

Water Resources Research



REVIEW ARTICLE

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Key Points:

- Mountain-block recharge confirmed as important source of recharge to basin aquifers in a variety of climatic and geologic settings globally
- Recent work advanced understanding of fundamental controls on mountain-block recharge and somewhat improved methods for characterization
- Future research should aim to acquire subsurface data in mountain block and at the mountain front

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Mountain-Block Recharge: A Review of Current Understanding

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Abstract Mountain-block recharge (MBR) is the subsurface inflow of groundwater to lowland aquifers from adjacent mountains. MBR can be a major component of recharge but remains difficult to characterize and quantify due to limited hydrogeologic, climatic, and other data in the mountain block and at the mountain front. The number of MBR-related studies has increased dramatically in the 15 years since the last review of the topic was conducted by Wilson and Guan (2004), generating important advancements. We review this recent body of literature, summarize current understanding of factors controlling MBR, and provide recommendations for future research priorities. Prior to 2004, most MBR studies were performed in the southwestern United States. Since then, numerous studies have detected and quantified MBR in basins around the world, typically estimating MBR to be 5–50% of basin-fill aquifer recharge. Theoretical studies using generic numerical modeling domains have revealed fundamental hydrogeologic and topographic controls on the amount of MBR and where it originates within the mountain block. Several mountain-focused hydrogeologic studies have confirmed the widespread existence of mountain bedrock aquifers hosting considerable groundwater flow and, in some cases, identified the occurrence of interbasin flow leaving headwater catchments in the subsurface—both of which are required for MBR to occur. Future MBR research should focus on the collection of high-priority data (e.g., subsurface data near the mountain front and within the mountain block) and the development of sophisticated coupled models calibrated to multiple data types to best constrain MBR and predict how it may change in response to climate warming.

1. Introduction

Hydrologists have long recognized the importance of mountains to global water resources (Bales et al., 2006; Viviroli et al., 2011; Wilson & Guan, 2004). Mountains receive disproportionately large amounts of precipitation due to the orographic effect and deliver this water via streamflow to populated areas at lower elevations. Often, mountain precipitation is stored in snowpack and glaciers, and meltwater maintains critical streamflows during warmer and drier months. What is less well understood, but equally important, is how mountain systems recharge lowland aquifers via mountain-front recharge (MFR) and mountain-block recharge (MBR) processes (Wilson & Guan, 2004). While the specific definitions of MFR and MBR vary in the literature, MFR is generally defined as all water that enters a lowland aquifer with its source in the mountain block. MBR, a component of MFR, is the subsurface inflow of groundwater to the lowland aquifer that comes directly from the mountain block. These sources of recharge can be significant, and in arid regions, MFR is the dominant source of recharge to lowland aquifers (Earman et al., 2006; Scanlon et al., 2006). Despite its importance, MFR estimates are usually poorly constrained, particularly the MBR component, because subsurface hydrogeologic data are limited within mountain blocks and often nonexistent at the mountain front itself.

MBR was first described by Feth (1964), who referred to it as “hidden recharge.” Feth (1964) observed that hydraulic head contours in a basin aquifer in northern Utah, USA, paralleled the adjacent Wasatch Range front, that basin wells near the mountain block exhibited chemistry similar to high elevation springs as opposed to local surface waters, and that water level response in these wells mimicked discharge fluctuations in a nearby mine tunnel. In the decades following, a handful of studies attempted to quantify mountain system recharge, often with conflicting definitions of MFR and MBR, very sparse data, and questionable assumptions. Wilson and Guan (2004) provided a parsimonious set of definitions of MFR, MBR, and their

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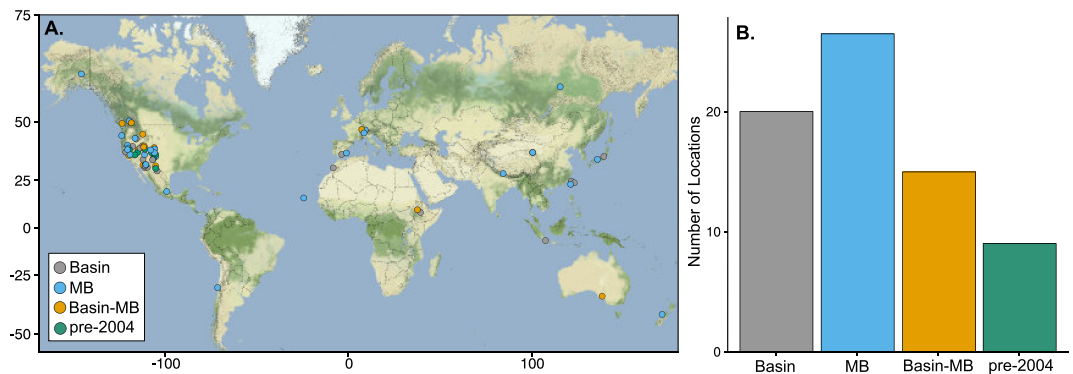


Figure 1. (a) Map of pre- and post-2004 mountain-block recharge studies, colored by type of study: basin-focused (Basin), mountain block-focused (MB), and combined basin-mountain block studies (Basin-MB). (b) Bar chart showing the number of studies by type.

components and compiled and reviewed the handful of MBR estimates published as of 2004. These early MBR estimates were predominantly basin focused (as opposed to mountain focused; see section 3.2), carried large uncertainties, and were all located in the western United States. Since then, numerous MBR-related studies have been performed around the world (Figure 1). Several of these have detected and quantified MBR utilizing a broader and more robust set of methods, confirming that MBR is not a limited regional phenomenon but instead an important component of recharge to many lowland aquifers globally.

Our motivation for presenting an updated review of MBR research is twofold. First, a considerable amount of work has occurred since the MFR review paper by Wilson and Guan (2004), leading to important advances in our understanding of MBR. A need exists to synthesize this work and summarize our current understanding in order to better focus future research efforts. Second, there is a growing urgency to understand and predict how climate and land use change is altering the timing and amount of recharge from mountain systems (Beniston et al., 1997; Meixner et al., 2016; Niraula et al., 2017a, 2017b, Viviroli et al., 2011). To date, the focus of research aimed at understanding the effects of climate change on mountain hydrology has largely been on surface water resources, where peak flows are shifting earlier (Barnett et al., 2005; Cayan et al., 2001; Cayan et al., 2008; Christensen et al., 2004; Stewart et al., 2005) and snowpack and streamflow volumes are on the decline (Luce & Holden, 2009; Mote et al., 2005; Musselman et al., 2017; Zapata-Rios et al., 2016). Studies of potential impacts to mountain groundwater are more limited but suggest that projected warming and reduction of snowpack will likely decrease recharge to many mountain aquifers (e.g., Manning et al., 2012; Meixner et al., 2016). This decrease could clearly impact MBR, though uncertainties in specific mountain recharge processes, potential feedbacks, and routing of groundwater through the mountain block mean that the magnitude and timescales of such impacts remain largely unknown. Distinguishing MBR from other MFR contributions infiltrating at lower elevation directly through the basin fill has always been necessary for developing effective groundwater source protection strategies for lowland aquifers. However, distinguishing these different MFR components has recently taken on yet greater importance because the different infiltration locations and residence times of these components mean that they could respond very differently to changing future mountain hydrologic conditions.

2. Conceptual Background and Definitions

A consistent conceptualization of MBR and associated set of definitions are important to allow scientists to effectively communicate and build on existing work. We believe the conceptual framework and definitions put forward by Wilson and Guan (2004) generally remain relevant and should continue to be applied in future work. We therefore describe them below only briefly, with the exception of some definition modifications discussed in more detail.

A *mountain block* is an area of topographically elevated and rugged terrain where soils and unconsolidated sediment are thin to nonexistent, such that the shallow subsurface is composed predominantly of bedrock. A mountain block is thus topographically and geologically distinct from adjacent lowland areas, which are relatively flat and underlain by thick unconsolidated to semiconsolidated sediments (henceforth “basin fill”) that often form highly productive aquifers. Note that a mountain block consists of both bedrock and

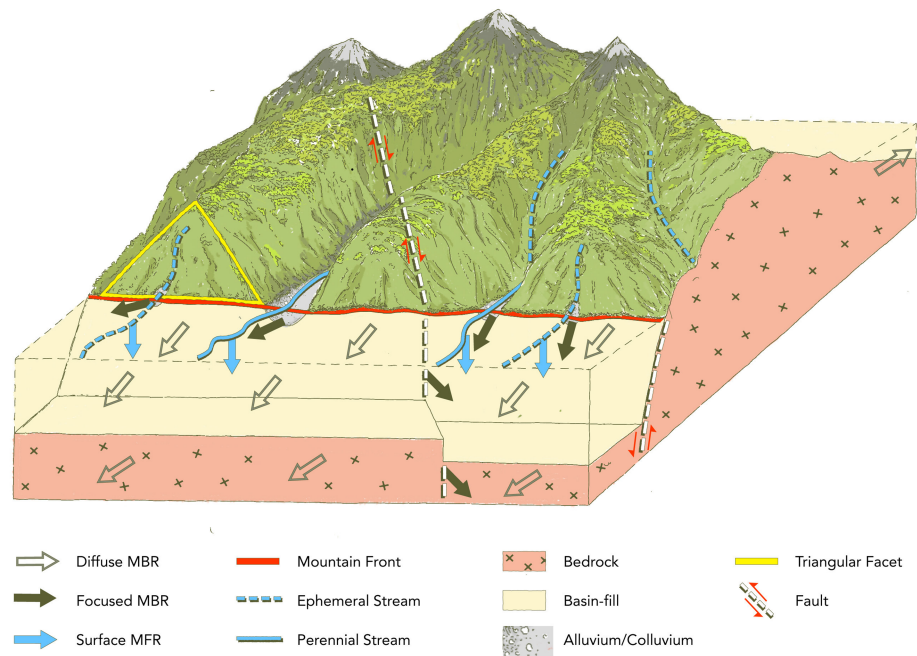


Figure 2. Conceptual diagram showing two mountain fronts: a sedimentary contact (far side) between the mountain block and basin fill and a fault-controlled contact (near side). Different components of mountain-front recharge (MFR) and mountain-block recharge (MBR) are also shown, including surface MFR or infiltration through the basin fill from a mountain-sourced perennial or ephemeral stream; focused MBR, which occurs either through discrete faults and fracture zones or underneath mountain-sourced streams; and diffuse MBR, which occurs widely across the mountain front.

all directly overlying colluvium/alluvium, soils, and vegetation. Mountain blocks can form as a result of multiple geological processes, the most common being uplift in extensional tectonic settings through normal faulting, uplift in compressional tectonic settings through thrust/reverse faulting, and emplacement of igneous rocks through volcanic eruptions.

We define the *mountain front* as the surface trace of the geologic contact between the mountain block and the adjacent basin fill. In other words, it is a linear feature defined by the intersection of two planar features, these being (1) the ground surface and (2) the subsurface geologic contact between the bedrock of the mountain block and the adjacent basin fill. Note that we consider shallow fingers/lenses of alluvium underlying mountain streams to be part of the mountain block (not the basin fill) where they overlie and extend into the mountain block. Our definition of mountain front differs somewhat from that of Wilson and Guan (2004), who define it as the piedmont zone between the mountains and the valley floor. While the transition from mountains to piedmont is in most cases relatively well defined, the transition from piedmont to basin floor may be poorly defined in many basins, particularly those with more human development and heavy vegetation. We therefore believe our definition is preferable because it is conceptually simpler and more easily applied across a wide range of mountain/basin settings. The mountain front may be either fault controlled or a depositional contact, a classic example of these two types being the east and west sides, respectively, of the Sierra Nevada mountain block in California, USA.

