Mountain-Block Hydrology and Mountain-Front Recharge*

John L. Wilson and Huade Guan

New Mexico Institute of Mining and Technology, Socorro, New Mexico

In semiarid climates, a significant component of recharge to basin aquifers occurs along the mountain front. Traditionally called "mountain-front recharge" (MFR), this process has been treated by modelers of basins as a boundary condition. In general, mountain-front recharge estimates are based on the general precipitation characteristics of the mountain (as estimated, e.g., by the chloride mass balance and water balance methods), or by calibration of a basin groundwater model. These methods avoid altogether the complexities of the hydrologic system above the mountain front, or at best consider only traditional runoff process. Consequently hydrology above the mountain front is an area ripe for significant scientific advancement. A complete view would consider the entire mountain block system and examine hydrologic processes from the slope of the highest peak to the depth of the deepest circulating groundwater. Important aspects above the mountain front include the partitioning of rainfall and snowmelt into vegetation-controlled evapotranspiration, surface runoff, and deep infiltration through bedrock, especially its fractures and faults. Focused flow along mountain stream channels and the diffuse movement of groundwater through the underlying mountain block would both be considered. This paper first defines some key terms, then reviews methods of studying MFR in arid and semiarid regions, discusses hydrological processes in the mountain block, and finally addresses some of the basic questions raised by the new mountain-block hydrology approach, as well as future directions for mountain-block hydrology research.

1. INTRODUCTION

The term "mountain-front recharge" (MFR) is generally used in arid and semiarid climates to describe the contribution of mountains regions to the recharge of aquifers in adjacent basins. Basin aquifer recharge is typically focused along stream channels and the mountain front; in many cases MFR is the dominant source of replenishment [*Hely et al.,* 1971; *Maurer et al.,* 1999]. Diffuse recharge of basin aquifers, through direct infiltration of precipitation, is limited or absent due to small precipitation volumes, deep vadose zones, and the water scavenging vegetation found in dry climates [*Foster and Smith-Carrington,* 1980; *Phillips,* 1994; *Izbicki ,et al.,* 2000; *Flint,* 2002a; *Walvoord et al.,* 2002]. Mountains, due to orographic effects, receive more precipitation than the basin floor, with a significant fraction in the form of snow. In addition, mountains have lower temperatures, and sometimes a larger surface albedo due to the snow cover, thus reducing the potential for evapotranspiration (ET). Mountains also have thin soils that can store less water, reducing the amount potentially lost by transpiration. Fast flow along bedrock fractures that underlie the thin soil cover may also limit water loss to ET (Plate 1). A study of 20 selected catchments worldwide shows that the area-weighted mountain contribution to annual river basin discharge is about 4 times that of the basin floor [*Viviroli et al.,* 2003]. In arid and semiarid regions, the mountain contribution can be greater.

MFR has been studied from one of two perspectives: (1) the traditional basin-centered view (Plate 2a), or (2) a mountain-centered view (Plate 2b). With a basin-centered perspective, the mountain front is viewed as a boundary condition for the basin aquifers, thus avoiding the complexities of the hydrologic system above the mountain front. Basin-centered methods include Darcy's law calculations along the mountain front [*Maurer and Berger,* 1997] and calibration of groundwater models of the basin aquifer [*Tiedeman et al.,* 1998a; *Sanford et al.,* 2000]. With a mountain-centered

* Preprint of paper to be published in *Groundwater Recharge in A Desert Environment: The Southwestern United States,* edited by Fred M. Phillips, James Hogan, and Bridget Scanlon, 2004, AGU, Washington, DC.

Feth et al. [1966] calculated MBR_2 from the Wasatch Mountains to the Weber Delta District of Utah using a similar approach. MBR_2 was reported to be 22% of annual precipitation with an ET loss of 53% (Table 2). Hely et al. [1971] estimated MBR_2 for another section of the Wasatch Mountains to be 19% annual precipitation, with an ET loss of 44% (reviewed by Manning [2002]).

