. A constant annual areal recharge rate is specified and a critical depth boundary is applied at the surface around all lateral boundaries which allows surface water to exit. The specified flux recharges the variably saturated subsurface and discharges at or below the water table, a result of the dual node approach to coupling surface water and groundwater. Discharged groundwater then flows out of the model domain via the stream network. By specifying an annual recharge rate, the following are not explicitly considered: evapotranspiration, the role of the orographic effects on precipitation, the seasonal effects of snow accumulation and melting, or transient conditions, such as perched groundwater conditions which have been observed in mountainous terrain [*Johnson and Yager*, 2006]. In addition, the role of alpine glaciers or permeable surficial geology units is not considered. Finally, the model is assumed to be an equivalent porous media under isothermal conditions. The assumption of an equivalent porous media is justified by the large scale of the model [*Wellman and Poeter*, 2006] and by the generalized nature of both the model and our objectives. Anisotropy and heterogeneity of the hydraulic conductivity tensor, expected in mountain belts, is examined in the sensitivity analysis described below. Potential thermal effects on the flow system are not simulated because they probably are small at the depths modeled (<1 km below the lowest point in the topography) compared to other factors [*Forster and Smith*, 1988].

3.1. Defining Topography

[11] Topography is defined using values derived from the geomatic and hydrology literature and topographic maps of representative mountainous terrain. Mountainous terrain is categorized by its overall relief roughness into three types herein referred to as low relief, moderate relief and high relief [*Meybeck et al.*, 2001]. Relief roughness is defined as the difference between the maximum and minimum elevation (m) within a cell divided by the half-length (km) of the cell [*Meybeck et al.*, 2001]. Relief roughness therefore has dimensions of m/km or ‰. The mean and variance of relief roughness decrease with increasing scale [*Ahnert*, 1984] so the cell length must be specified on the basis of the scale of the interest. *Meybeck et al.* [2001] calculated relief roughness globally at a relatively coarse scale of 30 min grid resolution whereas relief roughness at a 5 km grid resolution is important for this study. Therefore a relief roughness at a 5 km scale is derived for various mountain regions of interest from the global 30 arc-second elevation data set or GTOPO30 using the aggregation and raster math tools in ESRI ArcMap9.2 (Figure 2). In this way reasonable values for relief roughness at the scale of the model domain are directly derived from available global digital elevation models.

[12] The topographic relief in the model domain is defined by stream gradients and sinusoidal functions oriented at an angle from horizontal, to remain consistent with relief roughness values. Defining topography as a sinusoidal function is considered a reasonable simplification of more complex mountainous terrain. Therefore, in the direction parallel to regional flow ("x" in Figure 1d), topography is defined by *Tóth* [1963]:

$$z = z_o + x\tan\alpha + A\frac{\sin(2\Pi x/\lambda\cos\alpha)}{\cos\alpha}$$

where z (m) is the elevation, x (m) is the horizontal distance, and z_o (m) is the depth to the base of the domain, which is 1000 m in this study (Figure 1d). The sinusoidal function is defined by the angle from horizontal or flank slope α (degrees), amplitude A (m) and wavelength λ (m), which is 3700 m in this study. Reasonable values for flank slope and amplitude are derived from topographic maps of representative mountainous terrain. The first-order stream gradient is the critical variable for defining topography perpendicular to the regional groundwater flow. First-order stream gradients are derived from measured natural gradients of bedrock and nonbedrock rivers in mountainous terrain [*Rosgen*, 1994; *Wohl*, 2000; *Wohl and Merritt*, 2001; *Brocklehurst and Whipple*, 2002; *Whipple*, 2004]. Second- and third-order stream gradients are assumed to be less than the first-order gradient. All stream gradients are assumed to be linear, which is a reasonable assumption for short mountain rivers [*Wohl*, 2000]. Table 1 summarizes the topographic input parameters for the three relief types.

3.2. Defining Subsurface and Surface Properties

[13] Subsurface and surface properties for the model are derived from the hydrogeology and hydrology literature. Hydraulic conductivity within mountain areas may be highly heterogeneous and anisotropic because mountain belts comprise a wide range of rock types and are often structurally complex. However, a homogeneous and isotropic hydraulic conductivity (K) of 10^{-7} m/s is assumed in most of our simulations because the objective of the modeling is to explore only the general behavior of groundwater flow on a regional scale in mountainous terrain rather than specific characteristics of groundwater flow in a particular geologic setting. This hydraulic conductivity is consistent with basin-scale bedrock hydraulic conductivity values derived in other modeling studies of mountainous terrain and studies of water inflows in mountain tunnels [*Jamieson and Freeze*, 1983; *Tiedeman et al.*, 1998; *Maréchal and Etcheverry*, 2003; *Manning and Solomon*, 2005]. The absolute value of the hydraulic conductivity is less important in determining relative regional groundwater flow amounts (the focus of this paper) than the ratio of recharge (R) to hydraulic conductivity because the R/K ratio

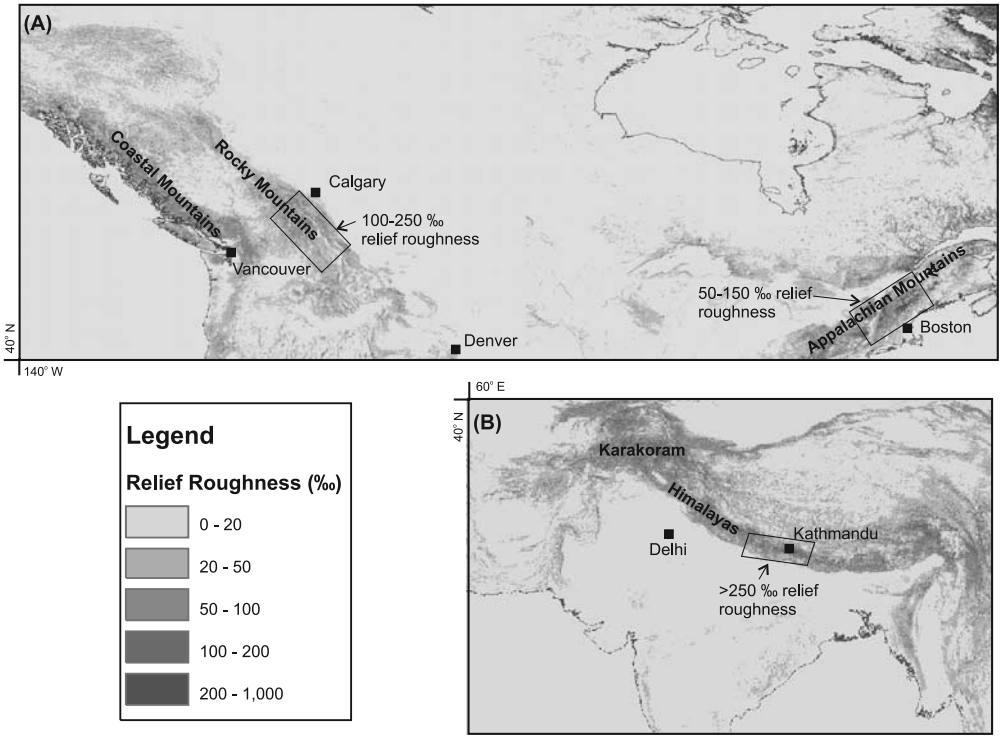

Figure 2. Relief roughness for the scale of a 5-km-long basin computed from GTOPO 30 global DEM for (a) northern North America and (b) northern Indian subcontinent. Both DEM are shown at a scale of 1:50,000,000.

directly determines the water table configuration [*Jamieson and Freeze*, 1983; *Haitjema and Mitchell-Bruker*, 2005]. A wide range of *R/K* values is implemented by varying *R* from 0.01 to 2 m/a. This range in *R/K* values represents a plausible range of values for arid to humid climates. The *R/K* ratio is directly analogous to the infiltration ratio (I^*) described by *Forster and Smith* [1988]. Table 2 outlines the variety of recharge rates and resultant *R/K* values for the various simulations.