MFR is all water that enters a basin-fill aquifer with its source in the mountain block. MFR is composed of two components: surface MFR and MBR. *Surface MFR* is infiltration through the basin fill of mountain-sourced perennial and ephemeral stream water after these streams exit the mountain block (Figure 2). Surface MFR is equivalent to the “focused near-surface” component of MFR as defined by Wilson and Guan (2004) with the modification explained in the following paragraph. Infiltration from mountain-sourced streams occurs near the mountain front because this is where the basin-fill aquifer water table (WT) is commonly well below the land surface (see plate 3 in Wilson & Guan, 2004). We consider the maximum distance from the mountain front that surface MFR can occur to be the point where the WT is

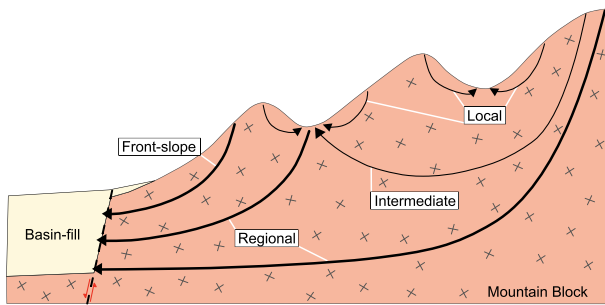


Figure 3. Conceptual diagram showing the four major flowpaths in mountain-block systems: (1) local, which discharges within the same subcatchment as where recharge occurred; (2) intermediate, which bypasses the local stream and discharges at a higher-order stream within the mountain block (often flowing largely perpendicular to the cross-section shown); (3) regional, which bypasses all mountain streams and exits the mountain block in the subsurface, becoming mountain-block recharge; and (4) front-slope flow, which recharges immediately above the mountain front and becomes mountain-block recharge. The mountain-block recharge flowpaths are shown in bold.

no longer predominantly below stream level—that is, where the stream ceases to be predominantly a losing stream. *Mountain-block recharge* is groundwater inflow to a lowland aquifer from an adjacent mountain block. *Diffuse MBR* is spatially broadly distributed and occurs widely across the mountain front. *Focused MBR* occurs through discrete permeable geologic features in the mountain block, such as steeply dipping fault zones or high-permeability sedimentary rock units that strike at a high angle to the mountain front (Figure 2). Focused MBR may also occur near the point where a mountain stream exits the mountain block (or “watershed mouth”) in the unconsolidated material or shallow bedrock underneath the stream. Our consideration of shallow subsurface inflow beneath streams to be MBR is a break from Wilson and Guan (2004), who considered this a component of “focused near-surface” MFR, not MBR. We feel including this component as MBR provides a more logically consistent definition of MBR—that is, MBR is all groundwater that enters the basin aquifer from the mountain block (where the mountain block includes immediately overlying shallow colluvium/alluvium). Further, most studies characterizing MBR do not distinguish deep from shallow flowpaths, so this definition is more in line with current research methods.

A common mistake in the literature is to refer to all recharge that occurs within the mountain block as MBR. As illustrated in Figure 3, groundwater within the mountain block can follow different flowpaths of potentially widely varying depth and length, and importantly, not all flowpaths contribute to MBR. We define four types of flow paths, expanding upon the three types (local, intermediate, and regional) defined by Tóth (1963) and applied to mountain topography in Wilson and Guan (2004) and Gleeson and Manning (2008). Local flow is groundwater that discharges to the nearest stream within the same subwatershed where it recharged. Intermediate flow is groundwater that exits the subwatershed where it recharged through the subsurface and discharges to a lower-elevation stream of higher order than the subwatershed where it recharged. Importantly, intermediate and local flowpaths discharge to the surface system *within* the mountain block and thus do not contribute to MBR. For this reason, we refer to all recharge to mountain aquifers as *mountain aquifer recharge* to distinguish it from MBR. Regional flow follows yet longer flowpaths than intermediate flow and exits the mountain block in the subsurface, thus becoming MBR. Here, we propose a fourth type of flow, *front-slope flow*, which is recharged on the slopes immediately above the mountain front between the mouths of major mountain watersheds (i.e., within triangular facets, Figure 2) and flows directly to the basin-fill aquifer as MBR. A unique definition for this flow path is justified because it does not neatly fall within one of the other three definitions above, and recent modeling studies suggest that it may be a major contributor to MBR (Welch & Allen, 2012; Manning & Solomon, 2005). In summary, regional and front-slope flows contribute to MBR, but local and intermediate flows do not.

3. MBR Review

A literature search revealed >200 studies since 2004 that mention MBR and/or cite the review by Wilson and Guan (2004). We refined this group (also adding some studies) by selecting those that attempt to distinguish, characterize, or quantify MBR or that conduct research directly related to it (e.g., estimating deep percolation and interbasin flow in headwater catchments). This resulted in 74 MBR studies, falling in four categories: (1) model-based conceptual studies; (2) basin-focused studies, which rely mainly on the relative wealth of data from wells in the basin-fill aquifer to estimate MBR; (3) mountain-focused studies, which directly examine mountain aquifers, mountain aquifer recharge, and mountain-block groundwater flow; and (4) combined mountain-basin studies. Here, we provide an updated review of MBR studies published since 2004, organized by the aforementioned categories, as well as an overview of studies addressing potential human impacts to MBR. All quantitative MBR estimates presented in these studies are presented in Table 1.

3.1. Conceptual Studies

Gleeson and Manning (2008) used an integrated hydrologic model of a three-dimensional mountainous domain to test how different topographic and hydrogeologic variables affect the relative proportions of

Table 1
Mountain Block Recharge Estimates Organized by Type of Study

Location	Authors	Type	Method	MBR amount			Climate ^a	Dominant MB lithology
				% Basin-fill		Mountain aquifer recharge		
				Aquifer-scale estimate	Mean (and range) of well estimates			
Spanish Springs Valley, NV, USA	Schaefer et al. (2007)	Basin	MODFLOW	13.3%	—	—	Cold semiarid	Metasedimentary and intrusive
Eagle Springs Valley, NV, USA	Schaefer et al. (2007)	Basin	MODFLOW	28%	—	—	Cold semiarid	Metasedimentary and intrusive
Grenchen Basin, Switzerland	Althaus et al. (2009)	Basin	NGTs, SIs, and age tracers	—	9% (0–91%)	—	Temperate oceanic	Karst
Southeastern Española Basin, NM, USA	Manning (2011)	Basin	NGTs and radiocarbon	—	24% (0–50%)	—	Cold semiarid	Metasedimentary and intrusive
Kanto Plain, Japan	Liu and Yamanaka (2012)	Basin	SIs and chemistry	—	22% (0–100%) ^b	—	Humid subtropical	Sedimentary
Middle Rio Grande Basin, NM, USA	Bexfield et al. (2016)	Basin	MODFLOW	6–25%	—	—	Cold semiarid	Intrusive and metamorphic overlain by karst
Langyang Plain, Taiwan	Peng et al. (2016)	Basin	SIs and chemistry	—	12% (0–35%)	—	Humid subtropical	Metasedimentary
Eastern Coastal Plain, Taiwan	Peng et al. (2018)	Basin	SIs and chemistry	—	33% (22–54%) ^c	—	Humid subtropical	Metamorphic
Dry Creek Watershed, ID, USA	Aishlin and McNamara (2011)	MB	Chloride mass balance	—	—	40%	Cold semiarid	Intrusive
Qilian Mountains, China	Yao et al. (2017)	MB	MODFLOW	—	—	35%	Humid continental	Metamorphic and volcanic
Salt Lake Valley, UT, USA	Manning and Solomon (2005)	Basin-MB	FEMWATER	27–62%	—	—	Cold semiarid	Intrusive and metasedimentary
Tobacco Root Mountains, MT, USA	Magruder et al. (2009)	Basin-MB	Biome-BGC and MODFLOW	36%	—	—	Cold semiarid	Metamorphic and intrusive
Northern Utah Valley, UT, USA	Gardner (2009)	Basin-MB	MODFLOW	46%	—	—	Cold semiarid	Sedimentary and metasedimentary
Central Valley, CA, USA	Brush et al. (2013)	Basin-MB	IWFM	10–13%	—	—	Mediterranean	Intrusive
Northwestern South Park Basin, CO, USA	Ball et al. (2014)	Basin-MB	FEFLOW	60%	—	—	Cold semiarid	Metamorphic and intrusive overlain by sedimentary
Gibsons Basin, BC, Canada	Doyle et al. (2015)	Basin-MB	NGTs and MODFLOW	45%	—	—	Humid coastal	Metasedimentary and metavolcanic
Gidabo River Basin, Ethiopia	Mechal et al. (2016)	Basin-MB	MODFLOW	35%	—	—	Subtropical highland	Volcanic
San Joaquin Valley, CA, USA	Gilbert and Maxwell (2017)	Basin-MB	ParFlow-CLM	7.7–23%	—	—	Mediterranean	Intrusive

Note. IWFM = Integrated Water Flow Model; MB = mountain block; MBR = mountain-block recharge; NGT = noble gas temperatures; SIs = stable water isotopes.
^aAccording to the Köppen-Geiger climate classification system (Peel et al., 2007). ^bRange is for means from different aquifer sectors—individual well estimate values not provided. ^cMean is approximate, estimated from well MBR fractions reported in a plot, not a table.

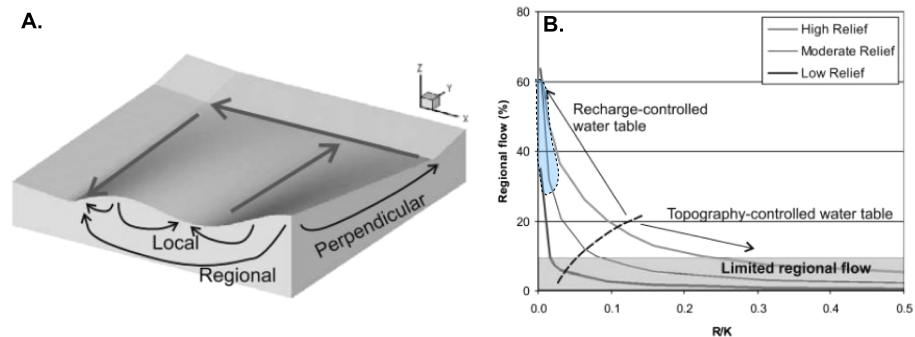


Figure 4. Modeling results from Gleeson and Manning (2008). (a) Base domain indicating local, perpendicular (intermediate), and regional flow paths. (b) Relationship between the proportion of regional flow (as a fraction of total recharge) and the ratio of recharge to mountain-block hydraulic conductivity (R/K). Low R/K ratios result in a deep “recharge-controlled” water table (WT) and higher proportions of regional flow, and high R/K ratios result in a shallow “topography-controlled” WT and lower proportions of regional flow. The dashed black line differentiates between the two types of WTs using the definition in Haitjema and Mitchell-Bruker (2005). The dashed blue area indicates R/K ratios commonly associated with first-order streams being within the unsaturated zone (perennial). High-, moderate-, and low-relief terrains were tested with topographies characteristic of the Himalaya, Rocky Mountains, and Appalachian Mountains, respectively.

regional and local groundwater flow (Figure 4). The study is essentially a three-dimensional extension of Tóth's (1963) seminal regional groundwater flow study applicable to mountainous areas. Their model domain contained connected first-, second-, and third-order drainage basins with representative mountain topography, and they defined regional groundwater flow as water that recharges in the first- or second-order basin and discharges in the third-order basin (Figure 4a). Although their model did not explicitly include a mountain front, their results are directly relevant to MBR because, as stated by the authors, their simulated regional flow would be equivalent to MBR if the third-order (lowest-elevation) watershed in the model domain contained sedimentary fill. They found that regional flow is mainly controlled by the mountain-block WT elevation (Figure 4b). Their work adopted the WT classification of Haitjema and Mitchell-Bruker (2005), which defined two fundamental types of WTs: (1) a topography-controlled WT resulting from high recharge (R) and/or low hydraulic conductivity (K), producing a WT high enough to sustain perennial streamflow in mountain catchments, and (2) a recharge-controlled WT resulting from low R and/or high K , producing a WT below mountain stream beds. For topography-controlled WTs, which should be more common in mountains (given typically low fractured-rock K s), they found a theoretical maximum regional flow fraction of about 20% of total model recharge. This suggests that the mountain WT must be recharge controlled (i.e., deeper, so more deep circulation) for large fractions of MBR to originate from parts of the mountain block farther back from the mountain front. For topography-controlled WTs, they also found that less deeply incised stream drainage networks promote larger regional flow fractions, because a deeper level of incision draws more local flow to the streams. Finally, they confirmed that higher mountain elevation above the basin and greater mountain aquifer thickness both promote larger regional flow fractions.

