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Mountain-Block Hydrology and Mountain-Front Recharge*

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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

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perspective, precipitation amounts over the mountains are crudely related to MFR rates, and do not consider the subsurface hydrologic mechanics in the mountains. Examples of mountain-centered methods include: (1) comparing the geochemical or isotopic characteristics of mountain precipitation with the groundwater at the mountain front (e.g., the chloride mass balance method) [*Dettinger,* 1989; *Maurer and Berger,* 1997; *Anderholm,* 2000]; (2) using locally developed empirical relations between MFR and precipitation [*Maxey and Eakin,* 1949; *Anderson et al.,* 1992; *Maurer et al.,* 1999; *Anderholm,* 2000]; and (3) subtracting estimated ET from precipitation [*Feth,* 1966; *Huntley,* 1979]. The studies of MFR in either perspective so far neglect detailed hydrologic processes in mountains.

Hydrologic processes in mountains have been studied in detail at the hillslope scale, with a focus on streamflow responses to precipitation in humid regions (e.g., *McGlynn et al.,* 2002; *Peters et al.,* 1995; *Tani,* 1997). Few of these studies were conducted in arid and semiarid regions [*Wilcox et al.,* 1997; *Puigdefabregas et al.,* 1998]. Hillslope studies typically only examine hydrologic processes in the thin soil layer above the bedrock surface (Plate 1). Studies of semiarid mountain hydrologic processes below the bedrock surface have mostly been limited to Yucca Mountain, the proposed vadose zone nuclear waste repository in Nevada, with an emphasis on solute migration issues.

Plate 1. Vegetation, thin soil cover, and limestone bedrock on a hillslope of the eastern Sandia Mountains, New Mexico. The rock is dipping to the north (left). The vegetation is mainly Pinõn and Juniper.

Hydrologic science above the mountain front, incorporating a full view of the entire mountain block system and not just the thin soil cover and its vegetation, is an area ripe for significant scientific advancement. This more complete perspective examines hydrologic processes from the slopes of the highest peak to the depths of deepest circulating groundwater. It includes the focused flow of mountain stream channels, and the diffuse movement of groundwater through the surrounding and underlying mountain blocks. It considers recharge from rainfall, snowmelt, surface runoff, and through fractures and faults, as well as water returned to the atmosphere through vegetation-controlled evapotranspiration. When water is discharged from the mountain block to the adjacent basin, through focused and diffuse surface and subsurface components, it becomes MFR.

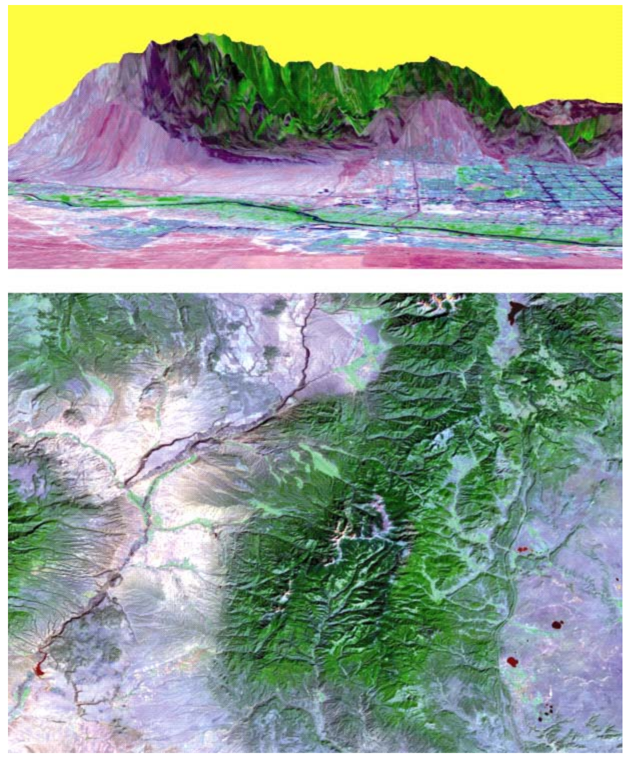

Plate 2. Two different remote sensing perspectives on MFR. (a) The valley-centered perspective is represented by this horizontal view of the Albuquerque Basin bounded by the Sandia Mountains Mountains (~25 km visible in this view). The view is east across the city of Albuquerque, with a 5-times vertical exaggeration (TM image 7, 4, 2 bands draping over a DEM). (b) The mountain-centered perspective is represented by this ~130 km wide vertical view of the southern Sangre de Cristo Mountains, New Mexico and part of Rio Grande valley, with a 5-times vertical exaggeration (TM 7, 4, 2 bands draping over a DEM). The east slopes of the Jemez Mountains are on the left.