[14] The impact of the assumptions of isotropy and homogeneity are evaluated by considering simple anisotropic and heterogeneous hydraulic conductivity (*K*) regimes. In anisotropic cases, K_x and K_y are both changed in order to maintain a constant bulk hydraulic conductivity of 10^{-7} m/s. In heterogeneous cases, we invoke a conceptual model in which an active layer of higher-permeability rock hundreds of meters thick overlies an inactive layer of lower-permeability rock at depth [*Snow*, 1973; *Maréchal*, 1999; *Manning and Caine*, 2007]. An active layer of varying thickness with a hydraulic conductivity of 10^{-7} m/s is simulated, and a hydraulic conductivity of 10^{-9} m/s is assigned to the inactive layer consisting of the entire domain below the active layer. Active and inactive layers are probably the norm in mountainous terrain [*Maréchal and Etcheverry*, 2003; *Mayo et al.*, 2003; *Manning and Caine*, 2007]. However, these layers are omitted (homogeneous *K* assumed) in the other model runs in this study because the purpose of these runs is to explore the influence of topography and water table configuration on regional flow independent of *K* heterogeneities. In all cases the vertical hydraulic conductivity (K_z) equaled the mean horizontal hydraulic conductivity.

[15] Surface properties (Manning roughness coefficient, the rill storage height and the obstruction height) are kept constant for all simulations and represent typical literature values for moderately rough terrain. The Manning roughness

Table 1. Topographic Parameters for the Three Relief Types[a]

Parameter	Value		
	Low Relief	Moderate Relief	High Relief
Flank slope, α (deg)	4°	**10°**	24°
Amplitude, A (m)	150	**250**	500
First river gradient, S	0.005	**0.03**	0.1
Second river gradient	0.005	**0.01**	0.05
Third river gradient	0.001	**0.01**	0.01
Relief roughness (‰)	80	**160**	380

[a]Simulation results for the three different relief types are presented in Figures 5–7. The base case in the sensitivity analysis is indicated by bold.

Table 2. Recharge Rate and Resultant *R*/*K* Value[a]

Recharge Rate (m/a)	*R/K* (unitless)
0.01	0.003
0.05	0.016
0.07	0.022
0.1	0.03
0.2	0.06
0.3	0.09
0.4	0.13
0.5	**0.16**
0.7	0.22
1	0.32
2	0.63

[a]The base case for the sensitivity analysis is indicated by bold.

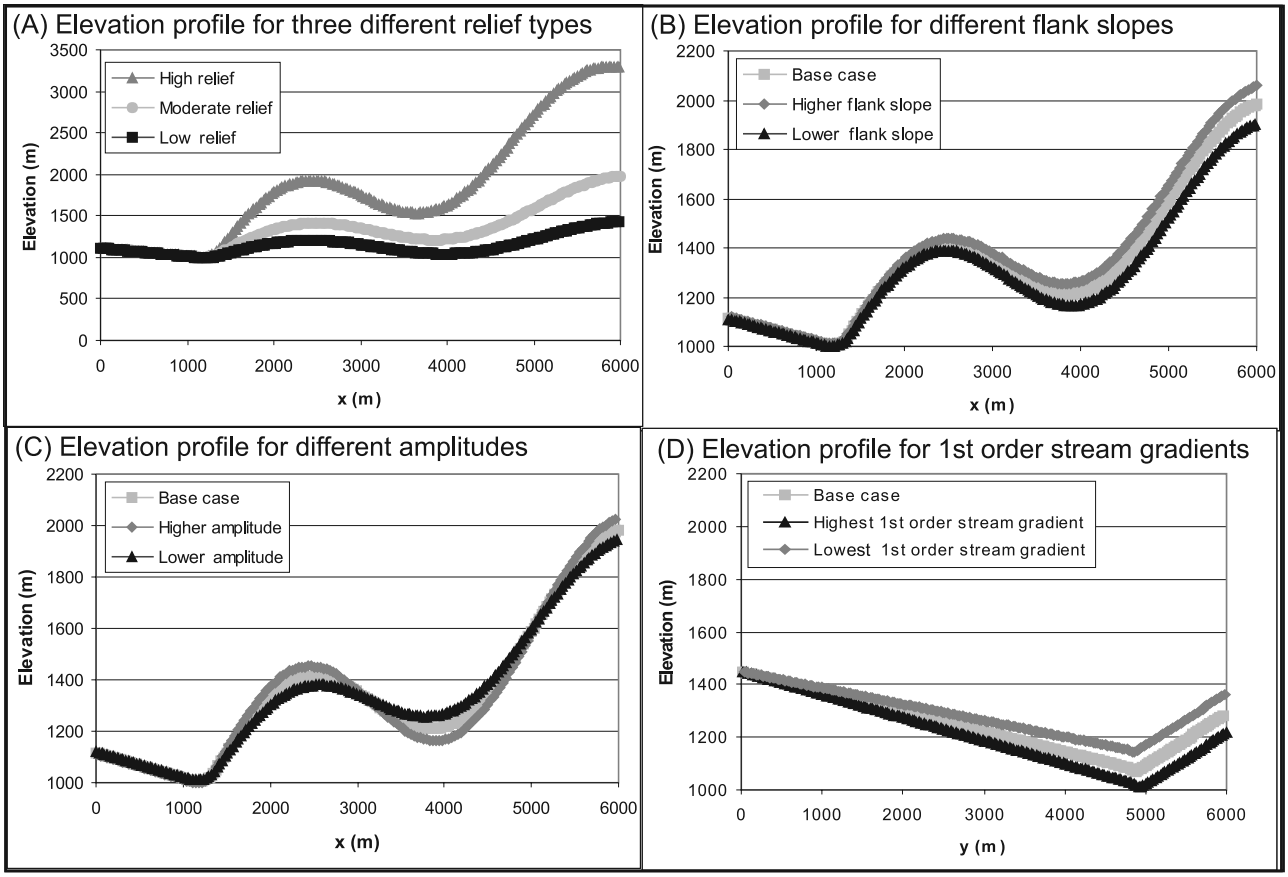

Figure 3. Elevation profiles for (a) the three different relief types and for (b) different flank slopes, (c) amplitudes, and (d) first-order stream gradients. The high and low values of Figures 3b–3d reflect the relief of simulations in the first component of the sensitivity analysis. All profiles are oriented in the x direction (parallel to regional flow) except Figure 3d, which is oriented in the y direction (perpendicular to regional flow). Note that the elevation scale on Figure 2a is larger than the remaining figures.

coefficient (in x and y), rill storage height and obstruction height are 3.5×10^{-6} $m^{-1/3}s$, 0.002 m and 0.25 m, respectively. Discharge patterns are insensitive to the surface properties because these values are sufficiently small to prevent ponding, which would redistribute hydraulic head and thus groundwater flow paths. A thorough description of the surface input parameters for *HydroGeoSphere* is given in the work of *Therrien et al.* [2006].

3.3. Simulated Cases

[16] The study consists of simulations of three different types of mountain relief and base case simulations for sensitivity analysis. The input parameters for the simulations of the three different mountain relief types are summarized in Table 1. Figure 3a illustrates representative topographic profiles for the three different relief types. High-relief topography represents extremely incised mountainous terrain such as the Himalaya or Karakoram. The Rocky Mountains or Alps are representative of moderate relief topography. Low-relief mountain topography is found in many parts of the world such as the Appalachian Mountains, Ural Mountains, and the Columbian or Tibetan Plateaus.