Welch and Allen (2012) conducted a similar theoretical study of mountain groundwater flow paths using a larger-scale, three-dimensional numerical model that included complete mountain watershed systems with multiple tributaries. They varied the topographic configuration to explore a variety of plausible mountain groundwater unit geometries. A mountain groundwater unit is defined by a regional-scale mountain surface watershed, containing a dominant stream valley, with the important exception that it also includes the adjacent triangular facets immediately above the mountain front (Figure 5), these being a common geomorphological feature (Figure 2). Welch and Allen (2012) assumed a mountain aquifer thickness of 100 m, typical for fractured crystalline rock, with a relatively low K of 10^{-8} m/s at greater depth. They found that the majority of flow paths generating MBR (73–97%) are front-slope flow, originating on the triangular facets, shown in Figure 5 as the red pathlines. This was consistent with the findings of Manning and Solomon (2005), whose modeling of the Wasatch Range, UT, found that 90% of MBR was front-slope flow for the case of an aquifer thickness of 200 m. However, the modeling of Welch and Allen (2012) provided evidence that this was a common and widespread, rather than just a local, phenomenon. Manning and

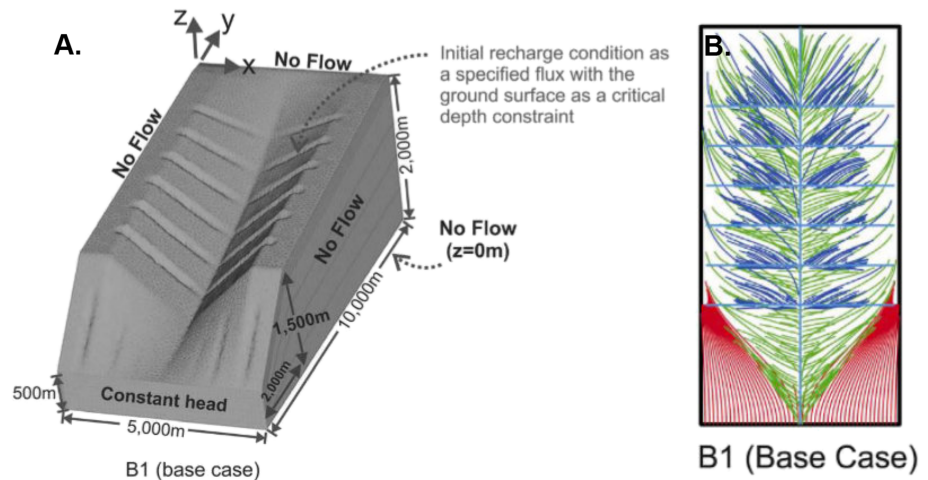


Figure 5. Modeling results from Welch and Allen (2012). (a) Base-case model space including a single mountain groundwater unit. (b) Reverse pathlines taken from $z = 75$ m for base case model, where red lines indicate mountain-block recharge, green lines indicate groundwater contributions to the dominant stream, and blue lines indicate groundwater contributions to the small perpendicular tributary streams. The light blue lines indicate streams. Modified from Welch and Allen (2012).

Solomon (2005) showed decreases in the fraction of MBR originating from front-slope flow with increasing aquifer thickness (43% for a thickness of 2,000+ m) but noted that such large circulation depths are probably uncommon. Welch and Allen (2012) also found that changing the mountain-block drainage and/or topographic configuration did not substantially change MBR, and they attributed this to the triangular facet topography varying little. Finally, their modeling provided further support for the hypothesis put forward by Gleeson and Manning (2008) that less stream incision promotes larger MBR contributions from areas behind the facets farther back from the mountain front.

In summary, these conceptual studies found that more MBR can be expected in mountain systems with higher K , greater aquifer thickness (modestly high K to greater depth), deeper WTs, less stream incision, and higher elevation above the adjacent basin (Gleeson & Manning, 2008; Welch & Allen, 2012). They also found that MBR is most inclined to originate closer to the mountain front, particularly as front-slope flow from triangular facets (Welch & Allen, 2012).

3.2. Basin-Focused Studies

Basin-focused studies primarily use models for observations from the basin-fill system to estimate MBR. In the case of models, this involves treating the contact between the basin fill and the mountain block as a boundary and estimating MBR as a flux across this boundary. For observational studies, this involves using groundwater chemistry, tracer, and age data from wells located mainly within the basin-fill aquifer to estimate the source and amount of recharge. These studies take advantage of the large number of wells in basin-fill aquifers compared to mountain blocks and the resulting abundance of hydrogeologic information, such as measurements of hydraulic conductivity, WT elevation, aquifer storage properties, and water chemistry. Prior to 2004, most MBR studies were basin focused, and almost all were located in the intermountain basins of the southwestern United States (Figure 1). These studies mainly utilized water balance methods, calibrated numerical basin-aquifer models, and Darcy flow calculations. As Wilson and Guan (2004) pointed out, each of these methods carried large uncertainties due to uncertainties in evapotranspiration, model nonuniqueness, and homogeneity assumptions, to name a few. Since then, numerous basin-focused studies have been performed in mountain areas around the world. Though model nonuniqueness and difficulties in distinguishing MBR from surface MFR remain major challenges, many of these more recent basin-focused studies employ new methodologies that show promise for reducing MBR estimate uncertainties.

In several of the observational basin-focused studies we reviewed, MBR was inferred primarily based on stable isotopes of water (Blasch & Bryson, 2007; Earman et al., 2006; Kohfahl et al., 2008; Eastoe & Towne, 2018). However, a major limitation of this approach is that, although stable water isotopes effectively identify a high-elevation precipitation source, they do not distinguish the elevation where this water actually

recharged (i.e., whether the water is MBR or surface MFR). For example, Blasch and Bryson (2007) used stable water isotopes in an elevation-weighted mixing model to determine the likeliest elevations contributing precipitation to recharge in the Verde River Basin, AZ, and found that the great majority of recharge originated as mountain precipitation (MFR). They then inferred substantial MBR to the basin-fill aquifer, but this conclusion relied largely on ancillary climatic and geologic information regarding the apparent favorability of different parts of basin and mountain block for infiltration. Further, many of these stable water isotope studies do not appear to consider the significant potential variability and uncertainty in isotopic signature of precipitation from a single elevation. Studies have demonstrated large variation within storms (McDonnell et al., 1990), based on aspect (Dahlke & Lyon, 2013), based on seasonal storm-track variations (Pape et al., 2010), and over the course of a snowpack melting (Taylor et al., 2002, 2001). Finally, Eastoe and Towne (2018) demonstrated how depleted isotopic signatures may represent paleorecharge as opposed to high elevation recharge in some intermountain basins in Arizona. In short, the numerous studies relying primarily on stable isotope ratios have identified MFR to basin-fill aquifers with some degree of confidence, but their conclusions regarding MBR contributions, specifically, remain highly speculative.

Other basin-focused studies inferring the presence of MBR have applied a broader sampling approach, combining stable isotopes with water chemistry and groundwater age tracers. Bouchaou et al. (2008), Gillespie et al. (2012), and Wahi et al. (2008) combined stable water isotopes with groundwater age information from radiocarbon and tritium data to assess recharge sources in the Souss-Massa Basin, Morocco; the Snake and Spring Valley Basins, UT and NV; and in the Upper San Pedro Basin, AZ, respectively. All three studies report large MFR fractions in the basin aquifer based on depleted stable isotopic signatures combined with groundwater ages being younger closer to the mountain front. They further state that at least some of this MFR is likely MBR given apparently high mountain-block permeability based on geologic evidence (extensive carbonates) or measurements in mountain-block wells. Although these studies provide stronger evidence for high MFR fractions than those relying primarily on stable isotope data, conclusions regarding MBR contributions remain highly speculative. Hopkins et al. (2014) characterized recharge sources to wells completed in a shallow unconfined and a deeper confined aquifer in the San Pedro Basin, AZ, using stable isotopes, water chemistry, age tracers, and numerical modeling. They were able to distinguish MBR from surface MFR by examining isotopic signatures and water age in both deep and shallow wells, attributing the combination of high-elevation stable isotopic signatures and long residence times in the deep confined aquifer to MBR and short residence times in the shallow unconfined aquifer to surface MFR. Longer residence times are to be expected in a confined aquifer and do not necessarily indicate MBR; however, the geochemical and numerical flow path modeling employed by Hopkins et al. (2014), further informed by some wells screened within the mountain block, allowed for a robust evaluation of recharge pathways. This study demonstrates the importance and utility of sampling from a range of well depth completions in the basin fill, particularly if perched and confined aquifers are present.

Several basin-focused studies have stepped beyond simply inferring the presence of MBR and have attempted to quantify MBR with the use of either endmember mixing analysis (EMMA) or noble gas recharge temperatures (NGT). EMMA relies on the assumption that the chemical signatures of endmembers can be characterized, are distinct, and either do not vary or that variations are considered (Buttle, 1994; Klaus & McDonnell, 2013; Liu et al., 2008). Liu and Yamanaka (2012) used deuterium and chloride to quantify the proportions of recharge from low-elevation precipitation, surface MFR from a mountain-sourced river, and MBR to wells in the Ashikaga area of central Japan. They found MBR contributed 40–100% of recharge to wells in a portion of the basin adjacent to a synclinal structure in the mountains, which they believed promoted subsurface flow in the mountain block. Importantly, they found much lower MBR contributions (down to 0%) in other wells, with a mean contribution of 22%, which points to a large spatial variability in MBR tied to geologic features within the mountain block. Such local variability in MBR is often overlooked when quantifying basin-wide estimates but is clearly evident in Table 1 for studies like Liu and Yamanaka (2012) and others discussed below that report MBR contributions for individual wells. Peng et al. (2016) attributed a modest mean fraction (12%) of total recharge to the Langyang alluvial fan aquifer in Taiwan to MBR using stable isotopes and electrical conductivity (EC) in an EMMA model. They later applied this same approach in the eastern coastal plain of Taiwan and found more significant fractions of MBR (22–54%) that correlated with mountain-block geology (Peng et al., 2018). These studies demonstrate the potential of EMMA to quantify MBR, based on the often unique combined isotopic and chemical signatures of recharge from low-elevation precipitation on the basin floor, surface MFR, and MBR. However, all three studies relied

on a limited number of samples from mountain springs and/or shallow wells to identify the signature of MBR and did not rigorously address potential spatial or temporal variability in endmember signatures.

To date, the most effective method for distinguishing MBR from surface MFR in basin-fill aquifers is using groundwater dissolved noble gas concentrations to determine the shallow ground temperature at the recharge location (NGT). NGTs can be used to estimate a recharge elevation when a relationship between shallow ground temperature and elevation is assumed or derived for the study area (Aeschbach-Hertig et al., 1999; Manning & Solomon, 2003). Surface MFR will typically have a relatively warm NGT, reflecting low-elevation recharge, whereas MBR will typically have a cooler NGT, reflecting recharge at higher elevation. Building on the suggestion of Aeschbach-Hertig et al. (1999) that noble gases might be applied as recharge elevation tracers, Manning and Solomon (2003) further developed this approach and used NGTs to detect MBR in a proof of concept study in the eastern Salt Lake Valley, UT. They first used NGTs from mountain springs and mine tunnels to derive a local recharge temperature lapse rate, which they found to be similar to the local atmospheric temperature lapse rate as theoretically expected. They then used NGTs from basin aquifer wells to place constraints on the MBR fraction in the basin-fill aquifer, finding >50% MBR in 17 of 22 wells in the southeastern part of the valley. Later studies have demonstrated the use of NGTs with stable isotopes and age tracers to provide both qualitative and quantitative estimates of MBR. Althaus et al. (2009) measured all of these tracers in the Grenchen aquifer system, Switzerland, and found an absence of MBR from the adjacent Jura Mountains in most wells (though not all) based largely on warm, low-elevation NGTs. Manning (2011) used NGTs and radiocarbon ages to determine minimum MBR fractions of 0–50%, with a mean of 24%, for the southeastern Española Basin, NM. The radiocarbon ages further revealed that the majority of MBR likely enters the basin-fill aquifer near watershed mouths. Manning (2011) also found much cooler NGTs in samples of Pleistocene age (>12,000 years old), as expected given the cooler climate during the Pleistocene epoch, and cautioned that radiocarbon ages should be collected along with noble gases in basins where very old groundwater may be present. Gardner and Heilweil (2014) applied a similar approach as Manning (2011) for a large number of springs and wells in the Snake Valley area of the north-eastern Great Basin, NV and UT. They found that the NGTs and radiocarbon ages suggest that most recharge within the study area is MBR from the Snake Range. Thoma et al. (2011) measured NGTs in Treasure Valley, Idaho, and identified the presence of MBR from the adjacent Boise Front Range. They also measured some unexpectedly warm NGTs exceeding the mean annual air temperature at the well location and applied an infiltration-weighted recharge model to determine that the likely cause was infiltration of summer irrigation water in the valley. Their work underscores the importance of taking into account possible NGT variations at a given elevation due to seasonally shallow WTs when deriving local NGT lapse rates. Overall, NGTs have proved to be a reliable method for distinguishing surface MFR from MBR, but their effectiveness requires a significant difference in recharge elevation between these two components. Distinguishing low-elevation MBR, which might be focused beneath streams exiting the mountain block or front-slope flow (Figure 2), from surface MFR using environmental tracers remains a challenge.

