Groundwater in the Tibet Plateau, western China

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Received 2 June 2008; revised 30 July 2008; accepted 15 August 2008; published 26 September 2008.

[1] The Tibet Plateau in western China embraces a variety of hydrologic processes. Water cycling plays an unequivocal role in buffering or intensifying climate impact on water resources and ecosystems. Although much research has focused on climatic aspects, little is known about the subsurface component of the water cycle, particularly groundwater-flow patterns and recharge and discharge characteristics. This study shows that groundwater flow in the Plateau is driven and sustained by the topographic gradient and recharge at high elevations. Groundwater is recharged at the rate of approximately 100–200 mm/year. Groundwater discharge on the order of 10−8–10−7 m/s occurs in valleys and fault zones, supplying baseflow to rivers and springs. Reliable recharge is critical for sustaining the water cycle and reduced recharge could diminish groundwater replenishment to rivers and springs, adversely impacting the ecosystems on the Plateau. Citation: Ge, S., Q. B. Wu, N. Lu, G. L. Jiang, and L. Ball (2008), Groundwater in the Tibet Plateau, western China, Geophys. Res. Lett., 35, L18403, doi:10.1029/2008GL034809.

1. Introduction

[2] The Tibet Plateau in western China (Figure 1), a source area for several rivers in Asia such as the Yellow River and the Yangtze River, embraces a variety of hydrologic processes. Warming climate has brought attention to shrinking glaciers, permafrost degradation, and deterioration of ecosystems on the Plateau [Cheng and Wu, 2007; Yang et al., 2007]. Water cycling plays an unequivocal role in buffering or intensifying climate impact on water resources and ecosystems. Much research has focused on climatic aspects [Xu et al., 2007; Bei and Xu, 2004], but little is known about the subsurface component of the water cycle. The objective of this study is to provide a conceptual understanding of the groundwater-flow system in the Tibet Plateau. Through numerical modeling along the Qinghai-Tibet Railway, groundwater-flow patterns, recharge characteristics, and groundwater contribution to rivers and springs are examined.

2. Geologic Background

[3] The rising of the Tibet Plateau is the result of the Indo-Asian collision over the past 50 to 70 million years [Molnar, 1989]. This tectonically active region is characterized by the continued uplift of the Himalayas in the south and extensive active faulting throughout the region [Kidd and Molnar, 1988; Wu et al., 2004]. The Plateau consists of three major terranes (Figure 2) that are underlain by Proterozoic crystalline rocks [Yin and Harrison, 2000; Xu et al., 1985; Harris et al., 1988; Dewey et al., 1988; Yin et al., 1988], described here from south to north: the Lhasa terrane comprises Paleozoic volcanic clastics, shallow marine carbonates, and Mesozoic turbidites; the Qiangtang terrane comprises Mesozoic shallow marine carbonates; the Songpan-Ganzi-Hoh Xil terrane comprises a thick sequence of lower Mesozoic deep marine deposits. Veneering the surface are various Quaternary sedimentary deposits. Extensive permafrost is present on the northern portion of the Plateau and becomes discontinuous or absent to the south [Wu et al., 2000].

3. Hydrologic Background

[4] At an average elevation of greater than 4000 m, the Plateau is cold with an average annual temperature of −3.5°C, windy, and dry. Precipitation varies from approximately 200 to 500 mm/yr on the Plateau to about 40 mm/yr as the Plateau drops to the Qaidamu Basin in the north (Figure S1 of the auxiliary material). Evaporation on the Plateau is intense, ranging from 600 to 2500 mm/yr, leaving little precipitation available for infiltration to groundwater. Permafrost coverage on the Plateau is extensive but not continuous everywhere and its thickness varies from a few meters to more than one hundred meters [Wu et al., 2007]. The groundwater-flow system in the Plateau can be conceptualized in three regimes (Figure S2): the first is the near-surface shallow groundwater above the permafrost base, which is most sensitive to seasonal climatic changes; the second is below the permafrost and much less affected by seasonal variations; the third is the regime under low-lying valleys and fault zones where upwelling groundwater interrupts permafrost continuity and discharges to rivers and springs [Wu et al., 2005]. The focus of this study is on the second and third regimes, i.e., the groundwater system below the permafrost and in valleys and fault zones. While near-surface processes and permafrost hydrology associated the first regime are undoubtedly important, studying these processes in detail merits a different approach with a high level of details.