[17] Figure 4 outlines the methodology for the sensitivity analysis. A base case for the sensitivity analysis is chosen

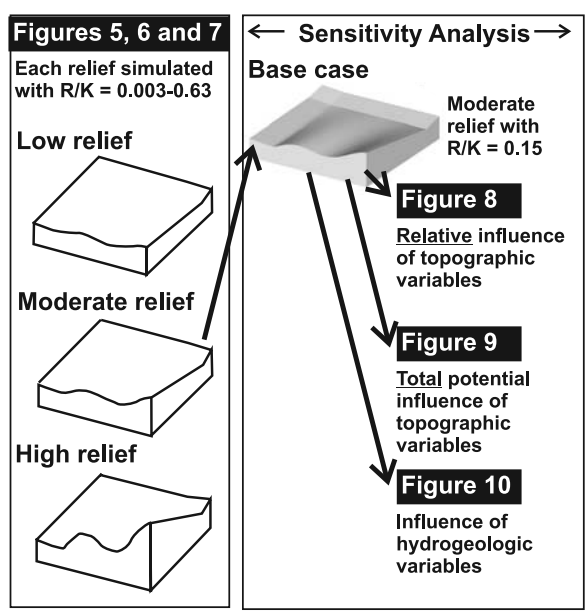

Figure 4. Outline of simulation methodology including sensitivity analysis.

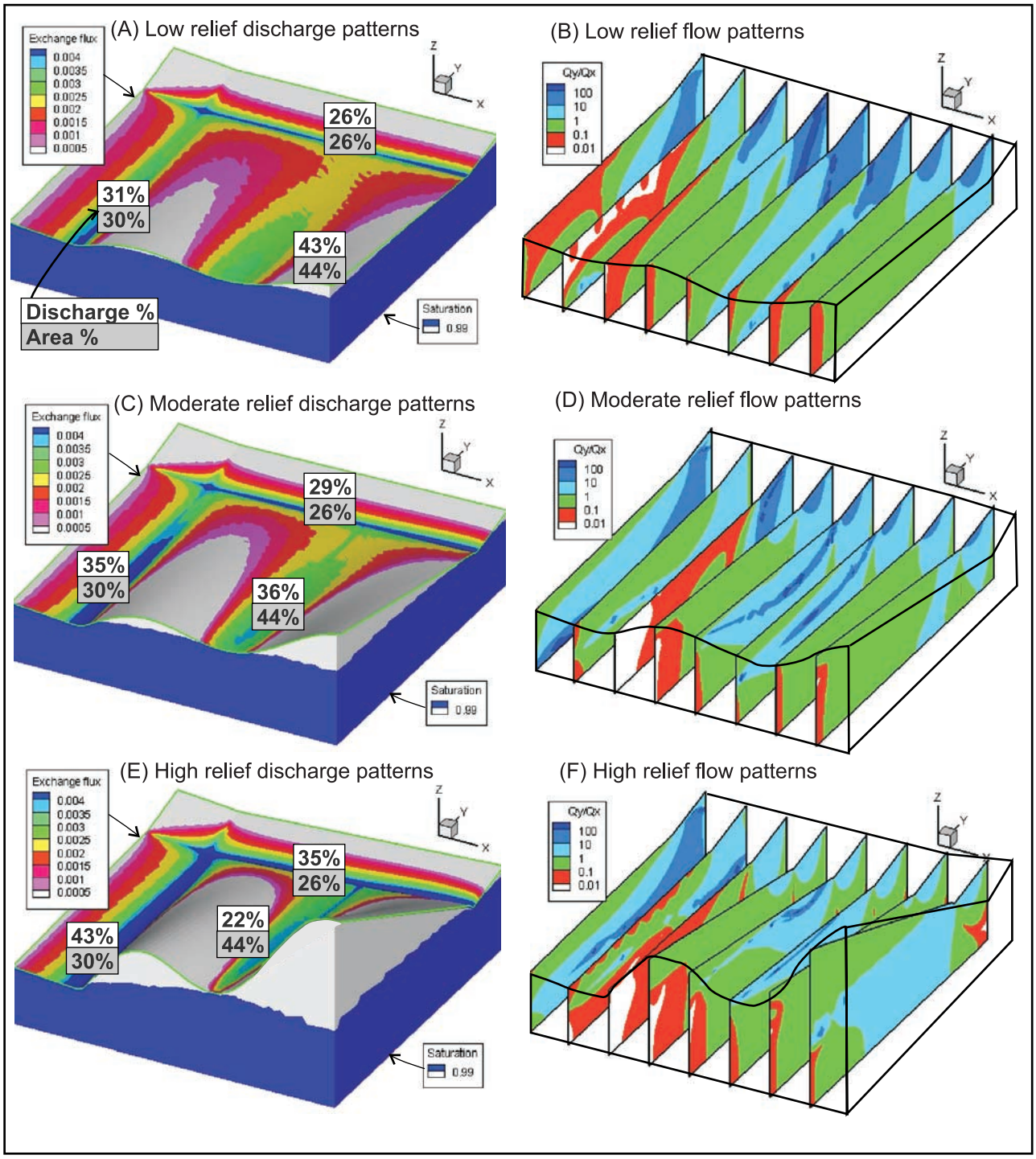

Figure 5. Discharge and flow patterns from simulations in different topographic settings with *R/K* equal to 0.16. Exchange flux (m^3/d) is the discharge rate. The percentage of total discharge (in white box) for the first-, second-, and third-order stream basins is compared to the percentage areal extent of each basin (in gray box). Zones where perpendicular flow is greater than regional flow are highlighted by Qy/Qx > 1.

which represents a topography-controlled water table configuration in a mountainous terrain of moderate relief. The recharge rate and *R/K* value for the base case are 0.5 m/a and 0.16, respectively. The sensitivity analysis is divided into three components each with a different purpose. In the first component, topographic parameters were varied moderately to determine the relative influence of each parameter on regional and perpendicular flow. The topographic variables (α, *A* and *S*) are independent only within a limited range of variation (independent range); larger changes in one of the variables outside of its independent range necessitate changes in one of the other two variables in

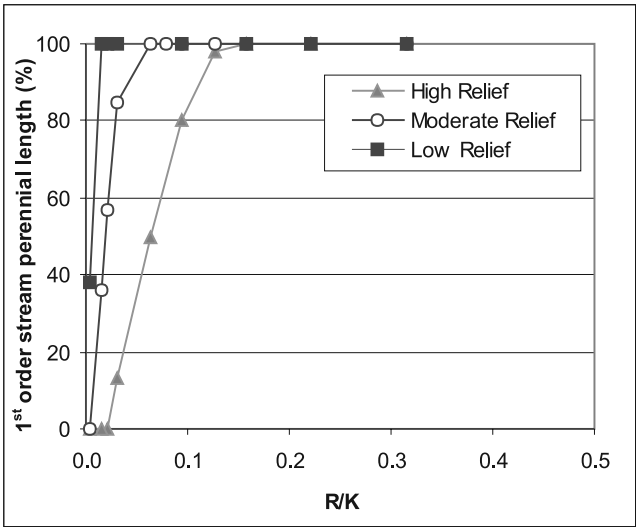

Figure 6. Increasing *R/K* values leads to higher water table elevations which result in higher percentage of perennial flow in the first-order stream.

order for all river gradients to remain positive and plausible. For example, a large decrease in flank slope results in negative second- and third-order stream gradients unless the first-order stream gradient is decreased. Therefore, in the first component of the sensitivity analysis topographic variables are only varied moderately, remaining within their independent range. Flank slope, amplitude and first-order stream gradient are varied from 9 to 11°, from 200 to 300 m and from 0.015 to 0.045, respectively. For each variable, changing its value results in a different part of the domain changing in elevation. For example, the first-order stream gradient modifies the elevation of the second-order drainage whereas the amplitude affects the elevation at the top of the first-order stream. Results of the different sensitivity runs are comparable because the elevation change of the affected part of the model domain is perturbed by approximately the same amount (~100 m) in each run (Figure 3).