MFR is an important, if not predominant, source of recharge to basins in arid and semiarid regions, however it is simultaneously the least well quantified. Estimates of the basin-margin recharge to the Middle Rio Grande Basin vary by one order of magnitude [*Sanford et al.,* 2000]. Uncertainty is amplified by climate variability, climate change, and increasing anthropogenic disturbances that alter mountain environments [*Luckman and Kavanagh,* 2002], mountain hydrology, and thus mountain-front recharge. Some direct human impacts (e.g., septic systems, transportation, resort development, mine dewatering/contamination) also affect water quality in mountains. A more complete approach to studying MFR in a mountain-centered perspective would provide observations of the temporal and spatial variations of its different components, and improve prediction of how the mountain hydrologic system (including MFR) responds to climate and to local disturbances such as changing vegetation patterns. Mountain-centered observations and predictions are essential for effective groundwater resource management in adjacent basins.

This paper first defines some key terms, then reviews methods of studying MFR in arid and semiarid regions, describes hydrologic processes in the mountain block, and finally addresses some of the basic questions raised by a proposed new mountain-block hydrology approach, as well as future directions for mountain-block hydrology research.

2. MOUNTAIN BLOCK, MOUNTAIN FRONT, AND RECHARGE

A mountain block includes all the mass composing the mountains, including vegetation, soil, bedrock (exposed and unexposed), and water. A mountain block can be formed through a number of geological processes, such as normal faulting in extensional settings, thrust faulting in compressional settings, and volcanic eruption. These processes yield the mountain block's most important characteristic: significant topographic relief. Mountain-block hydrology examines all hydrologic processes in the mountain block, including the temporal and spatial distribution of precipitation, vegetation interception, snow and snowmelt, ET, runoff, interflow (throughflow) in the soil layer, water flow through bedrock matrix and fractures, and surface water and subsurface water interactions.

The term mountain-front recharge is frequently used to describe the contribution from mountains to groundwater recharge of the adjacent basins along the mountain front. The mountain front is positioned somewhere between the mountain block and the basin floor. However, a clear and consistent definition of the mountain front is lacking. Estimates of mountain-front recharge are consequently ambiguous and difficult to compare. Is the mountain front a strict line or a narrow zone? If it is a line, how is it determined? If it is a zone, what criteria are used to identify this zone?

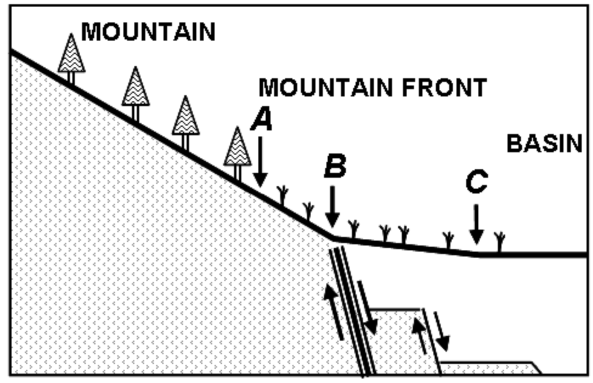

Figure 1. Schematic cross-section showing naturally occurring map lines for potential mountain front definitions. *A* = point of vegetation change, *B* = point of piedmont angle (often a major mountain bounding fault, or master fault, is located in this vicinity), and *C* = point of plinth angle. In extensional settings, like the Rio Grande Rift and Basin and Range, there are a series of normal faults along the mountain front and beneath the alluvial fan leading down into the basin [Russell and Snelson, 1990].