4. Groundwater Flow Modeling

[5] To examine the groundwater-flow processes in the Plateau, we developed a two-dimensional groundwater-flow model using MODFLOW [McDonald and Harbaugh, 1988] along the 1143 km Qinghai-Tibet Railway between
the cities of Lhasa and Golmud (Figure 1). The transect, approximately perpendicular to the trend of geologic features, contains river baseflow and spring discharge data that can be used to constrain modeling (Figure S3 and Table S1). The model is steady state, simulating groundwater flow under long-term averaged conditions. Hydraulic conductivity is one of the major model input parameters [Domenico and Schwartz, 1990]. A limited number of in-situ hydraulic conductivity data have been reported, ranging from $10^{-8}$ m/s to $10^{-4}$ m/s [Bian et al., 1990; Shang et al., 1977]. On the basis of lithology and field data, we used conductivity values of $10^{-6}$ to $10^{-5}$ m/s for the upper bedrocks, from $10^{-6}$ to $10^{-5}$ m/s for the deep bedrock, and $10^{-3}$ to $10^{-2}$ m/s for faults (Figure 2). These conductivity values also reflect the notion that they increase with scale and decrease with depth [Ingebritsen and Manning, 2003; Rojstaczer et al., 2008]. The boundary separating the upper and deep bedrocks is approximate and the different hydrostratigraphic units serve to facilitate the notion of permeability decreasing with depth. Permafrost hydrologic properties are not well known and we treated the permafrost as a thin low-permeability layer with a conductivity of

Figure 1. Location map showing the Tibet Plateau in western China. The study transect is along the Qinghai-Tibet Railway between the cities of Golmud and Lhasa. Major east–west trending fault traces are marked.

Figure 2. Cross section of the study transect showing the groundwater-flow model setup, including the boundary conditions and modeled hydrostratigraphy and hydraulic conductivities of the three terranes. The lower portion (light gray) represents the crystalline basement; the upper portion (various colors) represents the sedimentary units described in the text. Major faults are represented by thin lines. Permafrost is not shown at this scale because of its relatively thin extent.
These conductivity values were arrived at by calibrating the model to achieve agreement with field observations, as described in Model Constraints.

The boundary conditions for the model are shown in Figure 2. The south boundary intersects the Lhasa River Valley where a constant head equal to the valley elevation of 3650 m is applied near the surface and a ‘no-flow’ condition for the deeper portion to approximate a water divide that is characteristic for regions under valleys. A constant head of 2810 m was applied to the north boundary where the Plateau drops steeply to the Qaidamu Basin at Golmud. This condition is based on the elevation at Golmud. The bottom boundary is assumed to be ‘no flow’ because it is sufficiently deep that there is little fluid exchange across it. On the surface, evaporation rates are much higher than precipitation rates (Figure S1). During the summer months, high precipitation may produce runoff or saturate shallow soils, but these short-term events are unlikely to generate enough water to penetrate the permafrost. Therefore, areal recharge from precipitation events is not included in modeling. Recharge at high elevations and discharge in valleys are much more relevant processes at the top boundary. Infiltration at the base of glaciers and snow packs provides a steady source of recharge to groundwater. The rate of recharge, however, is difficult to quantify in the absence of direct measurements and is a subject of active research [Lemieux et al., 2008]. We tested a range of recharge rates and arrived at 100 to 200 mm/year. In valleys and around faults, groundwater discharges to the surface when the subsurface heads are greater than the land surface.

Model output (Figure 3) illustrates the hydraulic head and the flow velocity field with flow lines superimposed. Groundwater flows from high-head regions where systems receive recharge to low-head regions under valleys. Ridges and valleys serve as groundwater divides, delineating subflow domains. Steep topographic drops in the north and south drive considerable groundwater discharge to adjacent basins.

5. Modeling Constraints

The model is constrained by observed river and spring discharge. Several rivers and springs are encountered along the transect (Figure 3). River baseflow estimates and spring discharges are good indicators of steady-state groundwater discharge and form a basic set of model constraints. These discharges are averaged over a period of eleven years (Figure S3). We use the low flow during winter months as a proxy for baseflow, ranging from 0.12 to 5.3 m$^3$/s. Model parameters, namely recharge rate and permeability, are adjusted so that modeled flow rates are consistent with field observations. Modeled groundwater discharge and observed baseflow estimates are compared in Figure 4a. The modeled discharge is calculated by multi-
plying the modeled velocity by river width and length. Generally good agreement is achieved for the major rivers considered: the Buqu, Tuotuo, Chumaer, and Golmud Rivers.

