ECOHYDROLOGIC-PROCESS MODELING OF MOUNTAIN-BLOCK GROUND WATER RECHARGE

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ABSTRACT

Regional mountain-block recharge (MBR) is a key component of alluvial basin aquifer systems typical of the western United States. Yet neither water scientists nor resource managers have a commonly available and reasonably invoked quantitative method to constrain MBR rates. Recent advances in landscape-scale ecohydrologic process modeling offer the possibility that meteorological data, and land surface physical and vegetative conditions can be used to generate estimates of MBR. A water balance was generated for a temperate 24,600 ha mountain watershed, elevation 1565 - 3207 m, using the ecosystem process model Biome-BGC (BioGeochemical Cycles) (Running and Hunt 1993). Input data included remotely sensed landscape information and climate data generated with the Mountain Climate Simulator (MT-CLIM) (Running et al. 1987). Estimated mean annual MBR flux into the crystalline bedrock terrain is 99,000 m^3/d or approximately 19% of annual precipitation for the 2003 water year. Controls on MBR predictions include evapotranspiration (radiation limited in wet years and moisture limited in dry years), soil properties, vegetative ecotones (significant at lower elevations) and snowmelt (dominant recharge process). The ecohydrologic model is also used to

investigate how climatic and vegetative controls influence recharge dynamics within three elevation zones. The ecohydrologic model proves useful for investigating controls on recharge to mountain blocks as a function of climate and vegetation. Future efforts will need to investigate the uncertainty in the modeled water balance by incorporating an advanced understanding of mountain recharge processes, an ability to simulate those processes at varying scales, and independent approaches to calibrating MBR estimates.

INTRODUCTION

Many of the world's people and sensitive riparian ecosystems found in semi-arid regions are dependent on basin ground water systems recharged from adjacent mountain ranges. Increasingly, growing urban populations, and industrial and agricultural interests are relying on mountain margin alluvial basin aquifers for water supply (e.g. Zickmund 1996; Montana DNRC 2003). However, the development of basin aquifers often proceeds without a clear ground water budget, mainly because the ground water contribution to the alluvial basin from the mountain-block is difficult to quantify. Long term sustainability of water supplies requires the development of more comprehensive methods to define basin ground water budgets (Wilson and Guan 2004; Maurer and Berger 1997; Gannett et al. 2001; Manning and Solomon 2004, 2005).

In mountainous regions, characterization of the processes that control mountain block recharge (MBR) is confounded by the heterogeneity of mountain meteorology, topography, vegetation communities, soil/bedrock types, and the scarcity of site hydrogeological instrumentation and monitoring data. The term mountain front recharge is often used to describe all components of recharge to basin aquifers which have their source in the mountains, including MBR and stream runoff infiltration. Here MBR is defined as the subsurface components of mountain front recharge including: 1) focused near-surface recharge of shallow ground water transmitted in the sediments of streams which drain the mountain-mass; 2) diffuse near-surface recharge that is the infiltration and deep soil drainage occurring during episodic runoff events in ephemeral drainages at the mountain front; 3) focused subsurface recharge that follows flow paths within faults and fractures; and 4) diffuse subsurface recharge through primary permeability in the bedrock matrix. Quantifying recharge to an alluvial basin aquifer from streams originating in the mountain block and flowing into and through associated basins generally requires the application of traditional stream gauging techniques and stream channel infiltration characterization (Constantz et al. 2002; Goodrich et al. 2004). In contrast, the subsurface lateral recharge from the mountain block and its alluvial stream valleys is more difficult to quantify. The focus of this paper is to assess if a climate driven ecohydrological process model can be used to provide annual estimates of MBR for settings like those found in the western Rocky Mountains of the United States.

Previous Investigations

In the basins of the semi arid southwestern United States quantification of mountain block recharge was first attempted using empirical precipitation-mountain front recharge regression analyses based on extrapolations of precipitation by elevation and estimates of basin discharge (Maxey and Eakin 1949). Other authors analyzed mountain block recharge based on water balance formulations, wherein ET was estimated from empirical data or mathematical models (e.g. Feth et al. 1966; Huntley 1979). In South Australia, Allison and Hughes (1975) used a tritium mixing model to estimate lateral ground water flow from a mountain range to an unconfined limestone aquifer. As computational power increased over the last four decades more process-based methods to estimate recharge, including the simulation of deep soil water percolation, were developed (Bauer and Vaccaro 1987; Hevesi et al. 2002; Khazaei et al. 2003).

