GROUNDWATER IN MOUNTAIN REGIONS

Gárfias J.
Autonomous University of the State of Mexico, Toluca, Mexico

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Contents

Summary

Groundwater in mountainous regions encompasses an enormous variety of hydrogeologic properties. It exhibits a tremendous diversity of flow and transport process. Thus, the purpose of this paper is to examine factors that control the patterns and magnitudes of groundwater flow and thermal regimes in mountainous terrain, and to explain how the character of mountainous terrain is incorporated in a conceptual model for fluid flow and heat transfer. Important aspects of the conceptual models in mountainous regions are summarized. In this paper, a conceptual model is simply a relevant set of concepts that describes, in a qualitative way, the behavior of a natural system. Numerical models of the same system, which also will be discussed in this paper, are based on the same set of concepts but describe the behavior of the system in a quantitative manner. For a mathematical modeling effort to be successful, perhaps the single most important prerequisite is to have very clear and specific objectives. A general problem with the modeling of flow in mountainous regions arises from the geometric complexity of the system. Finally, this paper provides an overview of the groundwater resources of the mountainous regions of British Columbia, Canada, and the conditions that favor its development for social and economics benefits. It is hoped that this information will assist in future groundwater resource planning initiatives in groundwater regions, to minimize the potential impact of humanity's land use activities on groundwater resources, thereby maintaining available quantities and a high degree of groundwater quality for future generations.

1. Introduction

Mountainous terrain occupies 20% of the earth's land surface yet little is known of the details of groundwater flow at depth within a mountain massif. Furthermore, mountainous regions promote deep circulation of groundwater, denying access to groundwater outcrops that aid in regional investigation. A further complication arises because mountainous regions are frequently fractured and may be in an active state of compression or extension, suggesting that fracture apertures may be functionally related to the state of stress in the earth's crust. Thus, the elevation of the water table may be intimately related to a changing hydraulic conductivity of the region and the variable climatic factors that influence infiltration. For a given hydraulic conductivity distribution, the lower the infiltration rate, as controlled by climatic factors, the deeper the water table.

It follows that the simple relations that are substantiated in numerous studies in low-lying sediments may not apply to mountainous terrain characterized by a fracture permeability. In such cases, the water table may be considered a free surface whose depth and configuration depend on the interplay between infiltration and permeability distribution. Numerical studies of mountain scale flow systems have been presented in several studies. One example of this approach used a free surface technique as applied to mountainous terrain in British Columbia. A fixed infiltration rate was utilized to estimate the range of hydraulic conductivity that might be expected to produce a water table at a given depth. Each hydraulic conductivity pattern resulted in a different elevation of the free water surface. This study was expanded in 1988 to include the effects of varying infiltration rates, surface topography, topographic symmetry, and permeable fracture zones. It was concluded that permeability has the greatest impact on the mountainous flow system. Asymmetry can cause the displacement of the groundwater divides from the topographic divides, and a relatively small increase in the vertical permeability of fractures relative to the horizontal permeability causes significant declines in the water table elevation (in the order of 400 m). The authors also state that high relief can promote deep groundwater circulation to elevated temperature regions, requiring a modeling of both the fluid flow and the thermal regime. In 1985 another research project used a coupled model to simulate the transient development of a parasitic steam field in a liquid-dominated geothermal system at Mount Lassen, California. Although topographic relief was assumed to drive the flow system, recharge was represented as a basal source of heated groundwater.

Upper regions of flow have been explored, to a limited extent, in field studies that emphasize the interface between surface hydrology and shallow groundwater flow. Although these studies provide insight into the hydrology of alpine watersheds and the relationships between water table fluctuations and seasonal snowmelt, they yield little information on deep flow systems.

The character of permeable zones within a mountain massif are described in reports describing inflows to alpine tunnels; however, measurements of fluid pressure that could aid in defining the nature of mountain flow systems are generally lacking. As a consequence, alternative approaches have assessed the hydraulic characteristics of fractured crystalline rock deep within Mount Blanc (France). The assessment was based on geochemical and hydraulic data obtained during construction of a highway tunnel. However, an integrated description of the flow system within the mountain massif was not attempted. Water table and hydraulic head data are rarely available at mountain summits because most wells and boreholes are located on the lower flanks of mountain slopes. Two summit water level measurements are noted in the literature: at a depth of 30 m in fractured crystalline rock at Mount Kobau, British Columbia, and at a depth of 488 m in the basalts of Mount Kilauea, Hawaii.