[9] Natural springs are abundant in the area, some in clusters and some geothermal. The spring discharges manifest groundwater-flow rates at corresponding locations. Figure 4b shows consistent variation patterns in observed spring discharge and modeled groundwater-flow rate. Spring water temperatures can be indicative of groundwater circulation depth. The Never Freeze Spring is a warm spring and the flow paths show that groundwater circulation reached to around 1-km deep (Figure 3). Similarly, the temperature of the Warm Springs is as high as 60–70°C, which is supported by the modeled flow paths of approximately 2-km deep.

[10] No direct or indirect measurements of subglacial recharge rates are currently available. Rates of 100 to 200 mm/year produced the most desirable results that are consistent with observed spring discharge and baseflow. Lower recharge resulted in dry model cells in the upper hundreds of meters and much smaller groundwater discharge values than the observed data. On the other hand, recharge rates greater than 100–200 mm/year would lead to much greater discharge in valleys that are inconsistent with the observed baseflow.

[11] Hydraulic conductivity is known for its spatial variability and uncertainty. The set of conductivity used in our model is achieved after the model results satisfied the field constraints. Several conductivity scenarios deviating from the basic set are tested. We found that increasing the conductivity drains the system significantly while decreasing the conductivity produces insufficient surface discharge. Faults can be conduits, barriers, or combined barrier-conduits to flow [Bredehoeft et al., 1992]. Quantifying fault permeability is still an area of active research [Caine et al., 1996; Fairley and Hinds, 2004; Bense and Person, 2006; Ball et al., 2007]. Field evidence suggests that faults in the study area actively channel water to the surface [Wu et al., 2005]. Therefore, we consider faults as conduits with a conductivity of 10⁻³ to 10⁻² m/s. Increasing or decreasing the fault conductivity by one order of magnitude leads to increasing or decreasing spring discharge and river baseflow by a factor of 1 to 3. The impact of varying fault conductivity on groundwater flow is generally localized.

[12] Numerical modeling results are often non-unique because different input parameter combinations may produce similar results. The model presented here is no exception. Using available data to constrain the model reduces but may not eliminate uncertainties. We address this issue by exploring model sensitivity to two major parameters: recharge rate and hydraulic conductivity. Although various combinations of permeability and recharge could reproduce the field observations, the combination of parameters presented in this manuscript seemed the most plausible to the authors.

6. Summary

[13] On the basis of available geologic and hydrologic data, a two-dimensional steady-state groundwater-flow model is developed along the Qinghai-Tibet Railway on the Tibet Plateau. Constrained by field observations, the model results support the conceptual groundwater processes summarized in Figure 5. (1) The regional-scale groundwater-flow system in the Plateau is driven and sustained by the topographic gradient and recharge at high elevations. Groundwater flows from recharge areas to valleys on the Plateau and to adjacent basins. Ridges and valleys serve as water divides that delineate numerous intermediate-scale flow systems. (2) Hydrologic connections exist between groundwater and surface water in valleys and around faults. Groundwater discharge rates are on the order of 10⁻⁹ to 10⁻⁷ m/s, which could be vital to sustaining river baseflow and spring discharge. Groundwater circulation can reach more than 1 to 2 km in depth and supply geothermal water to springs, which is a likely mechanism for disrupting permafrost and creating thaw areas on the Plateau. (3) Recharge at high elevations is an important source for the groundwater system and critical for sustaining the water cycle in the Plateau. The most plausible rate of recharge is at 100 to 200 mm/year. Reduced recharge rates will diminish groundwater discharge to rivers and springs and adversely impact the ecosystems on the Plateau.

[14] This study represents a first effort in modeling the groundwater-flow system in the Tibet Plateau under long-term averaged conditions. Future efforts may be directed...
Acknowledgments. Chinese National Science Foundation Outstanding Young Scientist Award (grant 40625004) to Q. B. Wu is gratefully acknowledged. We thank two anonymous reviewers for their comments and suggestions that have greatly improved the quality of the paper.

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