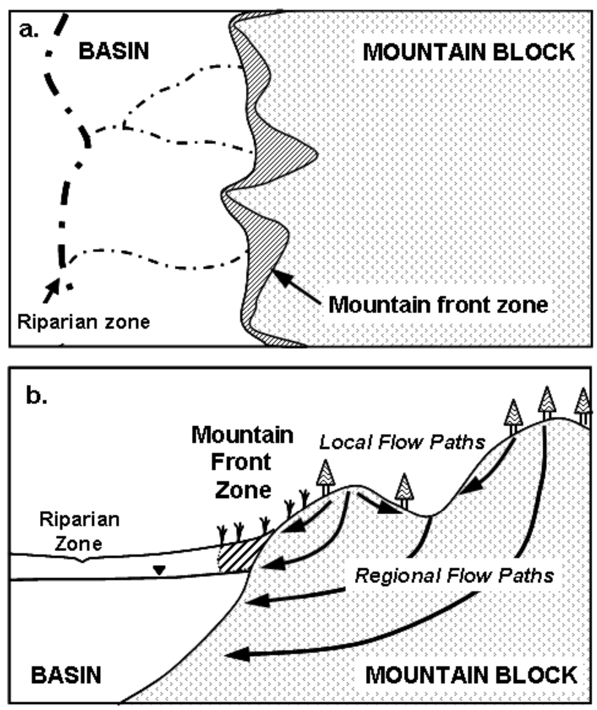

Figure 2. Schematic diagram showing four hydrologically distinctive units of the landscape in map view (a) and in cross-section (b). The cross section also shows various groundwater flow paths in the mountain block (modified from Toth [1963] and Keith, [1980]).

Consider the mountain front defined as a line. Several natural lines could be used, including vegetation boundaries, soil boundaries (e.g., the edge of bare rock), slope boundaries, mountain bounding faults, or even the snow line. Based on Ruxton and Berry's [1961] description of landforms and weathering profiles in arid regions, we define three alternative definitions of the mountain front boundary: the point where there is a change in vegetation (Figure 1, point A), the point where the mountain abuts the piedmont, often corresponding to a change in soil type and presence of the mountain bounding faults (point B), and the plinth angle where the piedmont meets the edge of the basin floor (point C). Each of these boundaries is a candidate for defining the mountain front because each might represent a distinct hydrologic transition (Table 1).

Suppose instead the mountain front is defined as a transition zone between the mountain and the basin floor. Theoretically, any zone that utilizes the boundaries defined in Figure 1 can be a potential mountain front zone. For the purpose of studying mountain-front recharge in arid and semiarid areas we believe that the piedmont zone (the area between points B and C) is the best definition of the mountain front. The streamflow at point B represents surface runoff from the mountain block; the stream loss between points B and C reflects the water returned to the atmosphere by ET and by recharge into the mountain front zone (and eventually to the basin aquifer). Mountain bounding faults are typically located within this zone, thus including their hydrologic effect on mountain-front recharge. With this defined as the mountain front zone, the landscape is then divided into four hydrologically distinctive areas: mountain block, mountain front, basin floor, and discharge zones (e.g., phreatic playas and basin riparian areas), illustrated in Figures 2a and 2b.

Table 1 Comparison of three potential boundaries for mountain front determination

Types of boundaries	Significant change across the boundary	Advantage	Disadvantage
A: Vegetation	Vegetation type, Evapotranspiration.	Good for ecological study.	Varies with climate, slope aspect, etc. Not good for studying mountain front recharge.
B: Piedmont angle	Slope, soil, infiltration and runoff characteristics.	Good point to quantify surface runoff from the mountain, generally accompanied with soil change and buried mountain bounding fault zone.	Recharge from surface runoff beyond this point is not included in mountain front recharge.
C: Plinth angle	Slope, soil, surface structures.	Surface runoff measured past this point is definitely excluded from mountain front recharge.	May be covered by anthropogenic structures; the point is difficult to identify.