Some basin-focused studies have addressed the important issue of major faults near the mountain front potentially acting to either impede or enhance MBR. Fault-zone architecture commonly includes a clay-rich core, which can impede cross-fault groundwater flow, surrounded by a highly fractured damage zone, which can enhance fault-parallel groundwater flow (Caine et al., 1996). Because the process of mountain building often involves significant tectonism and crustal deformation, mountain blocks commonly contain and/or are bounded by major faults. Theoretically, range-bounding faults, which accommodated uplift of the mountain block, could act as barriers to MBR because they are generally oriented at a high angle to MBR flow—that is, MBR must flow across them to enter the basin-fill aquifer. Conversely, major faults within the mountain block oriented more parallel to MBR flow paths could act as conduits for MBR, particularly regional flow. Chowdhury et al. (2008) used stable water isotopes, radiocarbon, and tritium to explore recharge processes in a normal-fault-bounded basin in West Texas. They interpret the deep WT in the basin fill near the fault combined with low tritium and low percent modern carbon in water samples from the same location as evidence that the fault impedes flow and that modern MBR is minimal. A steep head gradient across the mountain front is a common line of evidence used to support faults impeding flow; however, this can also simply be the result of the high-K basin fill juxtaposed against the lower-K mountain block, as discussed by Bresciani et al. (2018). Delinon (2009) came to a similar conclusion regarding the range-bounding Lembang fault, which appears to impede MBR to the Bandung Basin, Indonesia, based on hydraulic head, stable isotopes, and salinity. Kebede et al. (2008) conducted a thorough hydrogeological, hydrochemical,

and groundwater age assessment of basin wells in two transects within the Ethiopian rift having distinctly different structural characteristics. The first transect includes transverse faults that crosscut the mountain front at a high angle, whereas the second transect does not include such faults and also has fault-controlled grabens paralleling the mountain front at the foot of the mountain block. They interpret the presence of isotopically depleted and older groundwater in the first transect as evidence that the transverse faults provide permeable conduits for MBR. However, the isotopic and age data show little evidence of MBR in the second transect, suggesting that the mountain-front-parallel faults in the rift generally act as barriers to MBR. Caine et al. (2017) performed a detailed field examination of mountain-front faults near the foot of the Sangre de Cristo mountain block along the eastern margin of the Española Basin, NM, characterizing their brittle structure and possible hydraulic influence. They found that the faults are largely discontinuous when mapped in detail and are thus unlikely to significantly impede MBR. Taken together, the above studies provide evidence that faults can indeed either impede or enhance MBR, depending largely on their orientation, but also that mountain-front-parallel faults probably do not systematically and significantly impede MBR to such a degree as to render MBR a rare exception, rather than a common phenomenon. This general finding is thus consistent with the other widespread evidence of MBR found by other basin-focused studies.

Another widely used method for quantifying MBR in basin-focused studies is numerical groundwater flow modeling. Modeling studies generally treat the mountain block as a boundary in one of two ways: (1) assuming MBR is negligible and assigning a no-flow boundary or (2) initializing MBR based on results from other modeling or observational studies and adjusting it to match observations from the basin-fill aquifer during calibration. Basin-focused modeling studies of the second type thus essentially use head data and K estimates from the basin-fill aquifer to further constrain or revise prior independent MBR estimates. The first approach of assuming the mountain block is impermeable (no-flow mountain-front boundary) has historically been the most common (Bolger et al., 2011; Faunt, 2009; Mason & Bota, 2006). A major impediment to determining whether this no-flow assumption is appropriate is the typical scarcity of K data in the mountain block, particularly near the mountain front. Though treating the mountain front as a no-flow boundary may be justified in some cases, this assumption should be made with caution given the growing number of studies that find appreciable rates of groundwater flow in mountain fractured-bedrock aquifers, even in crystalline rock (see section 3.3). In basin-fill aquifers where MFR and MBR are suspected to be substantial portions of recharge, such as in intermountain basins in the arid and semiarid western United States, the second approach of specifying and calibrating MBR is more common. Siade et al. (2015) estimated natural MFR to the Antelope Valley, CA, with a groundwater flow model calibrated to both observed head and subsidence data. Their estimate of MFR included both surface MFR and MBR components, but they did not report separate results for the two. Their inverse calibration allowed for confidence intervals to be placed around MFR rates, as well as the ability to evaluate “reasonableness” of prior or higher recharge estimates. Schaefer et al. (2007) relied on prior MBR estimates from Maurer and Thodal (2000) to specify the lateral boundaries to their MODFLOW model of Eagle Valley and Spanish Springs Valley, NV. They computed MBR fractions of 28% and 13.3%, respectively, for the two basins, these being somewhat lower than the estimates of Maurer and Thodal (2000). Bexfield et al. (2016) relied on previous modeling and groundwater age-based estimates of subsurface inflow to specify MBR fluxes as lateral boundary conditions to their MODFLOW model of the Middle Rio Grande Basin, NM. Their calibration resulted in a slight increase of MBR in predevelopment (25% of recharge) and modern (6% of recharge) conditions compared to previous studies. Note that the postdevelopment decrease in MBR in their study is a relative decrease due to the addition of canal and crop irrigation seepage to basin-fill aquifer recharge.

Regardless of the chosen approach, using basin-focused groundwater flow models to estimate MBR or distinguish it from surface MFR is inherently uncertain due to poor constraints on K and resulting nonunique combinations of R and K that can reproduce observed head data in the basin during calibration (Wilson & Guan, 2004). Not distinguishing MBR from surface MFR in these models introduces bias to the hydrogeologic conceptualization and limits the robustness of prediction. Multiple studies have demonstrated the feasibility of calibrating basin-centered groundwater flow models to age tracers in addition to heads to reduce this uncertainty (Bexfield et al., 2016; Sanford, 2011; Sanford et al., 2004). However, establishing useful tracer-based age constraints for samples from long-screened production wells (short-screened monitoring wells are rarely available; McCallum et al., 2015) and realistically modeling age dispersion related to subsurface heterogeneity (Engdahl et al., 2012; Fogg & Zhang, 2016) remain major challenges to calibrating numerical models with age tracer data.

Despite their data advantage, basin-focused studies still produce MBR estimates that carry considerable uncertainty largely due to difficulty in distinguishing MBR from surface MFR, especially studies relying heavily on stable water isotopes or traditional calibration of groundwater flow models. Combined approaches, particularly those using stable water isotopes, age tracers, and NGTs, are the most robust and hold the greatest promise for distinguishing and quantifying MBR. Regardless of the uncertainties in MBR estimates, these studies as a group strongly argue that substantial MBR to lowland aquifers (5–50% of total recharge; Table 1) is common throughout the world. This is the case even for basins bounded by crystalline-rock mountain blocks of apparently low permeability. Importantly, some of these studies have also found an absence of MBR in some basins (or parts of basins), and most attribute this to major range-bounding faults, though the actual role of mountain-block faults in impeding (or enhancing) MBR remains largely speculative.

3.3. Mountain-Focused Studies

Mountain-focused studies directly examine mountain aquifers and processes related to groundwater flow in the mountain block. Wilson and Guan (2004) stated that MFR-related work up to that time had employed mainly “basin-centered approaches” and declared that “the mountain-block hydrologic system is ripe for new studies” (p. 18). Many researchers agreed, and by far the largest category of MBR-related papers published since 2004 has been mountain-focused studies, taking full advantage of a growth in instrumented watersheds with wells, advances in numerical modeling, and the novel application of tracers. As a result, the hydrology community has confirmed that mountain bedrock aquifers are an important component of the mountain hydrologic system, often having recharge rates as large as 10–50% of precipitation (30–300 mm/year; e.g., Andreu et al., 2011; Carrera-Hernández & Gaskin, 2008; Kormos et al., 2015) and contributing substantially to mountain streamflow (e.g., Hale & McDonnell, 2016; Hale et al., 2016; Gabrielli et al., 2018; Kosugi et al., 2006). Here, we review recent studies of mountain-block hydrogeology and mountain groundwater flow that are directly relevant to MBR, though this list should not be considered comprehensive.

The hydraulic conductivity (K) distribution within the mountain block and active circulation depth of groundwater, or depth to which groundwater circulates on human rather than geologic timescales, are first-order controls on the rate and distribution of MBR (Gleeson & Manning, 2008; Welch & Allen, 2012; Wilson & Guan, 2004). The multiple geological factors potentially controlling mountain-block K are discussed by Wilson and Guan (2004), and Welch and Allen (2014) present a compilation of fractured-bedrock K measurements and estimates for mountainous terrain. In general, K decreases with depth in fractured rocks owing to the decreasing influence of weathering (Worthington et al., 2016) and the decreasing aperture and number of open fractures and pores due to increasing overburden loads and mineral precipitation (Manning & Ingebritsen, 1999; Saar & Manga, 2004; Stober & Bucher, 2007; St. Clair et al., 2015; Voeckler & Allen, 2012). As reviewed in detail in Welch and Allen (2014) and Manning and Caine (2007), multiple lines of evidence presented in pre- and post-2004 studies have contributed to the development of a now widely invoked general conceptual model for mountain groundwater flow systems, in which a higher- K “active” zone (the aquifer) overlies a deep low- K zone (relatively impermeable bedrock). Some flow within the deep low- K zone still occurs but is on average small relative to mountain hydrologic budgets and is not spatially pervasive, instead limited to a few discrete features such as deeply penetrating major faults. Available data suggest general K ranges of 10^{-8} to 10^{-6} m/s for the active fractured bedrock zone and $<10^{-8}$ m/s for the deep low- K zone (Katsura et al., 2009; Welch & Allen, 2014).