In an alternate recharge approach, Dettinger (1989) used a basin chloride balance technique to quantify mountain front recharge. Other studies compare estimates of mountain front recharge based on chloride balances with estimates derived from precipitation-runoff regression, and computed ground water flows based on estimates of hydraulic conductivities, gradients and lateral cross sectional areas (Anderholm 2000; Maurer and Berger 1997). Basin centered numerical ground water modeling approaches have also been reported (e.g.: Tiedeman et al. 1998; Sanford et al. 2000). Dickinson et al. (2004) modeled the water level response in a synthetic basin to develop an analytical representation of water level fluctuations and basin recharge. Flint et al. (2002) provide a comprehensive comparison of techniques for quantifying spatially distributed recharge at Yucca Mountain, Nevada, USA. Manning (2002) and Manning and Solomon (2004) combined age dating and noble gas concentration data to isolate the fraction of mountain front recharge attributable to high elevation MBR. This approach was further refined by integrating chemical data with a numerical model of heat and fluid flow (Manning and Solomon 2005). Wilson and Guan (2004) provide an evaluation of the strengths and drawbacks of these other techniques. The primary difference between the approach presented in this paper and other previous investigations is that we evaluate the use of commonly available land surface and meteorological datasets to attribute a process based model. The appeal in applying an ecosystem process model to a mountain water balance problem lies in the fact that it incorporates both physical and biological processes in the water balance calculation.

In addition to basin scale ground water investigations, researchers attempting to track landscape scale water, CO_2 and nutrient budgets have developed process based tools that commonly include the calculation of soil water loss and/or ground water recharge. These soil-vegetation-atmosphere (SVAT) type models have been developed and applied to varied landscapes. Work in southeastern Australia has used both one-dimensional and quasi three-dimensional SVAT models to determine the hydrological implications of land use change on excess recharge and soil salination (Hatton et al. 1993; Pierce et al. 1993; Zhang et al. 1996, 1999a, 1999b, 1999c; Dawes et al. 1997). Researchers characterizing landscape scale ecohydrologic relationships recognize the relationship between measurable vegetative parameters such as leaf area index (LAI) and ground water recharge (Finch 1998; Hatton et al. 1993; Zhang et al. 1999a; Seyfried et al. 2005; Rodriquez-Iturbe 2000). Modeling of portions of the western U.S. has been attempted using the Deep Percolation Model (Gannett et al. 2001) and the Net Infiltration Model (INFIL) (Hevesi et al. 2002). However, these studies have not been focused on the comparative performance or sensitivity of the modeling tool in the various microclimates within these watersheds. In contrast to evaluations focused on arid and semi-arid landscapes of the southwestern U.S., mountain recharge studies from Northern Rocky Mountain intermontane basins are few. These systems are relatively temperate with large areas of the landscape occurring as mountains where annual precipitation on mountain crests may exceed 250 cm (Oregon Climate Service 1998).

Purpose and Objectives

This work provides an initial investigation of advantages and limitations of a specific ecosystem process model, Biome-BGC, and of how it can be used to develop estimates of annual MBR for the northern Rocky Mountains. The first objective of this work is to use Biome-BGC to formulate a conceptual model of how climate and vegetative gradients in a northern Rocky Mountain range influence the basic recharge processes. The second objective is to assess if a climate and landscape driven ecosystem process model attributed with commonly available land surface and meteorological data, can be used to generate reasonable estimates of annual MBR at the watershed scale. Finally, the sensitivity and limitations of the Biome-BGC modeling approach to generating MBR estimates are evaluated.

EXPERIMENTAL DESIGN

Study Site

The study area encompasses the southwestern portion of the Tobacco Root Mountain Range and adjacent Ruby River alluvial basin in Montana, U.S.A (Figure 1). The 401 km^2 study area includes four mountain watersheds that vary in elevation from 1430 m at the Ruby River to 3207 m at the study area boundary along the mountain crest. In deriving the mountain water balance it is assumed that the surface watershed is the same as the ground watershed. Bedrock within the study area includes Archean quartzofeldspathic gneiss and amphibolite underlain by a Cretaceous granite pluton (Ruppel et al. 1993). Local landowners within the study area have reported that mineral exploration drilling into the mountain block encountered high artesian pressures at several hundred meters depth. This anecdotal evidence suggests potential for regional bedrock ground water flow.