The accuracy of a water balance approach depends mainly on the estimation of ET, which is difficult to quantify, especially for the complex terrain and varied vegetation of mountains. In semiarid regions, ET is a dominant water balance component even in mountains [*Brandes and Wilcox*, 2000]. The uncertainty of the ET estimate is amplified by the uncertainty of other balance components. Take water balance equation (2) as an example. If the actual ET is 60% of P, and MFR_1 is 20% of P, then a 20% uncertainty in the ET estimate leads to a 60% uncertainty in MFR_1, assuming that P and DRO are measured exactly. This undermines the reliability of MFR quantification using the water balance method.

Due to large uncertainty in ET quantification, ET is often empirically related to the local mean annual precipitation, reflecting a direct function between MFR and the mountain's mean annual precipitation. Maxey and Eakin [1949] considered the high spatial variation of precipitation in mountains and demonstrated an empirical relationship between precipitation zones and the MFR to groundwater basins in Nevada. In the Maxey-Eakin method, MFR is estimated by the following steps [*Avon and Durbin, 1994*]: (1) identifying several mean annual precipitation zones; (2) assigning each zone a scaling factor to account for the loss of water by ET and runoff; and (3) summing the recharge amount of each zone. Since, both ET and runoff loss is considered in Maxey-Eakin method, the recharge estimate is conceptually either MBR_2 or MFR_1, depending on the spatial extent of precipitation estimation and the location of runoff estimation (see above). Since the Maxey-Eakin method crudely considers spatially distributed precipitation, it is preferable to other water balance methods that use only a single scaling factor for ET for an entire mountain area. Avon and Durbin [1994] reported that applications of the Maxey-Eakin method in Nevada were generally in fair agreement with estimates from other independent methods.

More recently, Anderson [1992] presented an empirical relationship between the total volume of direct MFR (or MFR_3) and the total volume of mountain precipitation exceeding 203 mm, based on basin-scale water balance estimates in south-central Arizona and parts of adjacent states. This relation can be approximated by

$$MFR_3 = 0.042\,(P_m - 203)^{0.98}\ , \qquad (10)$$

where MFR is direct mountain-front recharge in mm per year, and P_m is mean annual precipitation in mm per year.

Maurer and Berger [1997] gave another empirical regression for mountain water yield (including surface runoff and subsurface flow, approximately equivalent to MFR_2) at Carson Basin, Nevada,

$$MFR_2 = 2.84\times 10^{-5}\,P_m^{\ 2.43}\ , \qquad (11)$$

where P_m is the mean annual precipitation in mm per year.

When estimated recharge by the Maxey-Eakin method is plotted against the mid-value of each of four precipitation zones, with P_m = 8-12, 12-15, 15-20, and >20 inches, and with scaling factors 0.03, 0.07, 0.15, and 0.25, respectively (for the White River Basin, Nevada [*Maxey and Eakin*, 1949]), another power law empirical relationship is revealed,

$$MFR = 9\times 10^{-9}\,P_m^{\ 3.72}\ , \qquad (12)$$

where P_m is the mean annual precipitation in mm per year. Equation (12) deviates from Maxey-Eakin estimates when $P_m > 600\text{mm} \cong 23.6$ inches.

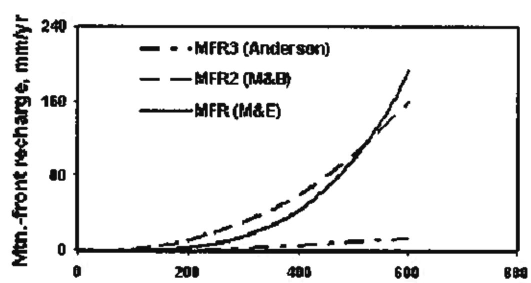

Figure 4. MFR vs. mean annual precipitation for three empirical relations provided by Anderson [1992], Maurer and Berger [1997], and Maxey and Eakin [1949], equations (10)-(12), respectively. Note that Anderson's equation gives direct MFR, while Maurer and Berger's version gives the total water yield [both surface and subsurface] from the mountain.

These three empirical equations (10)-(12) provide substantially different MFR estimates (Figure 4), even though they were all developed for portions of the Basin and Range Province of the southwestern United