Welch and Allen (2014) propose the following more specific vertical K zones for fractured crystalline-rock mountain systems based on their compilation, as illustrated in Figure 6: soil (0 to 3 m), saprolite and highly weathered bedrock (0 to 10 m), fractured bedrock (10 to 100–200 m), and deep low- K bedrock (>100 –200 m). Although available data converge on a depth estimate of 100–200 m for active circulation in crystalline rocks, the number of study locations remains relatively small, and this depth may vary widely depending on local tectonic history, specific lithology, and climate. Frisbee et al. (2017) used the quartz-silica geothermometer on mountain spring and well waters in the Rio Hondo watershed, Sangre de Cristo Mountains, NM, which is underlain by crystalline metamorphic rocks, to estimate active circulation depths upward of 1,000 m, though the substantial assumptions required for such geothermometers make them less than ideal for this application. Multiple studies have observed active groundwater circulation to depths of 500–1,500 m within steeply dipping faults and discrete fracture zones in tunnels and mines in the mountain block, as evidenced by modern recharge and hydraulic head data (Ofterdinger et al., 2014; Oyarzún et al., 2019;

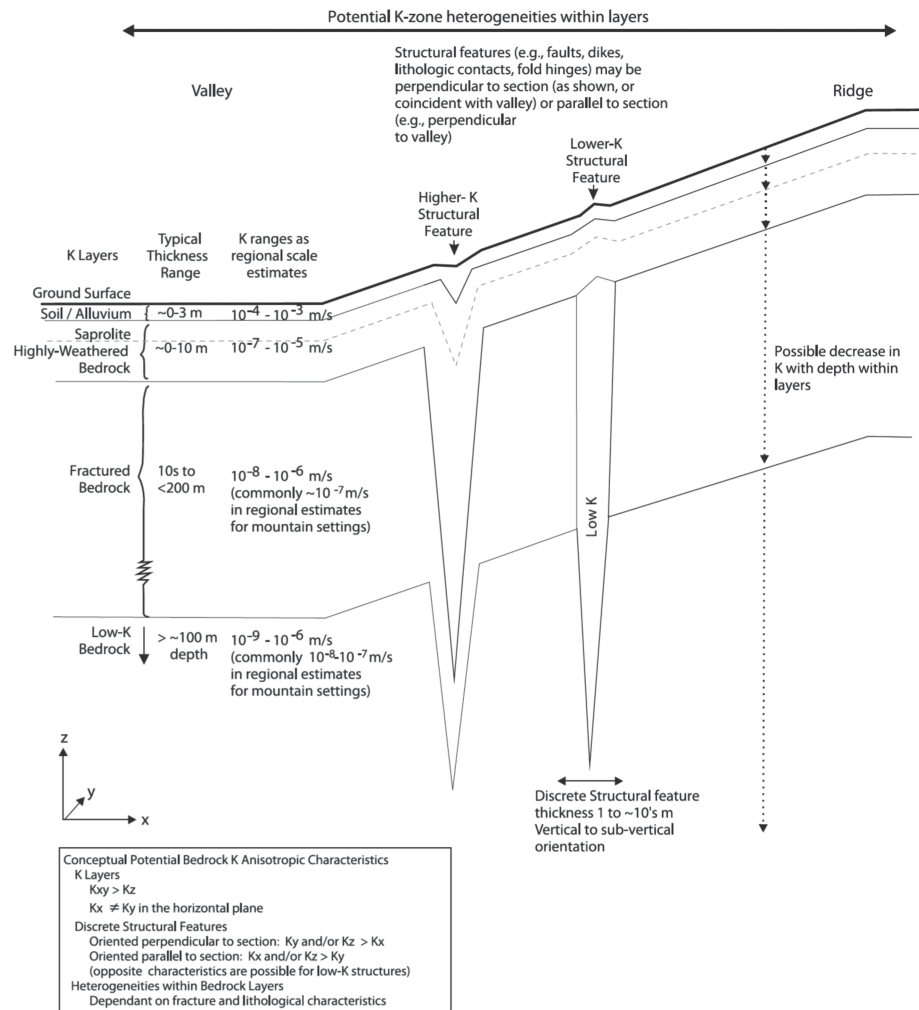


Figure 6. Conceptual model of catchment-scale vertical hydraulic conductivity (K) zones typical of fractured crystalline rock mountain aquifer systems, reproduced from Welch and Allen (2014).

Tomonaga et al., 2017; Wilson & Guan, 2004). However, whether or not these structures hosted active flow prior to tunnel or mine installation (which induces draining) and, if so, whether cumulative flow within them was sufficient to extend the active zone down to the tunnel/mine depth remain major unanswered questions. St. Clair et al. (2015) combined information from seismic refraction and electrical resistivity geophysical surveys for transects in three Critical Zone Observatory watersheds (Gordon Gulch, CO; Calhoun, SC; and Pond Branch, MD), all underlain by crystalline metamorphic rocks and were able to discern a zone of unweathered bedrock with low water content below a depth of approximately 40 m and a zone of fractured bedrock with high water content above. They concluded that circulation depths of <100 m may not be unusual in watersheds underlain by crystalline rocks. However, this conclusion assumes a close correlation between water content and K, and no corroborating subsurface data from boreholes or wells were presented. Nevertheless, St. Clair et al. (2015) demonstrated that ground geophysical surveys may be a useful screening tool for determining circulation depth over broad areas.

Regional-scale coupled heat and groundwater flow models of sedimentary basins and volcanic terrains compiled by Manning and Ingebritsen (1999) show $K_s > 10^{-8}$ m/s typically extending to depths of 2 km, suggesting that active circulation depths considerably greater than 100–200 m may be common in noncrystalline sedimentary and volcanic rocks. Available studies involving mountain blocks composed of volcanic rock appear to support such deep circulation. Saar and Manga (2004) derive a permeability-depth relationship for the volcanic rocks composing the Oregon Cascade Range based on hydrogeologic, thermal, seismic, and magmatic modeling constraints and find that $K_s > 10^{-8}$ m/s extends to depths of roughly 3 km. Heilweil

et al. (2012) use a coupled heat and fluid flow model combined with NGTs to constrain recharge rates and K_s for a volcanic island aquifer rising to 2,000 m above sea level in the Cape Verde Islands and report WT depths of 600–1,000 m and K_s on the order of 10^{-8} m/s to a depth of 2 km below the central caldera. Frisbee et al. (2017) apply the same previously mentioned quartz-silica geothermometer method in the Saguache Creek watershed in the San Juan Mountains, CO, which is underlain by volcanic rocks, and estimate active circulation depths of 900–1,700 m. In the only recent study, we are aware of examining circulation depth for a sedimentary rock mountain block; Lazear (2006) reports K_s on the order of 10^{-8} m/s extending to a depth of 1,500 m derived from a regional heat and groundwater flow model of the Tongue Creek watershed, Grand Mesa, CO. However, Mayo et al. (2003) and Mayo and Koontz (2000) used groundwater temperature, chemistry, and age data from mines and springs to estimate a circulation depth of only 150–300 m for very similar packages of sedimentary rocks in Colorado and Utah. This discrepancy might be explained by the model of Lazear (2006) failing to include K anisotropy, which can commonly cause vertical K to be 2–3 orders of magnitude less than horizontal K in sedimentary rocks, thus substantially reducing circulation depth.

Although the number of mountain K measurements is growing, estimates of active mountain groundwater circulation depth are typically very poorly constrained, even in well-instrumented watersheds, and circulation depth remains in general perhaps the most uncertain characteristic of mountain groundwater flow. The primary reason for this uncertainty is a continued scarcity of mountain wells of sufficient depth to penetrate below the active zone and allow direct observation of the transition from the active zone to the deep low- K zone.

A growing number of studies are attempting to determine the amount of mountain aquifer recharge that becomes baseflow within the same subwatershed (local flow) versus the amount that is lost to interbasin (intermediate and regional) flow (Figure 3). This interbasin flow has also been referred to as the “headwater groundwater subsidy” to the parent watershed (Ameli et al., 2018), and basins have been classified as “exporters” (recharge is greater than streamflow) and “importers” (streamflow is greater than recharge; Fan & Schaller, 2009). The portion of mountain aquifer recharge that becomes interbasin flow does not necessarily become MBR, though it is available to become MBR. Thus, these studies directly inform efforts to estimate and identify sources of MBR. Welch et al. (2012) explored interbasin flow using 3-D groundwater flow models of both generic and real (Daves Creek, Canada) mountain watershed configurations. They found that interbasin flow is a standard component of mountain groundwater flow systems and should be considered in studies of mountain streamflow generation. However, the amount of interbasin flow and the time scale on which it changes in response to changing mountain aquifer recharge are highly variable, depending on detailed characteristics of mountain watershed topography and recharge rates. Kormos et al. (2015) developed a spatially distributed soil-water infiltration method for estimating deep drainage from the bottom of the soil layer to the bedrock. They estimate roughly 34% of precipitation becomes “bedrock infiltration” in the ephemeral headwater Treeline catchment in the Dry Creek Experimental watershed, ID, which they define as water that leaves the catchment boundaries through subsurface drainage (i.e., interbasin flow). This estimate is in agreement with a prior estimate of 22–34% of precipitation for headwater catchments of the Dry Creek watershed based on chloride mass balance (Aishlin & McNamara, 2011). Installation of bedrock wells in the M8 catchment of the Maimai Experimental watershed, New Zealand, allowed for estimation of local versus interbasin bedrock groundwater flow through a combination of modeling and field measurements of WT depth and residence time (Ameli et al., 2018; Gabrielli et al., 2018). These studies concluded that roughly 50% of groundwater recharge in the headwater catchments becomes intermediate flow and subsidizes the parent watershed. Ameli et al. (2018) also perform model experiments to determine the sensitivity of the interbasin flow fraction to R and find that it increases markedly with decreasing R (as the WT falls), thus providing a real-world example supporting the findings of Gleeson and Manning (2008) that interbasin flow should generally increase with a progressively deeper WT (Figures 4 and 7). Such large interbasin flow fractions are consistent with other studies that have identified deep, old groundwater contributions to mountain streams, as well as increases in these old-water contributions with increasing watershed scale regardless of the underlying geology (Ameli et al., 2018; Frisbee et al., 2017; Hale & McDonnell, 2016; Hale et al., 2016). However, these large fractions appear in conflict with the theoretical maximum of about 25% interbasin flow (intermediate plus regional) found by Gleeson and Manning (2008) for first-order watersheds with a topography-controlled WT (observed WT depths are <10 m in the M8 headwater catchment).

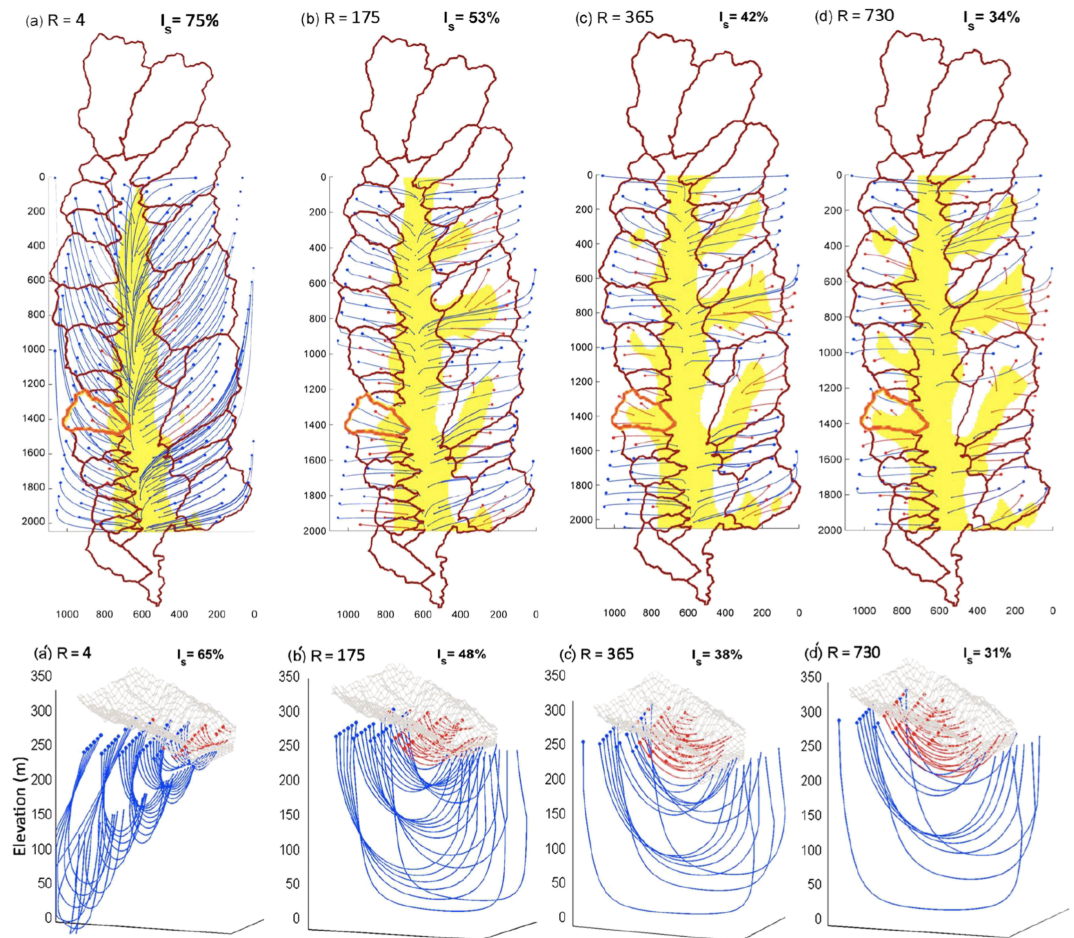


Figure 7. Modeled groundwater flow pathline results from Ameli et al. (2018) demonstrating the dependence of the amount and distribution of intermediate flow (blue pathlines) on recharge rate (R , in mm/year). I_s is the percentage of headwater catchment recharge that becomes intermediate flow. (a)–(d) show results for the entire Maimai Experimental watershed, and (a')–(d') show results for the heavily instrumented M8 headwater catchment. Decreasing R increases the amount of intermediate flow relative to local flow (red pathlines), as the WT drops farther below the land surface. These results provide a real-world example supporting the finding of Gleeson and Manning (2008) that the interbasin flow fraction increases as the water table drops from a higher- to a lower-elevation position (see Figure 4).