One mountainous region which does not qualify as “data poor” is Yucca Mountain in southern Nevada, a volcanic tuff pile located north of Las Vegas. Yucca Mountain is currently under study as the first site in the United States for disposal of commercial nuclear waste . As part of the southern Great Basin, a distinct feature of the Yucca Mountain region is crustal extension, which suggests that the mountain has become “wider,” during late Miocene–late Quaternary time, with the “widening” occurring in the form of vertical fracture development. The mountain is characterized by extremely low infiltration (less than 1 mm y^{-1}), a deep (600 m) rather contorted water-table configuration, and a layered permeability distribution that appears to decrease with increasing depth and which may reflect the tectonic history of the region.

The purpose of this paper is to examine the factors that control the patterns and magnitudes of groundwater flow and thermal regimes in mountainous terrain. It is explained how the character of mountainous terrain is incorporated in a conceptual model of fluid flow and heat transfer. Important aspects of the conceptual models in mountainous regions are summarized. In this paper, a conceptual model is simply a relevant set of concepts that describe, in a qualitative way, the behavior of a natural system. Numerical models of the same system, which also will be discussed in this paper, are based on the same set of concepts but describe the behavior of the system in a quantitative manner. Finally, this paper provides an overview of the groundwater resources of the mountain groundwater regions of British Columbia, Canada, and examines the conditions which favor its development for social and economics benefits.

2. Conceptual Model for Groundwater Flow in Mountains

Mountainous terrain is defined as rugged topography with local relief in excess of 600 m. In the Coast Mountains of British Columbia and the central Cascades of the Pacific Northwest, topographic relief of 2 km over a horizontal distance of 6 km is typical. In the Rocky Mountains of Canada and the United States, a more subdued relief of 1 km over 6 km is not uncommon. Vertical sections and schematic flow lines representative of the Coast Mountains of British Columbia and the Rocky Mountains at the Alberta–British Columbia border are shown in Figures la and lb. For comparison, Figure 1c shows flow systems in a low-relief topography.

Mountain flow systems differ from low-relief systems in two important respects:

- For a given set of conditions, with greater topographic relief, a greater range in water-table elevation and form is possible. In low-relief terrain, water-table configurations can be defined with reasonable accuracy using water level elevations and hydraulic head data obtained from boreholes and wells located across the region of interest. In many instances, estimated water table elevations are used in defining the upper boundary of regional flow systems. In mountainous terrain measured water-table elevations and hydraulic head data are sparse and, where available, usually concentrated on the lower flanks of mountain slopes. This restricted distribution of data leads to considerable uncertainty in defining water-table configurations beneath mountain summits.

- High-relief terrain enhances groundwater circulation to depths where elevated temperatures (in excess of 50 °C) may be encountered. Spatial variation in temperature has a strong effect on fluid density and viscosity which, in turn, have an important influence on the rates and patterns of groundwater flow. Thermally induced differences in fluid density produce a buoyancy-driven component of fluid flow that enhances vertical movement of groundwater. In addition, reduced fluid viscosity in regions of elevated temperature contributes to increased rates of groundwater flow .

Apart from the previously mentioned differences, it is important to note that rocks found in mountainous terrain have significantly lower permeability than materials commonly encountered in aquifer simulation studies. This reduced permeability means that considerably longer time scales are encountered when examining processes operating in mountain flow systems.