MFR is defined by Keith [1980] as groundwater recharge to a regional (basin) aquifer at the margin of the aquifer that parallels a mountain area. MFR is often divided into two components [*Anderson et al.,* 1992; *Chavez et al.,* 1994a; *Manning,* 2002]: (1) subsurface inflow from the adjacent mountains; and (2) infiltration from streams near the mountain front. In this definition, MFR includes the addition of water to the basin aquifer both from the saturated zone under the mountains and through the unsaturated zone at the mountain front. We, and others, call the first component "mountain-block recharge" [*Manning,* 2002]. Some scientists do not regard this as a component of recharge because it fails their strict definition of recharge as water reaching the water table through the unsaturated zone or from direct contact with surface water bodies [*Flint et al.,* 2001a]. With this definition, the combined saturated zone of mountain and basin is considered one system, and recharge is the process of adding water from above through the vadose zone. From this perspective, "mountain-block recharge" would perhaps be termed "underflow" between two portions of the system. If instead we consider only the basin aquifer as the system of concern, the broader definition acknowledges that "recharge" occurs when water is added to the aquifer. Meinzer [1923] distinguished these two contributions to aquifer replenishment as direct recharge (from the unsaturated zone) and indirect recharge (from other saturated formations). A recent National Research Council [2004] report appears to accept the less strict definition of recharge.

For compatibility with the traditional view of mountain-front recharge in basin hydrologic studies, we suggest that MFR be defined as all water entering the basin aquifer with its source in the mountain block and mountain front (zone). This definition includes direct water-table recharge at the mountain-front zone (direct MFR), and the transfer of subsurface water from the mountain bedrock to the basin aquifer (indirect MFR or mountain-block recharge). In addition to near surface (direct) and subsurface paths (indirect), one can also consider diffuse and focused paths for each, leading to four components of MFR (Figure 3).

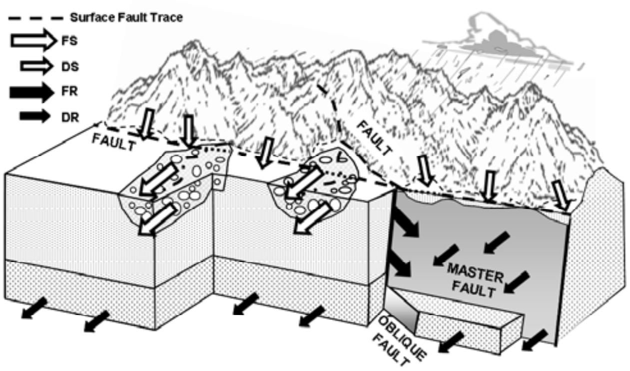

Figure 3. Schematic diagram illustrating MFR components. *FS* = focused near-surface recharge, *DS* = diffuse near-surface recharge, *FR* = focused subsurface recharge, *DR* = diffuse subsurface recharge.

1) *Focused near surface component* (*FS*). This represents MFR contributions at the mountain front from surface stream runoff ($FS_{1,}$, easy to measure) and shallow subsurface water transmitted by streambed sediments (FS_2, difficult to measure). We emphasize FS_2 here because it is sometimes neglected when MFR is estimated solely from the surface runoff. While the stream channel may be dry, there is often significant subsurface discharge in the sediments underlying the stream and above the bedrock surface. This subsurface flow includes the hyporheic zone beneath the stream, but it can be deeper and wider, especially at the mountain front. Theoretically, the surface runoff FS_1 is the amount of stream water runoff (*RO*) that crosses the piedmont angle (Point B in Figure 1) and enters the mountain front zone. In reality, FS_1 is always less than *RO*, because of ET losses, and because some surface runoff manages to flow past the downstream boundary of the mountain front zone and into the basin (*DRO*). In arid regions where streams are mostly ephemeral and disappear at the mountain front, FS_1 is equal to *RO* less the loss to ET.

2) *Diffuse near surface component* (*DS*). Diffuse near surface flow occurs along steep front slopes via ephemeral surface runoff (in small unmapped channels) and subsurface interflow (through the thin soil layer) originating in small catchments directly above the mountain front. This diffuse component also includes the vertical recharge from precipitation falling directly on the mountain-front zone. Both of these contributions are reduced by the local ET. Given the small area of the mountain front zone compared to the remainder of the mountain block, these contributions provide a relatively small component of MFR.

3) *Focused subsurface component* (*FR*). This is subsurface water transmitted along bedrock openings, including fractures (primarily tectonic origin, or due to unloading extension), faults, and pipes (e.g., lava tubes and dissolved openings in carbonates), that connect subsurface water in the mountain block and the basin aquifer. Structural enhancement of rock permeability due to faults and zones of intense fracturing within the bedrock are especially important factors in creating focused subsurface flowpaths, which Feth [1964] calls the 'hidden path'. Groundwater transmission is mostly by focused flow *FR* in mountain blocks composed of crystalline rock.