The discrepancy could be explained by complicating factors, such as perched WTs in the studied headwater catchments (the regional WT could be deeper and recharge controlled), or by real-world complexities in topography and bedrock K distribution not included in the idealized modeling of Gleeson and Manning (2008).

In contrast to the above studies, others employing tracer-based and modeling methods have estimated only very small amounts of interbasin flow from headwater catchments. For example, two studies using NGTs and groundwater age tracers in two different watersheds in the Sierra Nevada, CA (Martis Valley and Olympic Valley), found that groundwater from headwater catchments probably contributes little to the parent watershed (Segal et al., 2014; Singleton & Moran, 2010). This conclusion was based mainly on NGTs for groundwater samples collected from wells in the parent watershed being inconsistent with high-elevation (cold) recharge in the headwater catchments. Voeckler et al. (2014) calibrated a specified head outlet in a numerical coupled surface water and groundwater model of the Upper Penticton Creek, BC, and estimated that only 7% of recharge leaves the catchment in the subsurface and becomes interbasin flow. Two studies in Marshall Gulch, AZ, obtained very small estimates (1–2% of precipitation) for bedrock groundwater recharge in this headwater catchment based on a storage-discharge function (Ajami et al., 2011) and base-flow recession analysis (Dwivedi et al., 2019), though neither studies had access to bedrock wells for their analysis. Sandoval et al. (2018) applied a similar approach as Ajami et al. (2011) and estimated bedrock recharge to be 1–4% of precipitation in the Punitaqui Basin of northern Chile. The low bedrock recharge

estimates in these three studies indicate small absolute interbasin flow rates and are not surprising for these arid mountain regions. However, these studies did not discern relative amounts of local versus interbasin flow, and it remains possible (if not probable, given the results of Gleeson & Manning, 2008, and Ameli et al., 2018) that relative interbasin flow fractions are large.

Of the mountain-focused studies we considered, relatively few attempted to quantify MBR, specifically. Kao et al. (2012) estimated MBR in the Choushui-Wu River basin, Taiwan, from mountain aquifer recharge estimates and stream gage data. They estimated mountain aquifer recharge using two independent methods: modeled rainfall infiltration estimates over the mountain block and baseflow separation from gaging stations in catchments hosting perennial streamflow. They then applied these recharge rates over the entire mountain block (including areas without perennial streamflow) and subtracted streamflow to obtain two separate MBR estimates which agreed well (though these were never presented as a percentage of mountain aquifer recharge or basin-fill aquifer recharge). However, this approach carries significant uncertainty due to well-established difficulties in accurately estimating baseflow and mountain water budget components (particularly evapotranspiration [ET]) as discussed by Wilson and Guan (2004). Aishlin and McNamara (2011) used chloride mass balance to estimate interbasin flow leaving the Dry Creek Experimental watershed, ID, in the subsurface. They estimated that 14% of precipitation, or 40% of mountain aquifer recharge, becomes interbasin flow, which likely then becomes MBR to the adjacent Boise valley aquifer. They found larger percentages of interbasin flow (22–34% of precipitation) leaving the smaller headwater subcatchments of the Dry Creek watershed in the subsurface, in agreement with Kormos et al. (2015), but some of this water discharges as springflow or baseflow lower down on the mountain block and does not become MBR. However, applying chloride mass balance in mountain systems requires satisfying several major assumptions including (1) inert behavior of chloride, (2) accurate estimation of precipitation and chloride deposition rates, (3) no endogenous sources of chloride, and (4) chloride concentration values representative of groundwater for the entire mountain block. Wilson and Guan (2004), Bresciani et al. (2014), Guan et al. (2010a), and Guan et al. (2010b) present thorough examinations of where these assumptions may be violated or confounded in heterogeneous and shallow-soiled mountain systems. Yao et al. (2017) constructed a MODFLOW model of the Qilian Mountains in China to estimate MBR to adjacent valleys in which they assumed a prescribed rate of K decay with depth, a recharge rate of 20% of precipitation, and a head-dependent boundary at the mountain front. They calibrated the model to mountain stream baseflows and estimated that approximately 35% of mountain aquifer recharge becomes MBR, with the rest contributing to baseflow. However, they found that the MBR fraction ranged from 30% to 70% of mountain aquifer recharge when the rate of K decay (on which they had no independent constraint) was varied within reasonable limits. This study therefore clearly demonstrates the large uncertainty of model-based MBR estimates that result from highly limited subsurface K data.

Overall, the surge of mountain-focused studies since 2004 has helped advance our understanding of mountain-block hydrogeology, supporting the existence of mountain aquifers with considerable recharge rates, K values, and contributions to streamflow. The large increase in the number of bedrock monitoring wells in mountain watersheds has played a central role in this advancement, as well as the number of studies taking advantage of deep tunnels. Multiple studies have converged on active zone K values of 10^{-8} to 10^{-6} m/s and on active circulation depths of 100–200 m in fractured crystalline bedrock, an important advancement given the widespread occurrence of crystalline rock in mountain systems. Active circulation depths in mountain blocks composed of volcanic rocks are likely greater and commonly may be deeper for sedimentary rock mountain blocks as well, but the number of studies addressing active circulation depth in noncrystalline rock mountain blocks remains highly limited. Finally, estimates for the amount of interbasin flow (this being potential MBR) originating from mountain headwater catchments are in some cases considerable (up to 50% of catchment recharge) but also can be negligible, and the degree to which these large site-to-site variations stem from inherent uncertainty in the interbasin flow estimates (rather than real variations in watershed hydrogeology) remains unclear.

3.4. Combined Basin-Mountain Studies

Studies that combine the mountain block and basin are a considerable step forward from the basin-focused studies that predominated prior to 2004. The majority of combined basin-mountain studies employ numerical modeling to simulate MBR processes and are thus challenged by the difficulty of calibrating and/or validating model “correctness,” especially at the regional scale. Most of these modeling studies have addressed this through varying levels of sophistication in representing physically based recharge (Ball et al.,

2014; Gilbert & Maxwell, 2017; Magruder et al., 2009) and by employing NGTs, age tracers, and temperature data (Doyle et al., 2015; Manning & Solomon, 2005), in addition to heads and stream flows, for model calibration.

Mountain aquifer recharge estimates are typically uncertain, leading to large inherited uncertainties in MBR estimates. However, major advances in the acquisition of distributed precipitation and evapotranspiration data over the mountains using remote sensing, as well as advancements in coupled and integrated hydrologic models, have led to improved parameterization and estimation of MBR. Ball et al. (2014) developed a groundwater flow model of the South Park Basin, CO, and surrounding mountains, including spatially and temporally varying recharge and a K distribution representing complex geologic structures. They estimated that 17% of recharge to the mountain aquifer in the dominant mountain range bounding the basin (Mosquito Range) becomes MBR, accounting for 60% of recharge to the adjacent basin-fill aquifers in the northern part of the basin. They also found that most of the MBR originates from watersheds closer to the mountain front rather than the highest part of the range (~70% of groundwater flow in the mountain block circulates <1 km), in general agreement with the conceptual modeling studies discussed in section 3.1. Gardner (2009) constructed a MODFLOW model of the northern Utah Valley, UT, including the adjacent mountain blocks, and used a detailed spatially distributed water balance model to estimate mountain aquifer recharge using the Recharge Package (Harbaugh et al., 2000). They estimate that 17–33% of mountain precipitation becomes MBR, with MBR contributing 46% of basin-fill aquifer recharge, and this estimate is further supported by groundwater ages and NGTs presented by Cederberg et al. (2009) indicating substantial MBR fractions in the basin aquifer. Importantly, the substantial fractions of MBR in the Utah Valley are likely controlled by the presence of carbonate rocks with known karst development in the mountain block (Cederberg et al., 2009; Gardner, 2009). Brush et al. (2013) acknowledged the importance of surface and subsurface inflow from small, ungaged watersheds adjacent to the Central Valley, CA, and included these fluxes in their Integrated Water Flow Model of the basin. They estimated MBR in the small stream watershed percolation module—a simple water budget model that utilizes monthly distributed precipitation and evapotranspiration data to estimate streamflow and subsurface inflow to the basin. They found that this MBR accounted for 13%, 10%, and 12% of total groundwater recharge to the basin for the 1922–1929, 1960–1969, and 2000–2009 time periods, respectively. Magruder et al. (2009) estimated mountain aquifer recharge using an ecohydrologic process model and then subtracted surface water runoff to arrive at an MBR estimate of 19% of mountain precipitation (48% of mountain aquifer recharge). They then applied this MBR as a boundary condition to a groundwater flow model of the adjacent basin-fill aquifer in the Tobacco Root Basin, MT, and found that MBR accounts for 36% of basin-fill aquifer recharge. Similarly, Mechal et al. (2016) estimated recharge to the Gidabo River Basin in the Ethiopian rift valley using a semidistributed soil water model and then applied those values as recharge to a groundwater flow model. They estimate MBR composes 35% of recharge to the rift basin and found that including faults acting as both flow barriers and conduits improved model fit.

Integrated hydrologic models such as HydroGeoSphere (Brunner & Simmons, 2012) and ParFlow-CLM (Maxwell & Miller, 2005) reduce process uncertainty by simulating distributed recharge and allowing for seamless integration between the surface processes governing recharge and groundwater flow within underlying aquifers receiving this recharge. Gilbert and Maxwell (2017) developed a ParFlow-CLM model of the San Joaquin River Valley, CA, and estimated MBR to the Central Valley, applying a manual sensitivity analysis for mountain-block bedrock K. They found that MBR ranged from 7.7% of total recharge for a mountain-block bedrock K of 10^{-7} m/s to 23% for a K of 10^{-3} m/s. They also found this MBR contribution to be temporally constant despite the seasonality of snowmelt recharge in the Sierra Nevada. This result is important, given that other widely used models of the Central Valley aquifer system assume negligible MBR from the adjacent dominantly granitic Sierran mountain block (Bolger et al., 2011; Faunt, 2009). The combination of a sensitivity analysis of bedrock K with model fluxes rigorously validated to observational, remotely sensed and satellite data makes this study an important advancement in using models to estimate MBR.