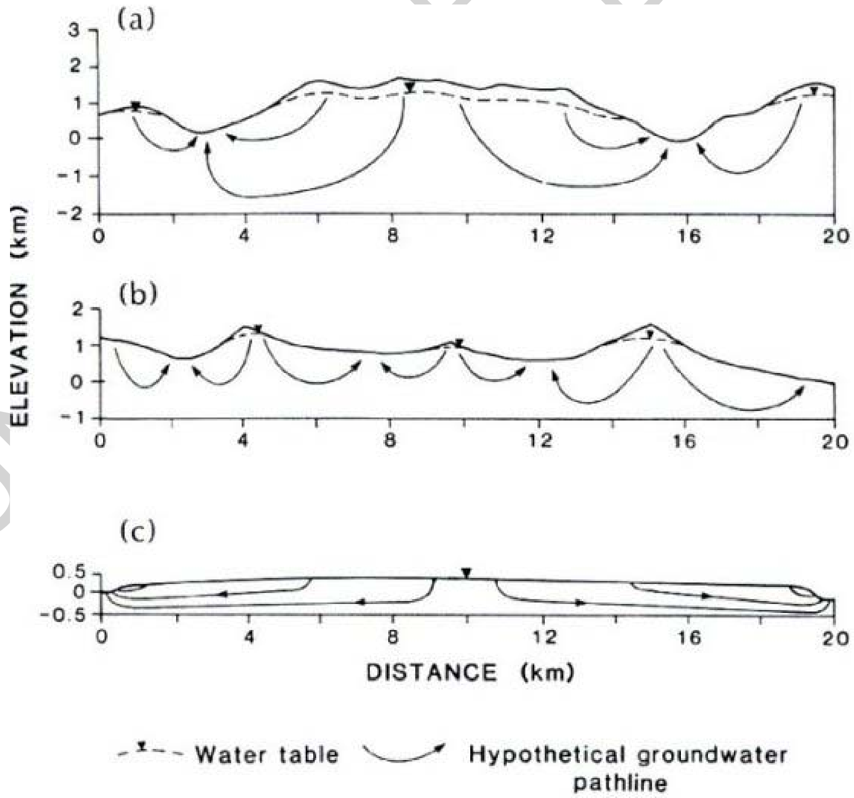

Figure 1. Hypothetical groundwater flow systems for homogeneous permeability (a) Coast Mountains of British Columbia (b) Rocky Mountains of British Columbia/Alberta (c) Conventional low-relief terrain after Freeze and Witherspoon (1967). Source: Forster and Smith, *Water Resources Research* **24**(7), 999–1010, 1988. Copyright American Geophysical Union.

2.1. Conceptual Model for Groundwater Flow and Heat Transport

An idealized flow system is shown, without vertical exaggeration, in Figure 2. Vertical no-flow boundaries are defined to reflect topographic symmetry at the valley floor and ridgetop. The domain shown in Figure 2 represents the region lying beneath a single ridge–valley segment of the topographic profile shown in Figure la. The basal boundary is presumed to be impermeable. The upper boundary of the groundwater flow system is the bedrock surface. Erosional processes operating in mountainous terrain often promote development of a thin cover of discontinuous surficial deposits, often less than 10 m thick, over upland areas of mountain slopes. In this conceptual model, these deposits are thought of as a thin skin of variable thickness which is not explicitly included in the model. Subsurface flow within this skin, in addition to overland flow and evapotranspiration, is lumped in a single runoff term. These processes are strongly affected by spatial variations in precipitation, slope angle, and soil permeability as well as by temporal variations in precipitation events. Field observations of the complex nature and interaction of these factors are lacking for individual mountain slopes. Therefore in this model, a lumped steady state approach is adopted and an available infiltration rate is defined. Available infiltration represents the maximum rate of recharge possible at the bedrock surface for specified climatic, geologic, and topographic conditions. In the absence of detailed site data, the available infiltration rate is best thought of as a percentage of the mean annual precipitation rate.

Recharge to the flow system reflects the magnitude of the available infiltration rate, the capacity for fluid flow through the system, and the nature of the thermal regime. In high-permeability terrain, groundwater flow systems may accept all the available infiltration and produce a water table that lies below the bedrock surface (Figure 2). In lower-permeability terrain, where recharge accepted by the flow system is less than available infiltration, the water table will be found close to the bedrock surface.

Conventional approaches to modeling regional groundwater flow recognize that a transition from groundwater recharge to groundwater discharge occurs at a specified point on the upper boundary. In this case, this point is termed the hinge point (HP) (shown in Figure 2). Due to the fact that the unsaturated zone is included in this conceptual model, it is also necessary to identify the point where the water table meets the bedrock surface. This point is defined as the point of detachment (POD) (shown in Figure 2). In developing numerical models to analyze seepage through earthen dams, an exit point is commonly defined that has the properties of both the POD and the HP. In high-relief terrain, the usual exit point cannot be identified because the POD and HP do not coincide. In the region between the point of detachment and the hinge point, the water table coincides with the bedrock surface and the saturated zone is recharged directly from overlying surficial deposits. This surprising result implies that recharge can occur on what is usually considered to be the seepage face.