4) *Diffuse subsurface component* (*DR*). There is also a diffuse component of groundwater transmission along the contact zone between the bedrock of the mountain block and the sediments of the basin aquifer. In a mountain block with high matrix permeability, such as a volcanic tuff, or regular and ubiquitous fracturing, such as a basalt, diffuse flow *DR* can be an important component of mountain-front recharge.

Based on these definitions, a simple water balance equation,

$$MFR_1 = (FS_1+FS_2) + DS + FR + DR \,, \qquad (1)$$

describes mountain-front recharge. Despite their simplicity, water balance equations are useful tools for conceptualizing mountain-front recharge. Another way of writing the water balance equation for MFR_1 is

$$MFR_1 = P - ET_b - ET_f - DRO \,, \qquad (2)$$

where P is precipitation input in the mountain block and the mountain-front zone ($P=P_b+P_f$, where $P_b \gg P_f$), ET_b and ET_f are evapotranspiration in the mountain block and mountain-front zone, respectively, and *DRO* is streamflow at the downstream end of the mountain-front zone into the basin.

In the arid and semi-arid southwest United States a number of simplifications are taken, leading to less comprehensive definitions of mountain-front recharge. First, stream runoff at the mountain front is generally ephemeral, and almost always disappears within the mountain front zone. Therefore, downstream runoff beyond the mountain front is often negligible (DRO = 0). In this case, MFR can be defined as

$$MFR_2 = P - ET_b - ET_f \ . \qquad (3)$$

This can be rewritten, in terms of the four components at the mountain front, as

$$MFR_2 = (RO - RET_f + FS_2) + DS + FR + DR \qquad (4)$$

where RET_f is the riparian ET along the focused stream channel across the mountain-front zone (there is a small diffuse component of ET_f throughout the rest of the zone, away from the stream channel, that is already accounted for by the DS component).

In some cases the subsurface water transfer from the mountain bedrock to the basin aquifer is neglected. In other words, only direct MFR is considered, with the component formula becomes

$$MFR_3 = FS + DS \ . \qquad (5)$$

Taking this one step further, the diffuse component and FS_2 are also neglected and mountain-front recharge is assumed to be equal to the surface stream flow measured at the mountain front, FS_1. This leads to a very simple definition of MFR,

$$MFR_4 = RO \ , \qquad (6)$$

where RO is streamflow at the upstream end of the mountain front zone. This model assumes that all stream runoff at the mountain front becomes recharge to the basin aquifer.

As previously defined, mountain-block recharge (MBR) is recharge to a basin aquifer from the mountain bedrock. It is expressed as the sum of subsurface components,

$$MBR_1 = FR + DR \ . \qquad (7)$$

This water balance equation excludes the subsurface water transfer in the streambed. If we broaden the definition of mountain-block recharge to include this component, then we have

$$MBR_2 = FS_2 + FR + DR \ . \qquad (8)$$

This mountain-block water balance equation can be written as

$$MBR_2 = P - ET_b - RO \qquad (9)$$

when the front-slope runoff is negligible.

Why bother to write out these various versions of the water balance equation? They illustrate the range of different conditions that apply in nature and the range of assumptions that people make in order to understand and estimate mountain-front and mountain-block recharge. In particular, for methods adopting a particular conceptual water balance model, they show what is being neglected and so point out bias. The assumptions used by analysts and modelers are not always consistent with the appropriate conditions for a particular mountain range and its bounding basins.

3. ESTIMATION METHODS

Various physical, chemical, and numerical methods have been applied to study MFR over the past five decades. Table 2 summarizes the methods used in several studies of MFR in arid and semiarid regions. While Flint et al. [2002b] summarizes methods used at Yucca Mountain for estimating recharge to the mountain block itself, here we review a wide variety of the methods employed to estimate MFR.

3.1 Water Balance Method

Generally, precipitation is the only water input to a mountain block. The amount of mountain-front recharge can be estimated if water loss by ET and surface runoff is known. Which MFR components are estimated is based on where ET and surface runoff are quantified. If ET is estimated in the mountain block, and stream runoff is measured at the upstream end of the mountain front zone, then equation (9) is applied. The resulting estimate is for mountain-block recharge, MBR_2. If, however, the ET is estimated over the mountain block and the mountain front zone, and the stream runoff is measured at the downstream end of the mountain front zone, equation (2) is applied. The result is an estimate of mountain-front recharge, MFR_1.