While traditional validation (e.g., to fluxes and heads) increases confidence in model parameterization, it typically still results in substantial model solution nonuniqueness in groundwater flow models (Schilling et al., 2019). To reduce this nonuniqueness, two studies have employed the use of nontraditional sources of information to constrain and validate combined basin-mountain models. Manning and Solomon (2005) attempted to constrain MBR, as well as active circulation depth, in the Wasatch mountain block, UT, by calibrating a coupled heat and groundwater flow model of the mountain block and adjacent southeastern Salt Lake Valley to mountain stream baseflow, groundwater temperature, and groundwater age. In the 38

model runs combining varying mountain bedrock aquifer K , effective porosity, and thickness, temperature data constrained the upper limit of MBR to 62% of basin-fill aquifer recharge and groundwater age data constrained the lower limit of MBR to 27% of basin-fill aquifer recharge. These constraints substantially reduced the range of possible MBR rates based on previous studies, but the modeling methodology was not successful in constraining the circulation depth. Notably, while this study found MBR to contribute an important fraction of basin-fill aquifer recharge, the estimated MBR range was lower than previous estimates for the basin derived from numerical models calibrated using traditional hydraulic data. Doyle et al. (2015) were the first to use NGTs as calibration targets for a groundwater flow model, simulating MBR to a coastal alluvial aquifer in British Columbia, Canada. Backward particle tracking from basin wells in the numerical model allowed for direct calibration to the NGT-based estimated recharge elevation, and R and K values were iteratively updated to match observed recharge elevations. They estimate MBR composes 45% of basin-fill aquifer recharge. Overall, these studies demonstrate the importance and feasibility of combining independent sources of information to constrain model estimates of MBR.

Combining substantial independent data sets from both the mountains and adjacent basin-fill aquifer is not only useful for reducing uncertainty in numerical models of basin-mountain systems but may also be an effective data-driven approach in MBR studies. A recent study combined stable water isotopes, groundwater age tracers, and chloride data from the layered Adelaide Plains aquifer system, Australia, and adjoining mountain block to examine aquifer recharge sources and rates (Batlle-Aguilar et al., 2017). The authors conclude that nearly all recharge to the deep confined aquifers is MBR based on the following lines of evidence: (1) Old groundwater is present near the top of the deep aquifers (inconsistent with substantial downward leakage), and groundwater age within them increases with depth and distance from the mountain front; (2) chloride in the shallow aquifer is often higher than in the deep confined aquifers (suggesting minimal vertical leakage); and (3) mountain aquifer recharge rates estimated from chloride mass balance roughly agree with Darcy groundwater flow velocities calculated from groundwater age gradients in the deep confined aquifers (meaning MBR alone can account for all deep flow). A follow-up study of the same aquifer system leveraged long-term and spatially extensive data sets of hydraulic head and groundwater EC from both the mountain block and the basin to determine the fraction of MBR versus surface MFR in shallow and deep aquifers (Bresciani et al., 2018). The head and EC data suggest that surface MFR predominates over MBR in both the shallow and deep aquifers based on relatively well-defined WT highs and EC lows underneath streams exiting the mountain block. Furthermore, head data in the mountain aquifer indicate predominantly local flow toward streams rather than regional flow toward the mountain front. These results are inconsistent with the conclusion of Batlle-Aguilar et al. (2017) that recharge to the deep aquifers is nearly all MBR, and surface MFR is minor. Two possible explanations for this discrepancy include the following: (1) The spatial resolution of EC data examined by Bresciani et al. (2018) is far greater than the chloride data examined by Batlle-Aguilar et al. (2017) and is thus better able to resolve spatial patterns relative to streams traversing the mountain front; or (2) MBR is indeed the dominant recharge source for the deep aquifers, but it is focused MBR leaving the mountain block mainly under streams and thus cannot be easily distinguished from surface MFR based on head and EC data. Repeat studies in other basins have led to substantial revisions in MBR estimates based on improved methods and more targeted or comprehensive sampling (e.g., the MBR range estimated by Manning & Solomon, 2005, for the southeast Salt Lake Valley was 50–100% of the prior estimate by Lambert, 1995), but these two studies reaching nearly opposite conclusions is unusual and clearly merits further work. Despite their conflicting results, these two studies demonstrate that extensive hydraulic and geochemical data sets collected from both the basin fill and adjacent mountain block may by themselves yield valuable information regarding MBR, and the abundance of hydraulic head and EC data in mountain-front systems around the world makes this approach potentially widely applicable.

Numerical-model-based combined basin-mountain studies appear to be the most promising for characterizing and quantifying MBR. This is particularly true when these studies also utilize novel calibration targets and sophisticated surface-process models for estimating mountain aquifer recharge. Combined basin-mountain models also have the greatest potential for successfully predicting MBR and MFR under future warming climate conditions. However, characteristic mountain-block K distributions and active circulation depths for various mountain geologic settings will have to be better constrained through field observations before these models can be considered truly predictive.

3.5. Studies Addressing Human Impacts

Human-induced changes in land use and land cover (LU/LC) and climate are rapidly changing the boundary conditions of mountain groundwater flow systems and thus could significantly influence mountain aquifer recharge and MBR. Since 2004, there has been a surge in studies seeking to understand how climate and LU/LC change may impact groundwater recharge. Here, we review studies that either specifically address impacts to MFR and MBR or have findings directly relevant to potential impacts. Comprehensive reviews of potential effects of climate and LU/LC change impacts on groundwater recharge in general are provided by Green et al. (2011), Taylor et al. (2013), and Smerdon (2017).

Global projections of climate change impacts to groundwater recharge are uncertain due to limited representation of groundwater in global climate models and poorly resolved precipitation trends (Green et al., 2011; Taylor et al., 2013). Projected future changes in precipitation in mountainous areas are especially uncertain due to complications introduced by local orographic effects (Beniston et al., 1997). That said, some regional and watershed-scale studies have substantially contributed to our understanding of how climate change could potentially influence mountain aquifer recharge and MBR. Regional studies reporting declining base-flows in mountain streams over recent decades (e.g., Rood et al., 2008), combined with studies indicating a close link between snowpack volume and mountain aquifer recharge rate (e.g., Manning et al., 2012), suggest that future mountain aquifer recharge rates are likely to decline in response to continued declines in snowpack in many areas. Meixner et al. (2016) synthesized regional climate change projection studies and expert knowledge to estimate recharge component shifts for eight aquifer systems in the western United States. They found that the MFR component (including MBR) would likely decrease across much of the region due to declining snowpack and increased ET, although they also note that this decrease may be less in more humid higher-latitude areas due to projected increases in total precipitation. As emphasized by Meixner et al. (2016), in mountainous systems, snowmelt commonly composes a disproportionately large fraction of mountain aquifer recharge compared to rainwater (e.g., Ajami et al., 2012; Earman et al., 2006), making mountain aquifer recharge potentially sensitive to an increasing rain/snow ratio due to warming alone. Snowpack declines will be greatest at lower elevations (Stewart, 2009), though the magnitude of decrease will vary since the snow rain transition elevation is different across mountainous regions. This is particularly concerning for MBR from crystalline-rock mountain blocks because, as discussed in section 3.1, much of this MBR may originate from lower-elevation areas closer to the mountain front (Welch & Allen, 2012).

The effect of decreasing snowpack on mountain aquifer recharge and MBR could vary widely across different mountain block zones composed of different lithologies. For example, Markovich et al. (2016) performed numerical climate change experiments using a low-K and higher-K hillslope, representing fractured crystalline and volcanic rock settings, respectively, and found large recharge reductions in the higher-K hillslope and relatively slight recharge reductions in the low-K hillslope. This suggests a mountain aquifer permeability threshold below which absolute MBR rates may be insensitive to warming and associated declines in precipitation available for infiltration. Other studies have found that recharge to mountain aquifers composed of fractured crystalline rock (i.e., lower K) commonly may be permeability limited rather than precipitation limited (Carroll et al., 2019; Flint et al., 2008; Manning & Solomon, 2005). Furthermore, Manning (2011) concluded that the absolute MBR rate from the crystalline-rock Sangre de Cristo Mountains, New Mexico, USA, probably decreased little from the cooler, wetter Pleistocene to warmer, drier Holocene epochs based on NGTs and radiocarbon ages from wells in the adjacent Española Basin. The manner in which climate-change-related shifts in mountain aquifer recharge would impact flow path partitioning within the mountain block and the relative importance of MBR versus surface MFR also remains largely unknown. For example, a decrease in mountain aquifer recharge could lead to lower WTs in the mountain block that could result in more regional versus local groundwater flow. This could in turn increase the relative amount of MBR compared to surface runoff/MFR, thus increasing the MBR fraction in the basin aquifer (though both the total recharge and absolute MBR rate would decrease). However, this shifting balance in the relative importance of MBR versus surface MBR could be buffered by increasing extreme precipitation events that might increase surface MFR but not MBR.

Most studies of climate change impacts to mountain aquifer recharge have focused on snowmelt, and few have addressed potential near-term and long-term changes in recharge resulting from glacier and permafrost melt. Alpine glaciers are melting rapidly across the world (Zekollari et al., 2019), and many are drained by permeable streambeds which, depending on the style of connection to the WT, can potentially conduct substantial amounts of recharge to mountain aquifers. Through a combination of stream loss gaging and glacier

mass balance, Liljedahl et al. (2017) found that glacier melt contributed disproportionately to stream runoff and that headwater streams lost up to 56% of annual runoff to mountain aquifer recharge in the Tanana River watershed, AK. This suggests that, while recharge in these headwaters may increase in the short term due to accelerated melting, it could substantially decrease in the long-term due to glacier loss. Permafrost melt may increase recharge to mountain aquifers in two ways: (1) increasing the active layer depth, or unfrozen zone, thereby increasing mountain aquifer thickness (Lamontagne-Hallé et al., 2018); and (2) direct contribution of permafrost melt to groundwater storage (Hiyama et al., 2013). Importantly, glacier and permafrost melt are generally not captured by current precipitation networks or recharge calculations, and so the quantification of this added component at the mountain-block scale remains a major uncertainty in climate change projections.

Historical LU/LC change in basins has been dominated by land conversion for agriculture. This has resulted in well-documented increases in direct recharge over the basin due to irrigation losses (Scanlon et al., 2006; Scanlon et al., 2005). Consequently, the fraction of MBR in overall basin-fill aquifer recharge has decreased in basins with high agricultural activity (Bexfield et al., 2016; Brush et al., 2013). However, the recent development and adoption of precision water application has led to a decrease in the “loss” of irrigation water to recharge and ET (Ward & Pulido-Velazquez, 2008), decreasing total basin-fill aquifer recharge in areas where this practice is applied and perhaps increasing the relative fraction of MBR toward predevelopment levels. The dominant LU/LC change in mountain blocks has been within forests. Studies have found that deforestation generally leads to increases in recharge and vice versa (Jobbágy & Jackson, 2004; Scanlon et al., 2006). Forest thinning (Roche et al., 2018) and tree die-off due to climate-exacerbated insect infestation (Bearup et al., 2014) have been shown to reduce ET and augment runoff and recharge during certain times of year. However, increases in total annual runoff and mountain aquifer recharge remain uncertain and may be compensated by increased snow sublimation (due to decreased canopy cover; Biederman et al., 2015), longer growing seasons (Mankin et al., 2018), and migrating treelines (Goulden & Bales, 2014). Finally, there have been documented increases in both runoff (Seibert et al., 2010; Wine et al., 2018) and baseflow (Kinoshita & Hogue, 2015) following fire disturbance in mountain headwater catchments.

Taken together, available studies suggest that LU/LC and climate change have the potential to significantly impact MBR. These studies indicate that LU/LC and climate change are currently driving, and will continue to drive, changes in factors directly linked to mountain aquifer recharge, such as decreasing snow fractions in precipitation, melting glaciers and permafrost, increasing ET, longer growing seasons, and increased fire frequency and intensity. These trends point to decreased mountain aquifer recharge in many regions, though uncertainties in precipitation projections, subsurface hydrogeologic characteristics, and system feedbacks limit our confidence in making specific projections regarding the extent or degree of changes in a particular mountain system. Projecting LU/LC and climate change impacts to absolute and relative MBR rates is yet more uncertain, further exacerbated by major gaps in our understanding of mountain-block hydrogeology outlined in sections above. Meaningful projections of future MBR rates and basin-fill aquifer water budgets will only be possible with improved precipitation projections, more comprehensive knowledge of MBR itself, and the development of sophisticated numerical models that represent both surface and subsurface conditions/processes at an appropriate level of detail.

4. Current Understanding of Controls on MBR

The studies reviewed above demonstrate that MBR can be an important fraction of recharge to basin-fill aquifers around the world, even in the case of apparently low-K mountain blocks. Here, we summarize our current understanding of the fundamental factors controlling where and how much MBR might be occurring.