Upslope of the point of detachment, the water table lies below the bedrock surface and infiltration is transferred to the water table by unsaturated flow. Significant lateral flow in the unsaturated zone could cause patterns of recharge at the water table to differ from patterns of infiltration at the bedrock surface. The nature and magnitude of lateral flow in unsaturated regions of mountain flow systems, however, is poorly understood. As a first approximation, a one-dimensional model of vertical flow from the bedrock surface to the water table is adopted.

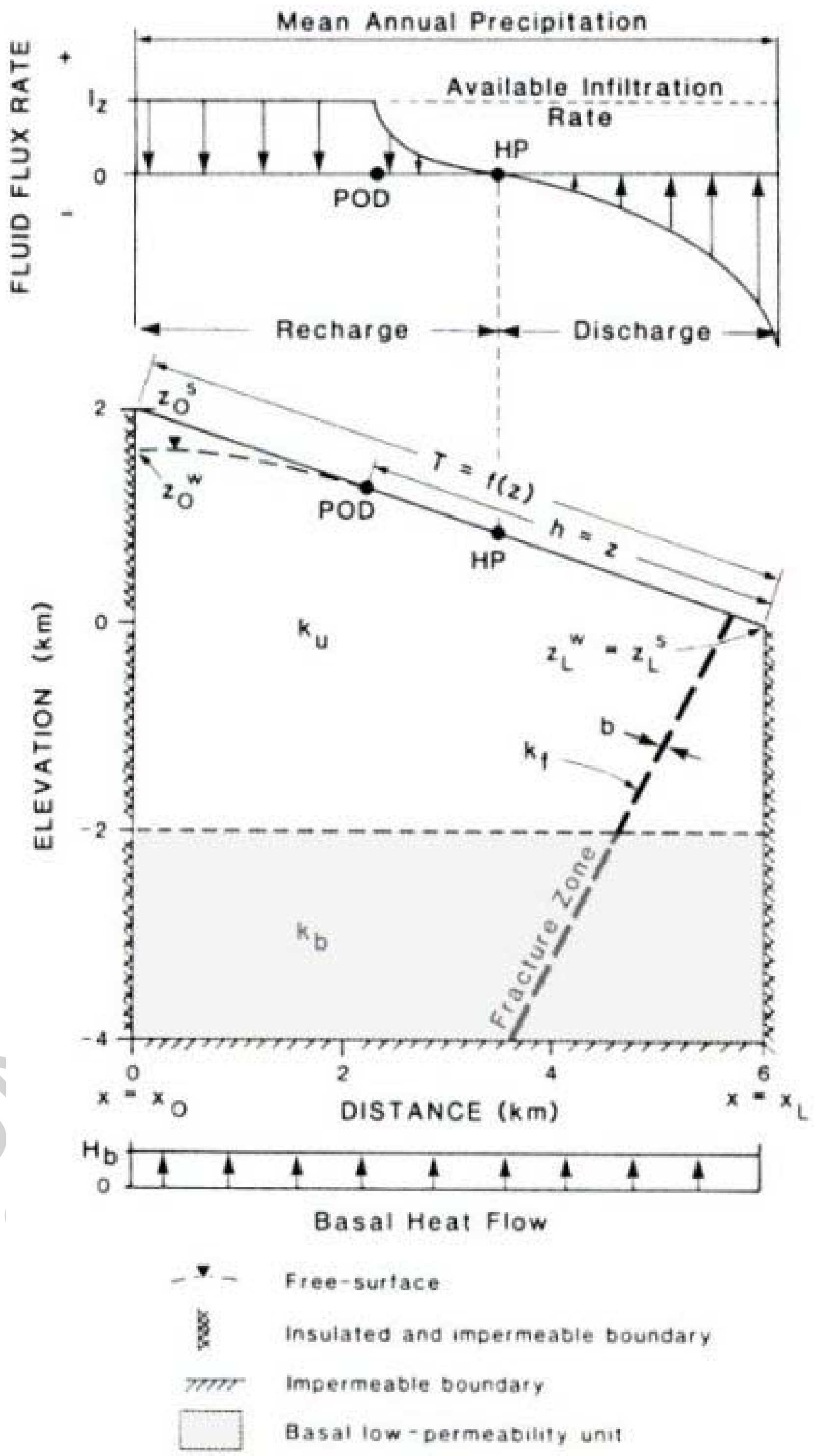

Figure 2. Conceptual model for groundwater flow in mountainous terrain. Source: Forster and Smith, *Water Resour. Res.*, **24**(7), 999–1010, 1988. Copyright American Geophysical Union.

Boundaries of the thermal regime coincide with those of the fluid flow system. A basal conductive heat flow supplies thermal energy to the mountain flow system. The basal heat flow, which represents heat transfer from deeper levels in the earth's crust, is a characteristic of the tectonic environment in which the mountain is located. It is assumed that temperatures at the ground surface reflect an altitudinal gradient in surface temperature (thermal lapse rate) with average annual temperatures at the ground surface a few degrees warmer than mean annual air temperature. Exceptions occur where fracture zones outcrop to produce groundwater springs. In such cases, temperature at the ground surface is assumed to reflect the temperature of groundwater flowing in the fracture zone, rather than the air temperature. Given the assumed presence of only a thin skin of surficial deposits on mountain slopes, temperatures at the bedrock surface are presumed to match temperatures at the ground surface.

Heat transfer occurs by conduction and advection both above and below the water table, therefore the influence of fluid flow on the thermal regime in the unsaturated zone must be considered. In this approach, the thermal effects of moisture movement in the liquid phase and heat conduction through the solid–vapor–fluid composite are considered. Thermal effects of condensation, evaporation, and heat transfer by vapor movement within the unsaturated zone are neglected. In developing a conceptual model of deep unsaturated zones, it is suggested that moisture transport by vapor movement becomes negligible