Basin fill geology is characterized by a 1.3 km thick sequence of semi-consolidated fine grained Tertiary silts and clays with intermittent sand and gravel conglomerate (KirK Environmental 2004). Relatively coarse grained Quaternary glaciofluvial and alluvial deposits up to 50 m thick overlie the Tertiary basin fill; these deposits are found at the land surface and host the principle unconfined basin aquifer. Mean annual precipitation varies from approximately 30 cm/yr at the piedmont zone to 110 cm/yr near the crest of the mountain range (Oregon Climate Service 1998). Irrigated hay production is the dominant land use within the valley.

Modeling Approach

Biome-BGC (Running and Hunt 1993; Thornton et al. 2002) is a SVAT model applicable to a range of biome types and spatial scales. Biome-BGC computes daily soil moisture storage/drainage; within this term MBR is represented as diffuse mountain recharge. The Biome-BGC derived MBR estimate was applied as a flux boundary in a ground water flow model of the alluvial basin aquifer to evaluate the sensitivity of the basin model to the MBR boundary and to attempt to provide constraints on the MBR estimate. Ecohydrological model results were also compared and contrasted with results of MBR investigations of similar basins found in the literature.

Ecohydrological Modeling

Visual Biome-BGC Version 0.69b (source code version 4.1) was used to simulate plant ecosystem and hydrologic processes over a 24,600 ha section of mountain bedrock (elevations between 1565 and 3207 m) (Figure 1). This process-based model calculates the flux and storage of energy, water, carbon, and nitrogen between the atmosphere, plant, and soil components of a terrestrial ecosystem at the landscape scale. The modeled plants in Biome-BGC respond dynamically not only to daily water variables but to nutrient, radiation, and carbon availability. In this model, Biome-BGC is resolving processes which some other ET models are missing (e.g.: the stomata in the needles of the trees respond to daily moisture potential differences between the air RH and soil moisture potential and modulate ET accordingly). The use of an actual ecohydrologic model also allows additional calibration points such as leaf area indices, vegetative greenness, and carbon flux.

Biome-BGC has been documented to realistically predict soil moisture dynamics (Kremer and Running 1996) and spatially averaged snowmelt and surface water discharge at the watershed scale in the northern Rocky Mountains (Coughlan and Running 1997; Running 1994; White et al. 1998). Biome-BGC requires daily maximum and minimum air temperature, humidity, incident solar radiation, and precipitation as climate inputs. MT-CLIM Version 4.3 (Running et al. 1987; Kimball et al. 1997; Thornton and Running 1999), typically used in tandem with Biome-BGC, uses a fairly complex algorithm to extrapolate the daily meteorological data that are recorded at automated weather stations associated with the modeled site. Biome-BGC routes precipitation minus canopy evaporation into soil water or snowpack as a function of daily temperature. Precipitation throughfall and snowmelt become available in the soil compartment for root uptake. ET is calculated by the Penman-Monteith equation using extrapolated site micrometeorology.

Biome-BGC was parameterized with data sets derived from remote sensing, topographic databases and soil maps (Table 1). A mountain weather station (U.S. Department of Agriculture Natural Resource Conservation Service SNOTEL) located 2.5 km outside the study area at 2,400 m elevation provided meteorological data (1991-2003) as input to MT-CLIM. Biome-BGC requires biome types to be specified based on landscape and vegetative properties. Default Biome-BGC ecophysiologic constants files (epc) were used for C3 (carbon fixation pathway) grass, deciduous and evergreen broadleaf and needleleaf forests, and evergreen shrubs and distributed based on LANDSAT Thematic Mapper classified land cover types. Modeling units were partitioned into a grid with thirty 2.9x2.9 km cells using standard GIS raster techniques. Assigned cell properties include soil texture, average annual precipitation, elevation, slope, dominant aspect, and vegetation. A higher resolution cell size is preferred; however Biome-BGC is not currently automated to model a distributed grid and the cell size was deemed appropriate for this screening level application. The Regional Hydrological and Ecological

Simulation System (RHESSys) (Band et al. 1991) incorporates Biome-BGC algorithms and allows for finer discretization of the landscape so that model cells represent a smaller and more homogeneous landscape. However, model programming required to apply RHESSys was not pursued for this project.