[18] In the second component of the sensitivity analysis, the total potential influence of the two most important parameters for both regional and perpendicular flow are simulated. Only two parameters for each flow type are included because when the parameters are varied through their full likely range (beyond their independent range), the third must be varied. For example, regional flow is most sensitive to flank slope and amplitude so these parameters are simulated through their full likely range while modifying the first-order gradient as necessary. Perpendicular flow is most sensitive to first-order stream gradient and amplitude. The full likely range of each parameter is derived from topographic maps of 35 mountain basins in moderate relief mountainous terrain in Colorado and western Canada. The representative moderate relief basins generally have a range of flank slope, amplitude and first-order stream gradient of 5–15°, 125–500 m and 0.015–0.1, respectively.

[19] In the final component of the sensitivity analysis, simple anisotropic and heterogeneous cases are evaluated to determine their potential influence. Anisotropic cases with a range of K_x/K_y of 0.25 to 4 are executed. Heterogeneous cases with an active layer of 100 m, 200 m and 500 m are also simulated.

4. Simulation Results

4.1. Groundwater Flow in Different Mountain Relief Types

[20] Results of steady state simulations in the three different mountain relief types, with the same *R/K* ratio of 0.16, are represented in Figure 5. The flank slope, amplitude and river gradients increase with increasing relief roughness (Table 1). The water table in each simulation is above the top of the first-order stream but the differences in sinusoidal amplitude result in large differences in the depth of the unsaturated zone beneath of the mountain ridges between basins. Water table gradients also increase with relief roughness. The relief roughness clearly affects groundwater flow paths, as highlighted by the ratio of flow parallel to regional flow (Q_x) compared to flow perpendicular to regional flow (Q_y). Zones where $Q_y/Q_x > 1$ lead to significant relative $Q_{perpendicular}$ (Figure 5).

[21] Instead of examining Q_y/Q_x ratios, discharge patterns can be examined as a composite of all groundwater flow paths directing water away or toward a basin. Figure 5 illustrates how the percentage of the total discharge in each basin compares to the areal extent of the basin. The discharge rates in the second- and third-order basin can be used to calculate relative or absolute $Q_{perpendicular}$ and $Q_{regional}$, respectively, since the areal recharge rate is constant across the domain. In the low-relief model, the discharge percentages are approximately equal to the areal percentages of each basin so regional and perpendicular flows are limited (about 1% of total recharge). In the moderate and high-relief models, discharge percentage diverges from the areal percentage, indicating that larger regional and perpendicular flows are occurring (about 5–13% and 3–9% of total recharge, respectively). These results confirm that relief roughness is an important control on regional and perpendicular flow, and that regional and perpendicular flow should be expected in moderate to high-relief terrain. However, they also suggest that regional and perpendicular flow percentages should typically be modest (<15% and <10%, respectively) when water tables are near the land surface, even in the most rugged mountainous terrain on Earth.

4.2. The Role of Water Table Configuration

[22] The water table configuration is controlled by the ratio of recharge rate to hydraulic conductivity [*Jamieson and Freeze*, 1983; *Haitjema and Mitchell-Bruker*, 2005]; the *R/K* ratio was varied by over two orders of magnitude during this study. Higher *R/K* ratios lead to higher overall water table elevations and discharge in the side of basins. Note that such discharge may not actually reach the ground surface as springs or seeps, but might instead be evapotranspired or flow to the nearest stream within a shallow higher hydraulic conductivity zone (not included in the model) composed of soil and/or more weathered/fractured bedrock. Lower *R/K* ratios result in a lower water table elevation which shifts discharge to lower elevations and can result in unsaturated conditions in first- and second-order streams. The percentage saturated length of the first-order stream is the percentage length of perennial flow (Figure 6). The first-order stream becomes unsaturated at very low *R/K*

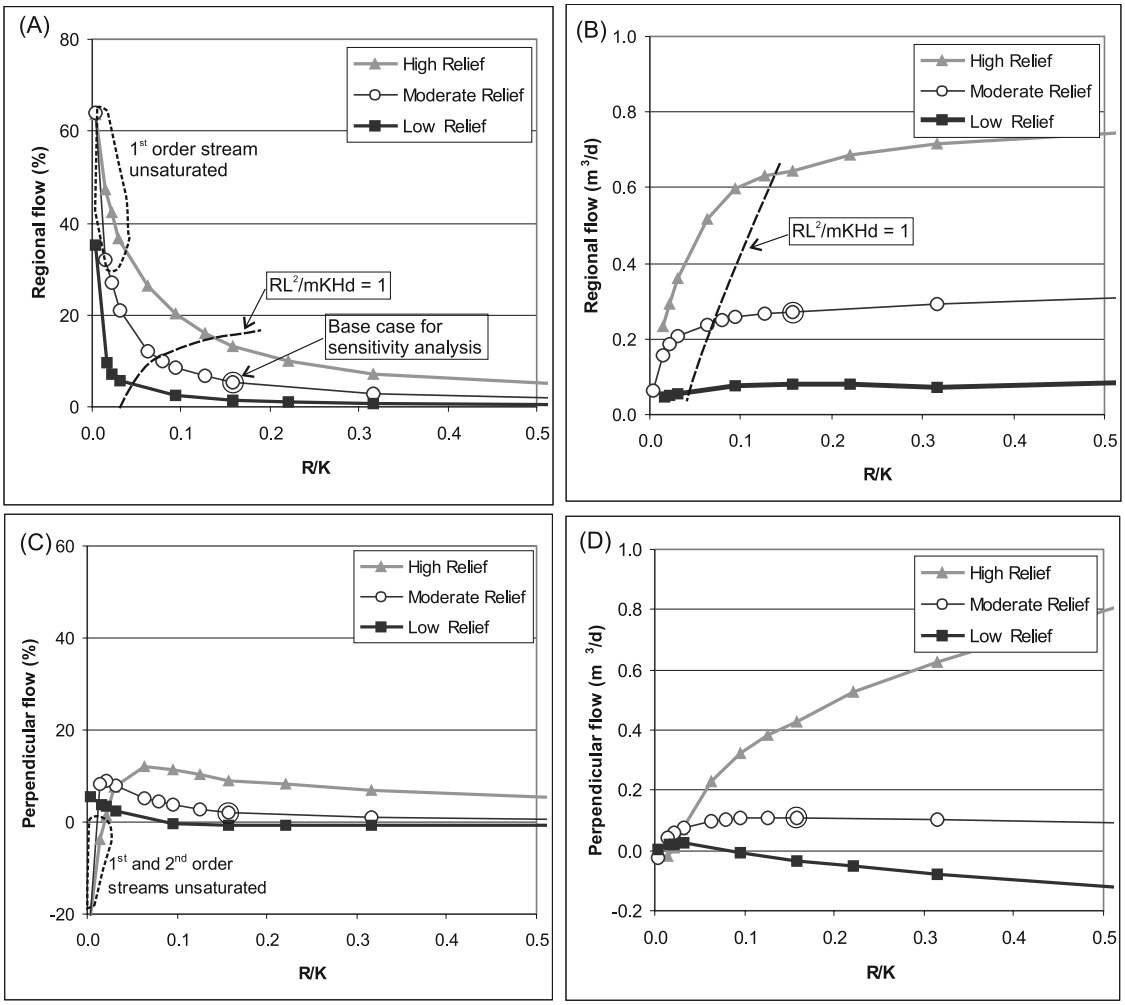

Figure 7. The role of *R/K* and resultant water table configuration in redistributing deep groundwater. (a and b) Regional and (c and d) perpendicular groundwater flow systems as a function of *R/K*. Relative (Figures 7a and 7c) and absolute (Figures 7b and 7d) flow volumes are quantified. See Figure 1c and sections 2 and 3 for definition of regional, perpendicular, relative and absolute flow, and *R/K*.

values in all relief types but it becomes unsaturated at higher *R/K* values in more rugged topography than in low-relief models (Figure 6). In all relief types, the perennial length of first-order stream is very sensitive to *R/K* once the water table is below the top of the first-order stream.