ET in mountains is usually estimated in relation to mean annual precipitation, pan evaporation, or derived from the water balance equation by assuming mountain bedrock impermeability. Huntley [1979] estimated actual ET loss in the Sangre de Cristo and San Juan Mountains of Colorado by multiplying calculated potential ET with an empirical factor, and reported that, respectively, 14% and 38% of annual precipitation becomes mountain-block recharge, MBR_2 (when comparing these numbers it is interesting to note that, among other differences, the Sangre's are crystalline rock whereas the San Juan's are volcanic).

Table 2 Quantitative assessment on mountain front recharge by various methods

Location	Authors	Methods	MFR or MBR amount in mm/year (percentage of precipitation)	Precipitation mm/year	Notes
Wasatch Range / Weber Delta Dsitrict, Utah	Feth et al. [1966]	Water balance method, precipitation and ET estimated by increments of elevation.	MBR_2 = 201 (22%)	926	Streamflow at mountain front is 25% annual precipitation in the mountain.
San Juan Mtns / San Luis Valley, Colorado	Huntley [1979]	Water balance method, ET estimated from calculated potential, ET multiplied by crop coefficient.	MBR_2 = (38%)	Not reported	Volcanic rock with high permeability in the mountain.
Sangre de Cristo Mtns / San Luis Valley, Colorado	Huntley [1979]	Water balance method, ET estimated from calculated potential, ET multiplied by crop coefficient.	MBR_2 = (14%)	Not reported	Shists, gneiss, and granitic intrusives, well-cemented sedimentary rocks in the mountain.
White River Valley, Navada	Maxey and Eakin [1949]	Maxey-Eakin method.	Not reported	Not reported	
Sandia Mtns / Albuquerque Basin, New Mexico	Anderholm [2000]	Precipitation-runoff regression method, using two empirical equations.	MFR_4 = 23 (4.6%) (Waltemeyer model) MFR_4 = 66 (13%) (Hearne and Dewey model)	510	Subsurface inflow and ET at mountain front was believed negligible.
Carson Mtns, Virgina Mtns / Eagle Valley, Navada	Maurer et al. [1997]	Chloride mass balance.	MFR_3 = 27 (7.8%) (data resulted from four subcatchments)	350	Weathered and fractured granitic, basaltic and metamorphic rocks.
Sandia Mtns / Albuquerque Basin, New Mexico	Anderholm [2000]	Chloride Mass Balance.	MFR_3 = 31 (6.1%)	510	0.3 mg/l chloride conc. used for bulk precipitation.
Santa Catalina Mtns / Tucson Basin, Arizona	Chavez et al. [1994]	Analytical seasonal stream flow model with stochastic estimation procedures.	MBR_2 = 1.1 (0.2%)	280-760	Layered gneiss with folds.
Carson Mtns, Virgina Mtns / Eagle Valley, Nevada	Maurer et al. [1997]	Darcy's law.	MFR_1 = 31 (8.8%) [data resulted from four subcatchments]	350	Weathered and fractured granitic, basaltic and metamorphic rocks.
Sandia Mtns / Albuquerque Basin, New Mexico	Tiedeman et al. [1998]	Modeling of basin aquifer, calibrated using inverse method.	MFR_1 = 132 (26%)	510	Precipitation data from Anderholm [2000].
Sandia Mtns / Albuquerque Basin, New Mexico	Sanford et al. [2000]	Modeling of basin aquifer, calibrated using ^{14}C groundwater age	MFR_1 = 15 (3%)	510	Precipitation data from Anderholm [2000].
Eagle Mtns / Red Light Draw Valley, Texas	Hibbs and Darling [1995]	2D Numerical modeling of both mtns and valley area, calibrated using groundwater age.	MFR_1 = 1.8 (0.6%)	300	Widespread, well-developed calcic soil horizon in basin.
Yucca Mtns, Nevada	Flint et al. [2001]	Modeling in mountains.	MBR_1 = 4.5 (2.7%)	170	Welded and non-welded tuff.