when recharge rates exceed about 10–12 m/s. Unsaturated zones with recharge rates less than this amount are only likely to be found in the most mountainous terrain of the Western Cordillera. Thus, in developing this conceptual model, the influence of vapor movement in the unsaturated zone is neglected and a minimum infiltration rate of 10–12 m/s is assumed.

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Biographical Sketch

Jaime Gárfias is a professor in the Inter American Center for Water Resources, Toluca, Mexico. He received his M.Sc. degree from the Laval University (1990), and his Ph.D. degree from Laval University in Quebec, Canada (February, 1994). He jointed the Inter American Center for Water Resources in July 1994. Currently, he teaches graduate students in Water Science and Technology, through M.Sc. and Ph.D. programs. Professor Gárfias has been visiting professor at the Waterloo Centre for Groundwater Research, Department of Earth Sciences, University of Waterloo, Canada (1995, 1997, 1998, 1999, 2001), at the University of the Basque Country, Department of Earth Sciences, Bilbao, Spain (1992, 1996, 1997), and at the Department of Civil Engineering, Laval University, Quebec, Canada (1997). He teaches numerical analysis, groundwater hydrology, mathematical modeling of groundwater flow, and contaminant transport in hydrogeologic systems at the Faculty of Engineering at Autonomous University of the State of Mexico (Toluca, Mexico), and hydrology in the Department of Earth Sciences at the National University Autonomous of Mexico (Mexico, D.F.). Sponsored by Waterloo Hydrogeologic, Inc., he has taught short courses for engineers, scientists and university personnel on modeling flow and pollution of groundwater and modeling transport phenomena in porous media (1998, 1999 and 2001). He is coordinator of the project HELP (Hydrology for the Environment, Life and Policy) in the region sponsored by UNESCO.

Dr. Gárfias's research projects are diversified in scope and objectives, and are often cast in a collaborative and interdisciplinary context. His main work has been on subsurface contamination by hazardous material and remediation of contaminated subsurface in a collaborative projects with the Department of Earth Science of the University of Waterloo (Ontario, Canada) and the Department of Geodynamics of the University of the Basque Country (Spain).