Table 1: Biome-BGC / MTCLIM Input Parameter Data Sources.

Input Parameter	Data Source
Daily temperature max/min, precipitation	*USDA SNOTEL*
Elevation, slope, aspect	*USGS DEM*
Biome type (plant ecological community)	*LANDSAT Thematic Mapper*
Soil texture	*USDA STATSGO*
Annual precipitation	*University of Montana NTSG Daymet*
Annual nitrogen deposition	*National Atmospheric Deposition Program (NADP)*
Shortwave albedo	*Matthews (1984)*

Model hydrologic outputs include daily precipitation, ET, the change in soil moisture storage and soil water outflow (SWO). SWO is determined by a daily soil water balance wherein water in excess of field capacity slowly drains. SWO is not partitioned by Biome-BGC between stream flow leaving the mountain mass and MBR. To calculate this partitioning outside of Biome-BGC runoff gaging (Rantz et al. 1982) was performed where streams leave the mountain front approximately bi-weekly during runoff and bi-monthly outside of the runoff period. Discharge was estimated during non-gaging periods by interpolating the discharge hydrograph between measurements (Figure 2). The error associated with interpolating the hydrograph is not quantifiable and adds significant uncertainty to the water balance. Annual MBR for the 2003 water year was estimated by summing model generated daily SWO minus estimated annual stream discharge:

$$\text{Equation 1} \quad MBR_{annual} = \Sigma_{(oct\ 1\ to\ sept\ 31)}\ SWO - Q_{sw\ annual}$$

Where SWO is Biome-BGC modeled soil water outflow and $Q_{sw\ annual}$ is the observed surface water runoff for the water year.

In addition, we also completed Biome-BGC sensitivity analyses with the purpose of better understanding how model components and assigned parameters impact computed values of MBR. These include investigating how averaged annual climatic parameters and seasonal conditions correlate with MBR estimates. We also examined the influence of soil and vegetative parameters on SWO across the orographic climate gradient of the study area and compared forecasted SWO with interpolated stream hydrographs to assess if the timing of model generated processes correlates with field observations.

Ground Water Flow Modeling

The computed MBR was applied as a boundary to a transient ground water flow model of the basin fill alluvial aquifer formulated using the finite difference MODFLOW code (Harbaugh et al. 2000). The active MODFLOW domain (Figure 1) is an 15,500 ha area corresponding to the basin fill alluvium of the study area. The model is a portion of a larger basin-scale MODFLOW model described in KirK Engineering & Natural Resources, Inc. (2008). This original model was scaled to include only those watersheds modeled using Biome-BGC and modified to provide greater control over the distribution of MBR by subdividing one of the original model layers and adding MBR using injection wells. The Biome-BGC generated MBR (equation 1) was assigned to the ground water model by proportioning it to underflow at the mountain stream valley mouths ($SV_{underflow}$) and diffuse recharge entering from the bedrock mass (DMBR) (Equation 2). $SV_{underflow}$ was derived by using the saturated alluvium cross sectional area multiplied by the water table gradient and an estimated hydraulic conductivity (K) value from aquifer testing and the interpretation of well logs. The DMBR was calculated by difference.

$$\text{Equation 2:}\quad MBR_{annual} = \Sigma_{(oct\ 1\ to\ sept\ 31)}(SV_{underflow} + DMBR)$$

The DMBR was applied evenly to the upper 250 m of the basin aquifer to approximate diffuse bedrock flux within a decompressed zone as suggested by Marechal and Etcheverry (2003). $SV_{underflow}$ was applied to the top model layer using injection wells where mountain streams enter the basin. The Biome-BGC generated MBR was held constant and other parameters were adjusted until the root mean squared (RMS) value of the modeled and simulated head differences were minimized, and flux rates fell within measured ranges (KirK Engineering & Natural Resources, Inc. 2008). This representation of basin ground water conditions was examined to determine the sensitivities of the calibration parameters to changes in all model fitted aquifer K values and the assigned MBR. These results were then evaluated to determine if the Biome-BGC derived MBR could be constrained by the basin numerical model. In an additional analysis we attempted to examine if the distribution of the MBR along the mountain front might be dominated by $SV_{underflow}$. This was accomplished by conducting a separate model run in which we assigned all of the Biome-BGC computed MBR to $SV_{underflow}$ and attempted to calibrate this alternative conceptual model by adjusting K within reasonable estimates.