[23] The relative and absolute values of regional flow ($Q_{regional}$) and perpendicular flow ($Q_{perpendicular}$) reveal the role of water table configuration in redistributing deep groundwater (Figure 7). The relative $Q_{regional}$ is always larger than the relative $Q_{perpendicular}$. Decreasing the *R/K* ratio lowers the water table, leading to increasing relative regional and perpendicular flows, but decreasing absolute flows. The increase in relative flow indicates a redistribution of groundwater flow paths, owing to changing water table elevations, whereas the decrease in absolute flow reflects the decrease in the total amount of groundwater flowing through the model domain.

[24] For *R/K* ratios greater than 0.15, where the entire first-order stream is perennial, the relative regional and perpendicular flow comprise <15% and <10%, respectively, of the total flow. Relative and absolute regional flow approach asymptotic minimum and maximum values, respectively, in all relief types (Figures 7a and 7b). The relationship between *R/K* and both relative and absolute flows are near linear to linear under these high water table conditions. The high-relief simulations have higher relative and absolute flows, which is related to the steeper hydraulic head gradients. In the high water table simulations, the relative perpendicular flow is relatively constant (Figure 7c) while the trend in absolute perpendicular flow depends on relief type (Figure 7d). In high-relief simulations, the absolute perpendicular flow increases with higher *R/K* values but in moderate and low-relief simulations the absolute perpendicular flow decreases at higher *R/K* values (Figure 7d). Only the high-relief simulations have the relief necessary to result in absolute perpendicular flows similar in magnitude to absolute regional flows when water tables are elevated. In low-relief simulations, perpendicular flow is negative because water recharged in the second-order basin is contributing to regional flow by discharging in the first-order basin. The low-relief simulations with high *R/K* values are comparable in relief and water table configuration to the 2-D simulations of *Tóth* [1963] and *Freeze and Witherspoon* [1966, 1967]. This suggests that regional flow in these early

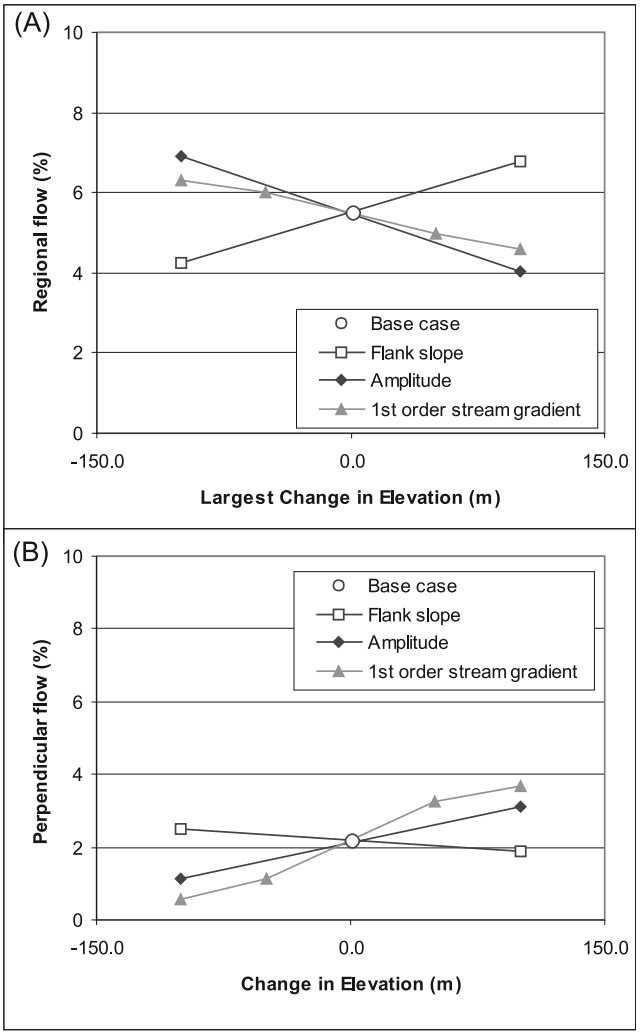

Figure 8. The sensitivity of (a) regional and (b) perpendicular groundwater flow systems to relative changes in topography during the first component of the sensitivity analysis.

2-D cross-sectional models was probably less than 5% of total flow.

[25] For *R/K* ratios less than 0.15 where the entire length of the first-order stream may not be perennial, relative regional flow increases dramatically (Figure 7a) as the first-order stream becomes unsaturated (Figure 6). However, at lower *R/K* values less water is infiltrating and exfiltrating the system, so the absolute regional flow actually decreases (Figure 7b). The relationship between *R/K* and both relative and absolute flow is highly nonlinear. The manner in which relative regional flow changes with *R/K* when $R/K < 0.15$ varies with relief roughness. In simulations of low, moderate and high relief the transition to significant (>10%) regional flow occurs at *R/K* values near 0.03, 0.06 and 0.15, respectively (Figure 7a). In low relief the transition toward more regional flow is less gradual than in high relief because in low-relief simulations there is a limited range of elevations in the first-order stream, so it switches abruptly from saturated to unsaturated (Figure 6). In these lower water table simulations, changes (mainly increases) in relative perpendicular flow (Figure 7c) are not as dramatic as the increase in relative regional flow (Figure 7a). In all relief types and *R/K* values, the relative perpendicular flow is less than about 10% of the total system flow. At very low *R/K* values, the second-order stream becomes partially unsaturated which results in negative perpendicular flow because $Q_{\text{recharge second}}$ is greater than $Q_{\text{dischange second}}$ (Figure 7c).

[26] *Haitjema and Mitchell-Bruker* [2005] developed the $RL^2/mKHd$ value to differentiate topography-controlled and recharge-controlled water tables. Since recharge-controlled water tables should have more regional flow [*Haitjema and Mitchell-Bruker*, 2005], the question of whether the $RL^2/mKHd$ value successfully predicts the shift toward more regional flow in mountainous terrain with topography more complex than that considered by *Haitjema and Mitchell-Bruker* [2005] is important. For all three relief types simulated in this study, $RL^2/mKHd = 1$ is indeed a good predictor for the onset of significant (>10%) relative regional flow (Figure 7a).

4.3. Sensitivity to Topographic and Hydrogeologic Variation

[27] The base case represents a topography-controlled water table configuration in a mountainous terrain of moderate relief such as the Rocky Mountains or Alps (Figure 4). The recharge rate and *R/K* ratio are 0.5 m/a and 0.16 respectively (Table 2). Relative regional and perpendicular flows are 5.5% and 2.2% respectively, of the total groundwater flow in the base case. In order to examine the sensitivity to topographic variation, the topographic variables were first varied moderately within their independent range (see section 3.3) such that the elevation in the affected part of the domain varied by a maximum of ~100 m in each simulation (Figure 3). The changes in relative flow are discussed below and represented in the remaining figures, but similar trends in absolute flow are observed.

[28] Figure 8 illustrates the relative sensitivity of regional and perpendicular flow to moderate topographic change. The sensitivity of regional or perpendicular flow is directly related to the steepness of the graphed function. Relative regional flow is sensitive to flank slope and amplitude, and somewhat sensitive to the first-order stream gradient (Figure 8). Relative perpendicular flow is sensitive to first-order stream gradient, somewhat sensitive to amplitude, and insensitive to flank slope. Flank slope is directly related to regional flow, as previously suggested by *Tóth* [1963]. Increasing amplitude and first-order stream gradient both decrease regional flow and increase perpendicular flow. Increasing amplitude intensifies local groundwater systems [*Tóth*, 1963], in effect strengthening the groundwater divide between the first- and third-order basins. This shifts more flow toward the second-order basin resulting in increased relative perpendicular flow. Increasing amplitude also corresponds to increased mountain valley incision which also decreases regional flow. Increasing the first-order gradient also shifts more groundwater flow paths away from regional flow and toward perpendicular flow.