First, MBR requires the existence of a mountain-block aquifer that hosts active groundwater flow. As discussed in section 3.3, apparent thresholds to produce active mountain groundwater flow are $K > 10^{-8}$ m/s and recharge rates greater than roughly 10 mm/year. If neither of these conditions are satisfied, MBR is probably negligible. If either is satisfied, then there is likely some MBR, with the caveat that MBR still could be locally obstructed by mountain-front parallel faults (Caine et al., 2017; Chowdhury et al., 2008; Delinon, 2009; Kebede et al., 2008).

If active mountain bedrock groundwater flow exists, making MBR possible, the next consideration is the depth of active circulation (i.e., mountain aquifer thickness). If the active circulation depth is less than the

approximate scale of topographic relief in the headwater catchments (commonly hundreds of meters), then MBR will mainly originate from slopes immediately above the mountain front as front-slope flow (Welch & Allen, 2012) and perhaps also enter the basin near the mouths of mountain watersheds immediately below streams (Figure 2). For many mountain systems, slopes immediately above the mountain front compose a small percentage of the total mountain-block terrain, so MBR rates will be more limited but could still be an important recharge component for the basin aquifer. If the active circulation depth is greater than the scale of topographic relief in the headwater catchments, MBR can potentially originate farther back in the mountain block and MBR rates will thus be higher (Manning & Solomon, 2005). In crystalline-rock mountain blocks, circulation depths appear to generally extend to depths of 100–200 m (Welch & Allen, 2014), though this contact may be highly variable (Clair et al., 2015; Frisbee et al., 2017). This aquifer thickness is substantially less than the topographic relief of typical mountain headwater catchments and has been shown to produce MBR predominantly near the front of the mountain block as front-slope flow (Manning & Solomon, 2005; Welch & Allen, 2012). Mountain-block faults may promote deeper (>500 m) active circulation in crystalline rocks (Ofterdinger et al., 2014; Tomonaga et al., 2017), but the volumetric significance of these localized fault-hosted flows relative to basin-fill total recharge rates remains unclear. Greater active circulation depths (>1,000 m) are likely in mountain blocks composed of volcanic rocks (Frisbee et al., 2017; Saar & Manga, 2004) and could be common in sedimentary rock mountain blocks as well (Lazear, 2006), but studies addressing circulation depth in such noncrystalline mountain blocks are limited.

If the mountain-block circulation depth is greater than the scale of the topographic relief in the headwater catchments, the WT position relative to the land surface in the mountain block becomes the primary control on the relative proportions of local versus interbasin (potential MBR) flow. If the regional WT is lower than the streambeds in the headwater catchments, such that headwater stream channels are dominantly ephemeral (recharge-controlled WT), a larger fraction of mountain groundwater is inclined to follow a regional flow path toward the mountain front and become MBR. If the regional WT is higher and headwater streams are dominantly perennial (topography-controlled WT), a larger fraction of mountain groundwater will discharge locally in the headwater streams, and a smaller fraction will become MBR (Bresciani et al., 2018; Gleeson & Manning, 2008). It should be kept in mind, however, that large fractions of regional flow in the mountain block do not necessarily equate with large absolute MBR rates to the adjacent basin. In other words, if the mountain-block regional WT position is very low due to very low mountain aquifer recharge rates (as could be the case in arid mountains), absolute MBR rates would also be low. The highest absolute MBR rates will occur when, in addition to the mountain-block WT being recharge controlled, the active zone K is high and the mountain-block WT remains as high as possible relative to the adjacent basin elevation (maximizing the head gradient between the mountain block and the basin)—a situation that can only occur if mountain aquifer recharge rates are high as well. Mountain WTs will be higher relative to the adjacent basin if the mountain topography is high relative to the basin surface and if the mountain stream network is less deeply incised (Gleeson & Manning, 2008; Welch & Allen, 2012). Finally, geologic heterogeneity could complicate the above general rules by producing perched aquifers, barriers, and conduits for interbasin flow, and more work is needed to explore how the presence of common types of heterogeneity would affect the proportion of local, intermediate, and regional flow paths.

In summary, higher mountain aquifer K and recharge rates, deeper mountain groundwater circulation, recharge-controlled mountain WTs, and higher mountains with less incised stream networks all promote greater MBR. The clarifications of the fundamental factors controlling MBR in conceptual studies, as well as their validation in some real-world case studies, are important advances in our understanding of MBR. However, significant challenges remain in the application of these governing principles to real, heterogeneous systems to successfully constrain and predict MBR. These conceptual studies also clearly demonstrate the close link between mountain aquifer recharge rates and MBR, underscoring the importance of understanding the effects of LU/LC and climate change on mountain aquifer recharge if we are to successfully forecast future MBR rates.

5. Conclusions and Future Research Priorities

Our understanding of MBR has advanced significantly in the 15 years since Wilson and Guan (2004), driven by a surge in MBR studies applying a broadening range of methodologies around the world. We believe that the hydrologic community has accomplished the first hurdle of confirming that MBR is a real and often substantial component of recharge to lowland aquifer systems in a variety of climatic and geologic

settings. The second hurdle lies in developing and validating robust methodologies for quantifying MBR (including its spatial distribution) and fully understanding controlling processes. Toward this end, we have made major progress through new observational techniques, technological and analytical advances, and well-conceived research programs. However, data limitations still impart large uncertainties in our estimates of MBR, particularly subsurface data from the mountain block and mountain front.

A major advancement since Wilson and Guan (2004) has been in our understanding of groundwater flow in mountain headwater catchments, driven by investment in surface and relatively shallow subsurface (<50 m deep) observational infrastructure aimed at understanding near-surface hydrological, chemical, and biological processes within the catchment. However, if we are to make significant further advancements in understanding MBR, we now need to apply a similar level of investment to directly investigating and characterizing larger-scale interbasin groundwater flow in the mountain block and lower-elevation front-slope flow. Thus far, studies attempting to characterize interbasin and front-slope flow have mainly done so using numerical flow models based on limited subsurface information between shallow depths in headwater catchments and the mountain front (Ameli et al., 2018; Doyle et al., 2015; Gilbert & Maxwell, 2017; Gleeson & Manning, 2008). Thus, there is a high-priority need for deep (>100 m) research monitoring wells and deep-imaging geophysical surveys located at different strategic positions in the mountain block, including near the mountain front, that would allow us to determine bedrock properties (particularly K) through a range of depths and to access and sample groundwater following deeper flow paths. Boreholes drilled for deep well installation should be logged using standard downhole geophysical logging tools and should be completed with multilevel well screens to better enable discrete-depth groundwater sampling. Airborne and surface geophysical surveys capable of discerning deep subsurface geologic framework (and potentially porosity and permeability) such as airborne time domain electromagnetic surveys (Vittecoq et al., 2019) and nuclear magnetic resonance (Legchenko et al., 2002) should be performed. These methods become yet more powerful when combined with downhole geophysical logs and drill core from a local deep borehole (Flinchum et al., 2018; Orlando et al., 2016; Vittecoq et al., 2019). Because installing wells and performing such surveys can be prohibitively expensive for individual researchers or institutions, we advocate for funding strategies that involve pooling investment in observational infrastructure and that lever existing infrastructure to the greatest degree possible. For example, the existing Critical Zone Observatory network could be targeted for deep well installation, since they already possess important infrastructure and are located in a range of climatic and lithologic settings around the world (Anderson et al., 2008), and expanded to include lower-elevation research sites farther down potential MBR flow paths. Also, transportation and water diversion tunnels and active mining operations (which often include monitoring well networks) have been largely underutilized in MBR studies and could provide valuable additional hydrogeologic data when combined with newly installed research monitoring wells.

Investment in subsurface observations in the mountain block and at the mountain front is key for advancing our understanding of MBR to the quantitative and predictive stage. We believe this stage is most likely to be reached if, in parallel, the following four major questions are prioritized in future field and modeling research efforts.

1. What are the active circulation depths in different systems? Of the primary factors controlling the amount of MBR, active circulation depth (i.e., the K vs. depth relationship) in the mountain block remains in general the most uncertain. Available studies point to a typical active circulation depth of 100–200 m for fractured crystalline rock settings, but the number of direct subsurface measurements at depths >100 m remains relatively few. These measurements are even more rare in other lithologies, such as volcanic and sedimentary rock systems. The deeper subsurface data obtained from wells and geophysical surveys discussed above would significantly tighten constraints on active circulation depth estimates for specific sites. These estimates could then be used to increase knowledge of characteristic circulation depths for different lithologies that have undergone different weathering and tectonic histories, which in turn could substantially improve our ability to predict MBR.
2. What is the spatial distribution of MBR in different systems? Several studies have identified a high degree of spatial variability in MBR (Table 1), but few have directly linked these variations with specific changes in geologic, topographic, or climatic characteristics of the mountain block. Furthermore, we are aware of no studies that have quantified how much MBR occurs as shallow focused flow near watershed mouths versus front-slope flow versus deep diffuse or focused flow (Figures 2 and 3). A clear need therefore exists to better understand the geologic, topographic, and climatic controls on the spatial distribution of MBR and

the relative importance of different MBR components. This includes a better understanding of the roles of structural and tectonic features in enhancing or impeding different MBR flowpaths. A potential approach for examining the spatial distribution of MBR with current methodological capabilities could be the installation of multiple monitoring wells distributed along the mountain front adjacent to different representative sections/features of the mountain block (e.g., at the mouth of a watershed composed of intrusive rocks, beneath a triangular facet composed of carbonates). Multiple different types of discrete-depth observations (temperature measurements, groundwater chemistry and age, NGTs, etc.) could then be combined with numerical modeling to elucidate and potentially quantify relative fluxes of different MBR pathways and link these to specific variations in the mountain block.

3. What is the relative fraction of MBR and surface MFR in different systems? Distinguishing MBR from surface MFR is critical for producing reliable MBR estimates. However, many studies still do not convincingly distinguish between these two sources, and challenges in doing so continue to contribute substantial uncertainty to most MBR estimates. This review covered some effective methods that could be more widely applied, and efforts should continue in developing new and improved methods for distinguishing MBR from surface MFR. As previously emphasized, combined approaches hold the greatest promise. For example, the approach of Bresciani et al. (2018) of using large and spatially extensive EC and hydraulic head measurements could be used in combination with EMMA (Liu & Yamanaka, 2012; Peng et al., 2018) and/or NGTs to detect the presence or absence of MBR in the basin-fill aquifer, distinguish it from surface MFR, and quantify its relative magnitude with reasonable confidence. Note that this approach would be yet more effective with the existence of deep monitoring wells at the mountain front.
4. How will MBR shift in response to climate and land use change? Available studies, though few, provide reason for concern that MBR could generally decrease in response to climate and LU/LC change. However, the magnitude of this decrease and the extent to which it may be locally buffered by factors discussed in section 3.5 (or perhaps even increase) are uncertain. This uncertainty is partially attributable to uncertainty in regional precipitation projections but is mostly due to our inability to confidently quantify and predict MBR under varying conditions. Thus, addressing the above three questions is essential for producing useful MBR projections. Physically based integrated hydrologic models are most capable of projecting MBR response to climate and LU/LC change, as they can capture feedbacks between temperature, ET, precipitation phase, and recharge (Markovich et al., 2016). Furthermore, advances in running large models with high-performance computing indicate the feasibility of large-scale integrated simulations (Maxwell et al., 2015). Though calibrating and validating these parameter dense models remains a major challenge, the development of multitarget calibration strategies including nontraditional calibration targets (temperature, groundwater age, and NGTs) have shown great promise in reducing model nonuniqueness and increasing our confidence in model projections (Schilling et al., 2019).

The “hidden” nature of MBR initially described by Feth (1964) has continued to present major challenges in its characterization and quantification over the past 15 years since the review of Wilson and Guan (2004). However, we believe answering the above questions is within reach given the current methodological and technological capabilities of the hydrologic community, provided there is a coordinated and significant investment in deeper subsurface data from the mountain block and near the mountain front. Thus, clearing the second hurdle of confidently quantifying MBR and reaching the important stage of useful prediction is possible. Given the importance of basin-fill aquifers as water resources globally and the potential for declines in MBR in the face of climate warming and LU/LC, the need for this progress is now pressing.

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