RESULTS AND DISCUSSION

The following sections present the results of the Biome-BGC ecohydrologic modeling including the computed mountain-scale water balance and calculated MBR, an evaluation of model performance and appropriateness, and how the variability in model parameters influenced model results. Finally, modifications to ecohydrological modeling that may improve simulated MBR estimates are discussed.

Simulated Mountain-Block Water Balance and MBR Estimate

Biome-BGC simulations produced a 2003 water year balance (Table 2) for the 24,600 ha area of the mountain-block (Figure 1). The computed annual MBR is 99,000 m^3/d or approximately 19% of annual precipitation. The change in soil water storage is related to ongoing drought in the region and represents an average loss of 1.7 cm of soil water storage across the entire modeled area.

Table 2: Mountain-block water balance 2003 water year.

	Water Balance Component	Annual Average Flux (m^3/d)	% of precipitation
Biome-BGC	Precipitation	532,000	100%
	ET	337,000	63%
	Δ Soil water storage	-12,000	-2%
	SWO	207,000	39%
Equation 1	Runoff (gaged)	108,000	20%
	MBR (equation 1)	99,000	19%

To evaluate how the predicted MBR for the 2003 water year compared with other water years in the weather station record, Biome-BGC was executed for a 13 year period (1991-2003). The 7.63 x 10^7 m^3 modeled 13-year mean annual SWO is similar to the 2003 modeled annual SWO of 7.55 x 10^7 m^3 suggesting the 2003 water year is representative of average conditions for this period. This is supported in the SNOTEL weather station data which shows that 2003 water year snow water equivalent was approximately average.

The modeling results were further evaluated to derive insight as to how principle hydrologic and ecosystem processes influenced computed MBR. Modeled annual precipitation, ET, SWO and temperature for the 13 year simulation were evaluated (Figure 3) to examine how model generated components of the mountain scale water balance correlate with simulated SWO (MBR + stream discharge). Simulations showed SWO and precipitation were strongly correlated ($R^2 = 0.70$); where as no correlation was indicated between SWO and ET ($R^2 = 0.14$). Modeling also suggests no significant correlation between ET and precipitation ($R^2 = 0.10$). Additionally, modeling suggests a weak, but inverse relationship between ET and temperature ($R^2 = 0.26$). Thus, we conclude that ET is radiation limited during years of above average precipitation and moisture limited during years of below average precipitation in this setting. The outcome of this climate regime on plant water use causes interannual variability in ET to be approximately 1/3rd of the variability in annual precipitation. The occurrence of significant variability in precipitation between years and the relatively constant nature of the ET signal appears to be an important factor controlling the amount of subsoil water available for diffuse recharge.

Further process based analyses involved an evaluation of seasonal controls on SWO in a generalized mountain setting. A daily water budget was modeled using the SNOTEL weather station record for a synthetic high elevation site (conifer forest, elevation 2783 m, 20° slope, west aspect, precipitation 865 mm/yr) (Figure 4). At the synthetic mountain site, during October through May soil water storage recovers quickly from the dry-season water deficit and is maintained near field capacity. The October to May period is coincident with snow cover in this climate and during this period soil moisture flux from snowmelt and rain contributes to SWO. The model indicates small releases of snowmelt to SWO occur from December to February. Observations of the mountain range in winter indicate that some snow does melt off of high elevation west aspects due to warm chinook winds and radiation exposure. Modeling results reveal that outside of the snow season not a single precipitation event, including the larger summer storms with magnitudes of 2 cm/d raised soil moisture above field capacity, and that ET quickly depletes additional soil moisture. This suggests that snowmelt as well as rain occurring during snowmelt periods drives the only significant non-localized recharge occurring in this setting and similar temperate mountain environments. Similar dependence of recharge on snowmelt has been demonstrated in semi-arid mountain areas (Winograd et al. 1998).