[29] In the second component of the sensitivity analysis, the total potential influence of the two most important topographic parameters for both regional and perpendicular flow are simulated (Figure 9). Only two variables are included because the topographic parameters are varied

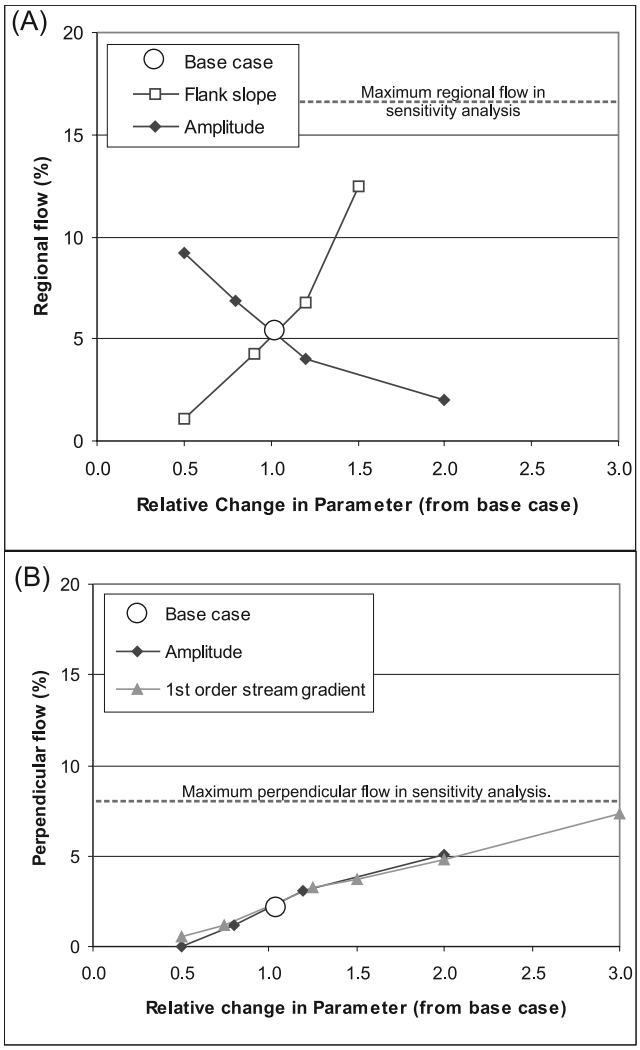

Figure 9. Sensitivity of (a) regional and (b) perpendicular groundwater flow to extending topographic parameters to their full probable range for moderate relief mountain terrain. Maximum regional and perpendicular flow (for topography-controlled water tables in moderate relief terrain) are simulated by modifying the both displayed parameters simultaneously to optimize regional and perpendicular flow.

outside of their independent range, meaning that one of three parameters must become dependent (see section 3.3). This larger range of topographic variation is consistent with the actual range in moderate relief mountainous terrain. Figure 9 shows the change in each parameter relative to the base case values. As expected, these simulations display similar trends to those in the first component of the sensitivity analysis, but variations in regional and perpendicular flow are larger. Relative regional flow varies from 1 to 13% and relative perpendicular flow varies from 0 to 7%.

[30] The maximum regional and perpendicular flows expected for a topography-controlled water table in moderate relief mountains are also simulated by modifying the two important parameters simultaneously to optimize regional or perpendicular flow. Regional flow was maximized by a high flank slope (15°) and low amplitude (125 m) whereas perpendicular flow is maximized by a high first-order gradient (0.1) and high amplitude (500 m). Resulting maximum regional and perpendicular flows are ~17% and ~7% of total recharge (Figure 9). In summary, the second component of the sensitivity analysis demonstrates that, for topography-controlled water tables in moderate relief terrain, expected variations in topography can reduce relative regional and perpendicular flow to <1%, but cannot increase these flows to greater than about 17% and 7%, respectively.

[31] The third component of the sensitivity analysis examines hydrogeologic variation with simple cases of anisotropic and heterogeneous permeability, again using the base case topography and same *R/K* ratio (Figure 10). Both regional and perpendicular flow systems decrease with decreasing depth of the active layer (Figure 10a). When the active layer is 200 m and less, the regional and perpendicular flow is <1%, suggesting nearly all groundwater flow is local and confined to individual basins. These results should not be misinterpreted to mean that only a negligible per-

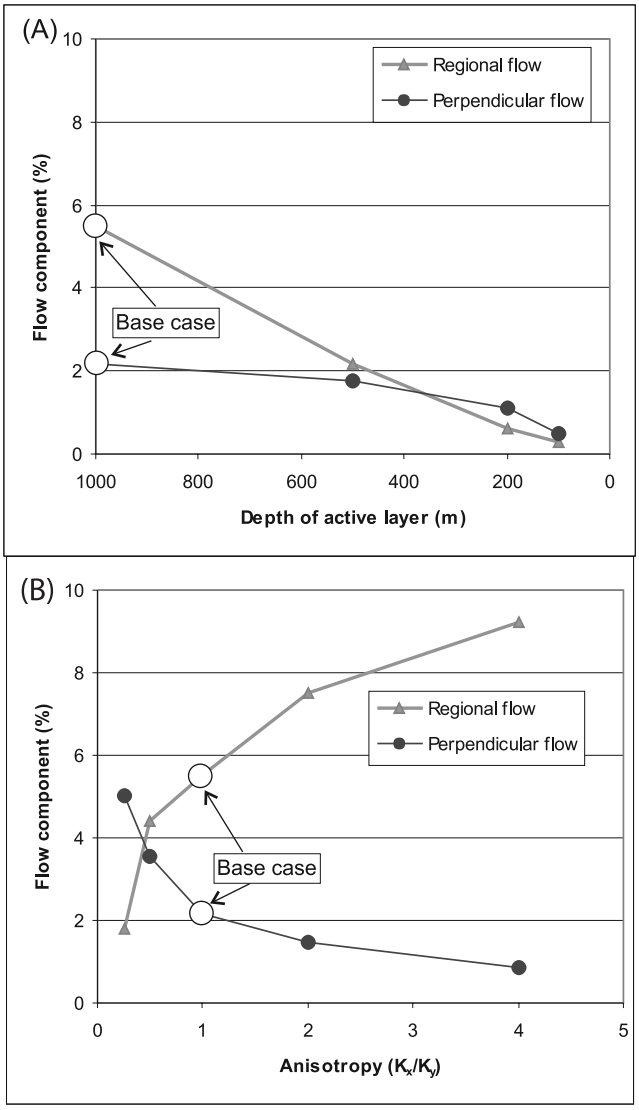

Figure 10. The sensitivity of regional and perpendicular groundwater flow systems to changes in (a) depth of active layer and (b) anisotropy.