The suggestion that MBR is derived predominantly from snowmelt occurring simultaneously with a period of minimal ET presents important implications as to how warmer global temperatures that either raise the minimum elevation of seasonal snow accumulation or cause snowmelt to occur sporadically throughout winter months would effect MBR dynamics. In the climate of the study area, the 13 years of mountain weather station temperature data correlate reasonably ($R^2 = 0.57$) with a positive linear trend in mean annual temperature with a slope of 0.2° C/yr, indicating a significant warming trend in recent years. As described previously, ET shows very little correlation with mean annual precipitation and a weak inverse correlation with mean annual temperature. However, this inverse relationship between ET and temperature is likely related to drought affecting moisture availability. Additional research is needed to fully characterize ecosystem response to climate in this environment and to predict the behavior of ecosystem affects on the water balance under prospective climate change scenarios (e.g.: Dettinger et al.2004; Earman et al. 2006).

Modeled Soil Water Outflow - Sensitivity to Vegetative, Soil Properties and Model Formulation

To examine the influence of soil and vegetative parameters on SWO across the orographic climate gradient of the study area, the Biome-BGC biome type and soil depth were varied at three sites, one at the mountain front near the piedmont zone (site A), a second site at mid-elevation (site B), and a third site near the mountain crest (site C). Assuming that the Biome-BGC model reasonably represents processes affecting MBR for the Tobacco Root Mountains, the sensitivity results provide insight into how biome type and soil depth affect recharge in the true ecohydrologic system. The analysis of model sensitivity to soil depth and vegetation type is an initial attempt to evaluate the hydrologic sensitivity of our modeled landscape to these parameters. The Biome-BGC model is complex and there are several dozen parameters that could potentially be manipulated, some of which may also influence computed SWO.

The total magnitude of SWO sensitivity to biome type is similar at all sites (Figure 5). Changing the modeled biome type at the low elevation grassland site to either evergreen shrubland or evergreen forest invokes a reduction in modeled SWO from 47 mm/yr to 37 mm/yr, suggesting a relatively significant degree of vegetative control on computed SWO at this location. In contrast, at the two higher elevation sites SWO change with modeled biome type is relatively small (<21 mm/yr) compared to the magnitude of outflow (300-500 mm/yr).

Varying the soil depth of these three sites suggests a significant degree of correlation between aridity and sensitivity to soil depth (Figure 6). SWO sensitivity to soil depth is high relative to SWO magnitude at the low elevation, most arid site for shallower soil depths as shown in the slope of the sensitivity curve and change in SWO (174 mm/yr) over the range of soil depths analyzed. Varying soil depth at the mid elevation site induces a much greater range of outflow magnitude (346 mm/yr) than the other sites and the sensitivity response is most linear at the mid elevation site. At the high elevation site SWO varies by 88 mm/yr over the full range of soil depths analyzed.

When considering the percent change in total SWO the sensitivity analysis suggests that vegetative parameters have a relatively greater influence on the simulated sub-soil water flux at the more arid, low elevation site than at the high elevation site. The relative lack of model sensitivity to the simulated biome type at both higher elevation sites indicates that snowmelt driven moisture flux is the dominant control on modeled MBR in this setting. Compared to biome type, SWO is much more sensitive to soil depth at all sites. Despite the apparent sensitivity to soil depth we should be able to resolve the water balance with a lower percent uncertainty at the high elevation sites which produce the majority of SWO within the modeled area.

Evaluation of SWO and MBR Estimates

In an effort to place model results in the context of field measured hydrologic response, results of monthly SWO generated with Biome-BGC were compared with stream flow gaging records (locations shown in figure 1). The observed stream flow peaked between May and July each year (Figure 7). Biome-BGC simulated SWO (runoff and MBR) peaked in April of 2002 and 2003. The observed peak in stream flow in 2002 did correspond with a model generated secondary peak in SWO, however, modeled SWO was about two months earlier than the observed period of runoff flow. This suggests the process based model does not account for factors that act to delay peak stream runoff. Part of the early runoff forecast is related to the coarse discretization of the landscape which inadvertently biased the cell aspect to the southwest, a condition that would limit modeled snow accumulation and promote rapid release of snow water in the spring. Factors may also include the delay of water entering streams due to interflow and near surface shallow ground water exchange. In addition, simulated baseflow was near zero in the late summer and winter months in contrast to observed stream conditions. Such ground water supported streams are not accounted for in the model used.

Based on the MODFLOW volumetric water budget the Biome-BGC estimated MBR accounts for 36% of the annual recharge to the modeled portion of the basin aquifer. Irrigation water loss accounts for 64% and aerial precipitation in the basin only 0.3% of total annual recharge. Flow paths in the model indicate an upward gradient along the mountain front suggesting that most of the DMBR converges to the higher transmissivity layer 1. Modeled stream loss occurs in the streams draining the mountain front; however on an annual basis there is a net gain in stream flow (dominated by the lower reaches of valley streams and the main channel of the Ruby River) throughout the model domain indicating that surface water features are discharge areas for the alluvial basin fill ground water.

The sensitivity of modeled surface water seepage to the DMBR is used to evaluate whether the model is sensitive enough to surface water seepage that actual seepage observations can be used to constrain the DMBR rate. Varying the DMBR in MODFLOW by +/- 50% from the Biome-BGC calculated value invokes a corresponding change of only +1.4% to -3.8% in net stream gain (Figure 8). The results suggest that net stream gain is relatively insensitive to the magnitude of DMBR. Stream gain is similarly insensitive to the parameterization of aquifer K; lower K values reduce total stream gain and loss, but net flux (Figure 9) remains similar.

It was further investigated to determine if head observations could be used to constrain the distribution of MBR at the mountain front. It was found that modeled heads are less sensitive to DMBR (Figure 10) than to assigned aquifer K (Figure 11). Additionally, it was possible to calibrate the modeled head, including at observation points near the mountain front, with all of the MBR applied as $SV_{underflow}$ by adjusting K within reasonable estimates. Characterization of the aquifer K distribution at the mountain front is limited because aquifer testing data for the study area is only available for a few production wells which are screened in the more productive shallow strata. The results indicate that our understanding of the spatial distribution of K near the mountain front is insufficient to provide useful constraints on MBR. Manning (2002) describes similar limitations to using numerical ground water modeling to provide constraints on MBR in the Salt Lake Valley, Utah despite the hydraulic properties of the alluvial basin being relatively well constrained.

The computed MBR was further evaluated by comparison with values reported in the literature (Table 3). These studies represent MBR estimates from settings with reasonably similar climate and physiography and are also examples of MBR estimated at the mountain-scale. The point based estimate of MBR given by Gannett et al. (2001) is the exception and is included here because the porous volcanic geology and extreme precipitation of that setting represents a probable upper limit of MBR. The computed MBR for the southwest portion of the Tobacco Root Mountain Range compares reasonably well with studies from semiarid settings in the Rocky Mountains. Feth et al. (1966), Huntley (1979), and Gannett et al. (2001) as well as the Biome-BGC approach all employ a water balance method and all are affected by similar uncertainty in the water balance. Manning and Solomon (2005) provides a unique comparison; their integrated modeling approach uses a combined heat and fluid flow model which is calibrated to ground water age and temperature. Their integrated modeling approach provides a well constrained example of MBR in a semiarid mountain setting.

Table 3: Calculated MBR: comparison to published studies.

Study	MBR (% of mean annual precipitation)	Mean annual precipitation (mm/yr)	Method	Location and dominant bedrock geology
this study	19%	887	Ecohydrologic water balance modeling.	Tobacco Root Mountains, northern Rocky Mountains in Montana, U.S.A. Gneiss/granite.
Feth et al. (1966)	22 %	926	Water balance, incremental precipitation and empirical ET with elevation.	Wasatch Range, central Rocky Mountains in Utah, U.S.A. Gneiss/schist/minor carbonate.
Huntley (1979)	14 %	not reported	Water balance with ET estimated by analytical equation.	Sangre de Cristo Range, southern Rocky Mountains in Colorado, U.S.A. Schist/gneiss/granite.
Manning and	7-16 %	1107[1]	Integrated environmental	Wasatch Range, central Rocky Mountains in Utah,

Solomon (2005)			tracer combined with modeling of age calibrated fluid flux and calibrated heat flux.	U.S.A. Granite/quartzite-shale/minor carbonate.
Gannett et al. (2001)	up to 70 %	up to 5000	Modeled water balance for individual 1829 m cells using Deep Percolation Model (Bauer and Vaccaro 1987).	Upper Deschutes Basin, Cascade Range in Oregon, U.S.A. Basaltic/andesitic lava.
1- Precipitation derived from values in Hely et al. (1971)				

Considerations for Refining Water Balance Mountain-Block Recharge Modeling

Our experience using Biome-BGC as well as that of other published studies employing recharge process modeling suggests current modeling approaches need to be modified for application to estimating recharge in mountain environments. MBR evaluations using multiple lines of evidence are needed to better evaluate and calibrate current process models (e.g.: Dettinger 1989; Anderholm 2000; Flint et al. 2002; Manning and Solomon 2005).