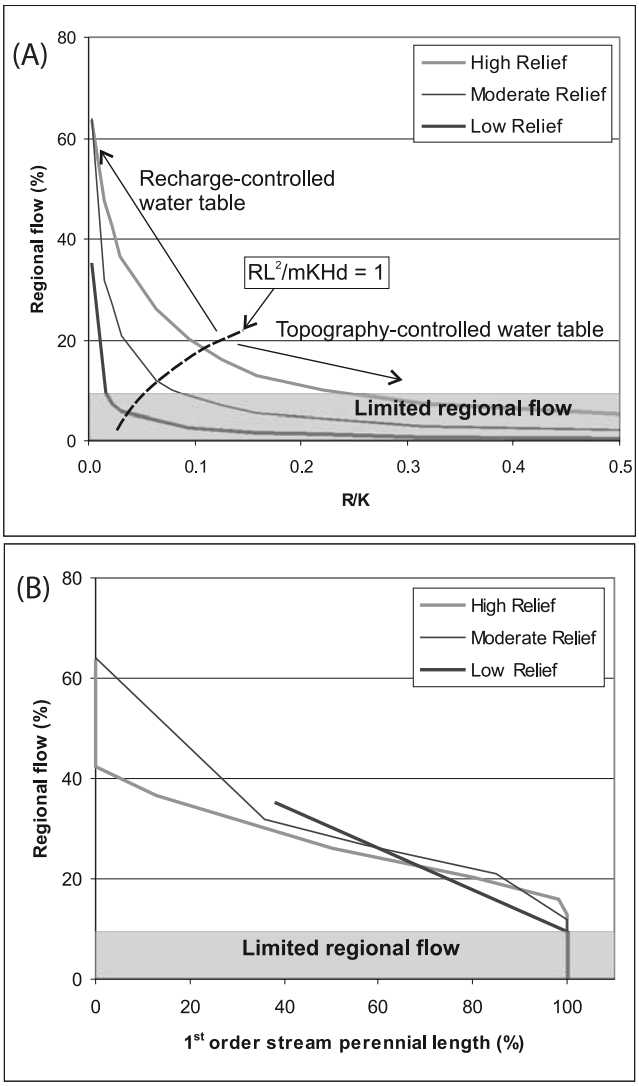

Figure 11. Key variables for characterizing and quantifying regional groundwater flow in mountainous terrain. (a) *R/K* in conjunction with relief roughness controls water table configuration, which directly controls relative regional flow. (b) Percentage length of first-order stream with perennial flow is a useful field-based indicator of relative regional flow if the top of perennial flow corresponds to the water table location.

centage of the water entering the inactive layer becomes regional flow. A negligible percentage of the water entering the model becomes regional flow (an important result in the context of water resources), but the percentage of water entering the inactive layer that becomes regional flow should be considerably higher, similar to values in the homogeneous runs (a potentially important quantity of water in the context of geologic processes). Anisotropic cases with a range of K_x/K_y of 0.25 to 4 indicate that even moderate anisotropy can redefine the relative importance of regional flow versus perpendicular flow (Figure 10b). The likely range of possible anisotropy was not simulated. However, the asymptotic shape of the regional flow line in Figure 10b suggests that further increasing K_x/K_y up to 10 or 100 should not increase relative regional flow to over 15%, similar to the amount achieved by varying topographic variables. As discussed above, regional and perpendicular flow is also sensitive to *R/K* which is a key hydrogeologic variable.

5. Discussion

5.1. Regional and Perpendicular Flow Characteristics and Controls

[32] The results of simulating a wide variety of hydrogeologic and topographic settings help define fundamental characteristics of and important controls on deep groundwater flows in multiple-basin, mountainous terrain. In all of the completed simulations, regional and perpendicular flow constitute only modest percentages (<15% and <10%, respectively) of total recharge if the first-order stream is entirely perennial (high water table conditions). Therefore, local flow systems dominate in elevated, topography-controlled water table settings. This occurs in humid or low-permeability settings where *R/K* is greater than 0.15. The relative regional flow can increase dramatically as *R/K* decreases and the first-order stream gradient becomes unsaturated and water tables become recharge controlled. However, under these conditions, the absolute amount of regional flow is lower, so groundwater it is expected to have longer travel times [*Tóth*, 1999]. The $RL^2/mKHd$ value developed by *Haitjema and Mitchell-Bruker* [2005] is a good predictor of the conditions where significant regional flow are expected (Figure 11a).

[33] Relative regional groundwater flow shows a consistent relationship with percentage of first-order stream perennial length in all relief types (Figure 11b). The percentage of first-order stream perennial length is a direct function of the water table elevation, which is in turn a function of the *R/K* ratio (Figure 6). It is therefore a physically meaningful and potentially useful variable for constraining regional flow in field settings, if the top of the perennial flow indeed represents the water table.

[34] Topographic variables including relief roughness, flank slope, amplitude, and first-order stream gradient all directly influence regional and perpendicular flow (Figures 8 and 9). In an attempt to discern additional important relationships between topography and regional flow for the case of a topography-controlled water table, plots were constructed of relative regional groundwater flow versus other topographic variables (such as highest water table elevation, upper ridge elevation, and highest elevation of first-order stream). None of the plots display any clear linear relationships except that of relative regional flow versus the middle elevation of the first-order stream (Figure 12a). The middle elevation of the first-order stream corresponds to the depth of incision of the mountain drainage network. A more incised drainage network more effectively drains the mountain mass and lowers the water table, providing less potential energy for regional flow. Interestingly, relative regional flow is not correlated with the elevation of the middle ridge dividing the first- and third-order basins (Figure 12b). The higher ridge elevations also provide higher potential energy, but little of this additional potential energy ends up driving regional flow. Figure 12 therefore suggests that the level of valley incision is a critical variable controlling relative regional flow in mountainous terrain with

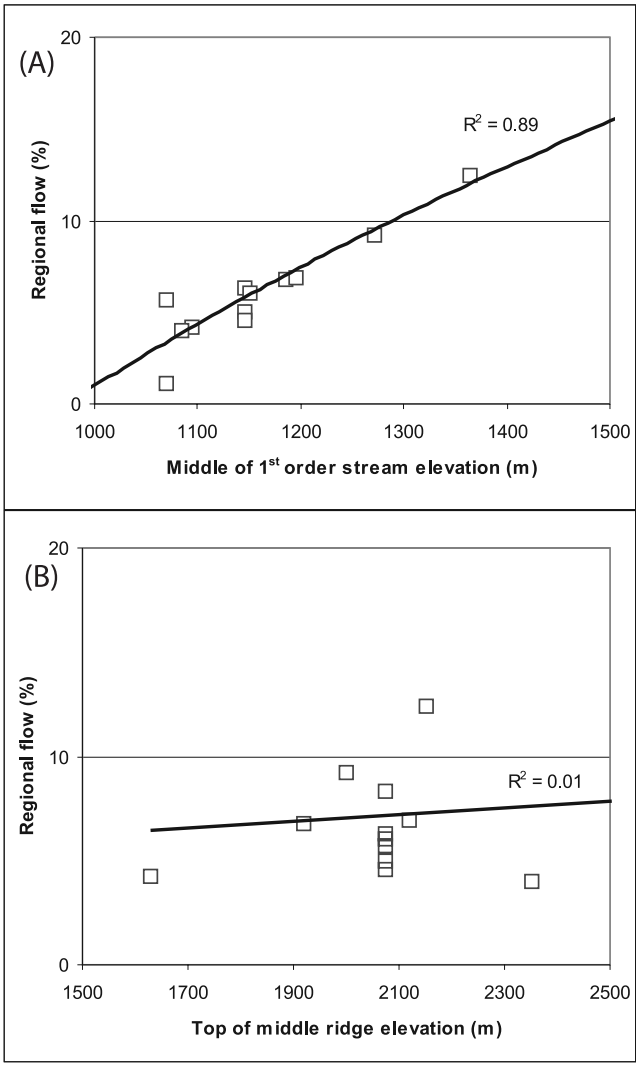

Figure 12. In topographically controlled water tables, the level of river incision controls regional groundwater flow more than the elevation of the ridge tops. Regional groundwater flow in relation to (a) the elevation of the middle of the first-order stream and (b) the ridge elevation.

high water tables, whereas the elevation of the mountain ridges is considerably less important.

[35] The modeling suggests that perpendicular flow is always smaller than regional flow, accounting for <10% of total flow in the simulations tested. However, perpendicular flow does occur in most of the moderate and high-relief cases simulated, and its absolute magnitude is similar to that of regional flow in cases of high relief and high *R/K* ratio. Therefore, perpendicular flow is a potentially important flow component in multiple basin water budgets and its exclusion, as in 2-D cross-sectional models, is potentially problematic. In general, perpendicular flow is negligible in the case of low relief. In all simulations, the absolute regional flow approaches an asymptotic maximum when the water table elevation exceeds the top of the first-order stream (Figure 7b). This suggests that the first-order stream elevation (i.e., the level of incision of the drainage network) is a critical control on both the maximum absolute regional flow and the relative regional flow, as discussed above. Both topographic and hydrogeologic variables can change deep groundwater flow patterns significantly (Figures 9 and 10), so both must be constrained to characterize deep groundwater systems in mountainous terrain.

5.2. Implications

[36] The simulations of deep groundwater flow systems under a wide variety of hydrogeologic and topographic settings have important implications for water resource management. The results provide a useful framework for understanding mountain-block recharge, determining appropriate groundwater management areas, and designing appropriate study and model domains. Mountain-block recharge is groundwater recharged in the mountains that subsequently flows in the subsurface to adjacent basin-fill aquifers [*Manning and Solomon*, 2004; *Wilson and Guan*, 2004] and it is a potentially important source of recharge in arid and semiarid regions. Results from this study are directly applicable to mountain-block recharge settings because our regional flow is equivalent to mountain-block recharge if sedimentary fill were to occupy the third-order basin. Note that regional flow percentages (% of total recharge to the three basins) are lower than potential mountain-block recharge percentages (percent of recharge to first- and second-order basins transferred to third-order basin). This study helps define the topographic and hydrogeologic variables controlling mountain-block recharge, and the results could be used to place at least rough constraints on plausible mountain-block recharge rates. For example, if the recharge budget for a groundwater flow model of a basin-fill aquifer indicated that 50% of recharge in an adjacent mountain range becomes mountain-block recharge, yet first-order streams in the mountain range were generally 100% perennial, the modeled mountain-block recharge rate is improbable according to our modeling results and should be re-evaluated.

[37] *Winter et al.* [2003] summarized results from disparate topographic and hydrogeologic settings which all had significant interbasinal flow. The field and modeling observations summarized in the work of *Winter et al.* [2003] and our modeling results from a variety of mountainous terrain raise the question of how to delineate "groundwatersheds" in mountainous terrain if groundwater commonly flows from one surface watershed to another. Delineating defensible groundwatersheds is critical for water management, understanding of groundwater processes, and groundwater modeling. In the case of a high water table configuration, assuming that a groundwatershed is defined by a surface watershed may be reasonable because regional flow should compose a small percentage of total flow. However, for lower water tables this assumption may not be useful or defensible. Our modeling results along with those of *Tiedeman et al.* [1998] suggest that the use of a surface water divide as a no-flow boundary, which is widespread practice, may not be appropriate or good practice in mountainous terrain.

[38] The modeling results provide a potential practical tool for predicting the vulnerability of mountain groundwater systems to climate change [*Eckhardt and Ulbrich*, 2003]. Climate change is expected to alter precipitation patterns, leading to increased aridity in some regions [*Holman*, 2006; *Intergovernmental Panel on Climate Change* (*IPCC*), 2007]. As discussed above, the perennial length of headwater streams is less sensitive to recharge rate if the entire stream is perennial but is extremely sensitive to changes in

recharge rate if it is partially perennial. Therefore, if headwater streams are partially perennial, local mountain groundwater systems and associated near-stream wetlands may be highly sensitive to increased aridity. Regional groundwater flow patterns in a mountain region may be sensitive to decreased recharge if part or all of the headwater streams are ephemeral, but relatively insensitive if headwater streams are all perennial.

[39] The fact that some amount of deep regional groundwater flow should be commonplace in mountainous terrain with moderate to high relief has important implications for the role of groundwater in geologic processes. Namely, meteoric water recharged in mountains may occur widely in Earth's upper crust in the vicinity of mountain belts, and fluxes of this meteoric water may be sufficiently high on a geologic timescale for it to play an important role in petroleum migration and the formation of mineral deposits [*Tóth*, 1980; *Garven and Freeze*, 1984a, 1984b; *Garven*, 1989, 1995; *Winter*, 1999].

6. Conclusions

[40] This study defines the salient controls on regional groundwater flow in three-dimensional mountainous terrain by systematically exploring the relationship between topographic and hydrogeologic variables and regional groundwater flow. Long-term regional groundwater flow and discharge patterns are examined in idealized mountainous terrain using a numerical model describing fully integrated subsurface and surface flow. Important conclusions include:

[41] 1. Regional and perpendicular flow (parallel and perpendicular to the primary regional topographic gradient, respectively) should be commonplace in mountainous terrain with moderate to high relief. Regional flow is always larger than perpendicular flow but groundwater flows and discharge patterns indicate that perpendicular flow is a fundamental characteristic of mountain groundwater systems. To fully characterize moderate- to high-relief mountain groundwater systems, they should be studied and modeled as 3-D multiple basins entities rather than 2-D cross sections or single watersheds. In lower-relief settings or when only the general characteristics of the flow system are important, 2-D cross-sectional models may be justifiable since perpendicular flow is generally <10% of total flow.

[42] 2. The primary factor controlling relative regional flow is the position of the water table, which is in turn governed mainly by the *R/K* ratio. Lower water tables result in larger regional flow percentages (potentially >60%), and higher water tables result in smaller regional flow percentages (potentially near 0%).

[43] 3. The relationship between the *R/K* ratio and the amount of regional flow is highly nonlinear. When the water table is below the level of the first-order stream, relative and absolute regional flow change rapidly (decrease and increase, respectively) with increasing *R/K*. When the water is above the level of the first-order stream such that it is perennial, relative and absolute regional flow change only slightly with further increasing *R/K*. Therefore, once mountain water tables are sufficiently high to afford perennial streamflow in first-order drainages, further gains in water table elevation (further up into ridges dividing first-order drainages) have a minimal impact on regional flow.

[44] 4. The percentage of the first-order stream that is perennial is a useful field-based indicator of relative regional flow, assuming the top of the stream corresponds to the regional water table. The perennial percentage of headwater streams may also be a useful indicator of the sensitivity of regional groundwater flow to climate change. If headwater streams are entirely perennial the groundwater system may be less sensitive to increased aridity. Regional groundwater flow may be sensitive to decreased recharge if part or all of the headwater streams in a mountain region are ephemeral.

[45] 5. The quantitative relationship developed by *Haitjema and Mitchell-Bruker* [2005] ($RL^2/mKHd = 1$) that identifies the transition from recharge-controlled water tables to topography-controlled water tables is generally valid for rugged 3-D mountainous terrain, correlating to the point at which the first-order stream becomes perennial.

[46] 6. Higher topographic relief generates greater regional and perpendicular flow, as expected. However, even in the most extreme mountainous terrain on Earth, relative regional and perpendicular flow generally should not exceed about 15% and 10%, respectively, in the case of a topography-controlled water table. This may not be true if hydraulic conductivity is highly anisotropic.

[47] 7. In the case of a topography-controlled water table, relative regional flow is sensitive to the topographic variables flank slope and amplitude, and somewhat sensitive to the first-order stream gradient. Relative perpendicular flow is sensitive to first-order stream gradient, somewhat sensitive to amplitude, and insensitive to flank slope. Varying these topographic parameters through their full expected range for moderate relief mountains results in relative regional flow varying from about 1 to 17% and relative perpendicular flow varying from about 0 to 7%.

[48] 8. In the case of a topography-controlled water table, relative regional flow is well correlated (R^2 = 0.89) with the mean elevation of the first-order stream, and poorly correlated (R^2 = 0.01) with the elevation of the ridge between the first- and third-order streams. This suggests that relative regional flow is largely controlled by the level of incision of the drainage network in mountainous terrain, and the elevation of the mountain ridges is considerably less important.

[49] 9. The depth of the active layer and hydraulic conductivity anisotropy are also important hydrogeologic variables controlling regional and perpendicular flow. Reducing the active layer from the full model thickness to <500 m reduces relative regional and perpendicular flow to <2% in the case of a topography-controlled water table in moderate relief mountains. Relative regional flow probably is not substantially more sensitive to hydraulic conductivity anisotropy than to topographic parameters.

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