As MBR is a key component of a basin water balance in the semi-arid mountainous regions it is critical to have frequent measurements of mountain streams discharging to the alluvial basins. This water balance component is generally the most easily measured; however, in semiarid Rocky Mountain settings its complex snow melt dominated and flashy temporal signal requires frequent measurements under challenging and sometimes dangerous conditions. Sites can be instrumented with continuous stage monitors, however, the development of stage discharge relationships is often difficult in these mountainous settings.

Researchers have shown that it is critical to accurately represent soil bypass/macropore flux in watersheds outside of mountainous areas (Finch 1998; Zhang et al. 1999b; Tague and Band 2001), a process not represented in Biome-BGC. Other research indicates that modeling three-dimensional moisture flow processes may be necessary in high relief terrains (Hatton et al. 1995; Dawes and Hatton 1993; Dawes et al. 1997; Zhang et al. 1999c). Alternatively, Tague and Band (2001, 2004) and White et al. (1998) implement the statistically based TOPMODEL (Beven and Kirkby 1979) to model lateral soil moisture redistribution.

The extreme heterogeneity in physical properties such as soil hydraulic properties and radiation flux in mountain terrain makes assignment of representative conditions to a model cell difficult. One solution is to focus landscape partitioning strategies on developing primary model units that exhibit either small internal parameter variance or that incorporate a range in parameter values over which the model behaves in a relatively linear fashion (Band et al. 1991). Figure 6 suggests that modeled SWO in the Tobacco Root Mountains study area responds in a fairly linear fashion at the mid-elevation site whereas radiation and precipitation limitations lead to significant nonlinearity at the high and low elevation sites respectively. This nonlinearity in model response suggests that soil depth will have to be modeled at a higher resolution. Automated techniques for landscape partitioning in tandem with distributed ecohydrologic process modeling within the framework of the Regional Hydro-ecologic Simulation System (RHESSys) have proven effective (Band et al. 1991; Tague and Band 2001; Tague and Band

2004). Currently, RHESSys allows a hierarchical approach to landscape partitioning in which the resolution of a particular processes' representation is tailored to the scale of the homogeneity in driving parameters (Tague and Band 2004).

CONCLUSIONS

Biome-BGC and streamflow gaging are used to calculate the mountain water balance in this temperate crystalline bedrock terrain. MBR is estimated to be 19% of the mean annual precipitation (887 mm/yr). Based on the MODFLOW water budget the Biome-BGC estimated MBR accounts for 36% of the annual recharge to the basin alluvial aquifer. The MBR estimate contains significant uncertainty due to averaging of landscape and meteorological parameter values in the coarse grid modeled and lack of continuous runoff gaging.

Ecohydrologic modeling provides evidence that springtime melt of snowpack provides the only significant source of diffuse recharge to mountain bedrock. Dominant controls on diffuse recharge include evapotranspiration (radiation limited in wet years and moisture limited in dry years), soil properties, and at lower elevations, vegetative ecotones. Modeled SWO is highly sensitivity to soil depth, but less sensitive to modeled biome type. Relative model hydrologic sensitivity to soil depth and vegetation properties is lower at higher elevations where soil moisture flux is greatest. Further research is needed to provide a rigorous review of the potential uncertainty of MBR estimates derived from ecohydrologic models.

Improvements in the understanding of mountain recharge processes and an ability to translate that understanding into models will allow researchers to better quantify and reduce the uncertainty in water balance approaches. Further development and dissemination of distributed modeling applications which provide automated landscape partitioning and model parameterization should provide researchers the efficiency and flexibility needed to evaluate available process models, quantify model uncertainty, and tailor modeling techniques to the specific processes governing mountain hydrology.

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Figures:

Figure 1: Study area location.

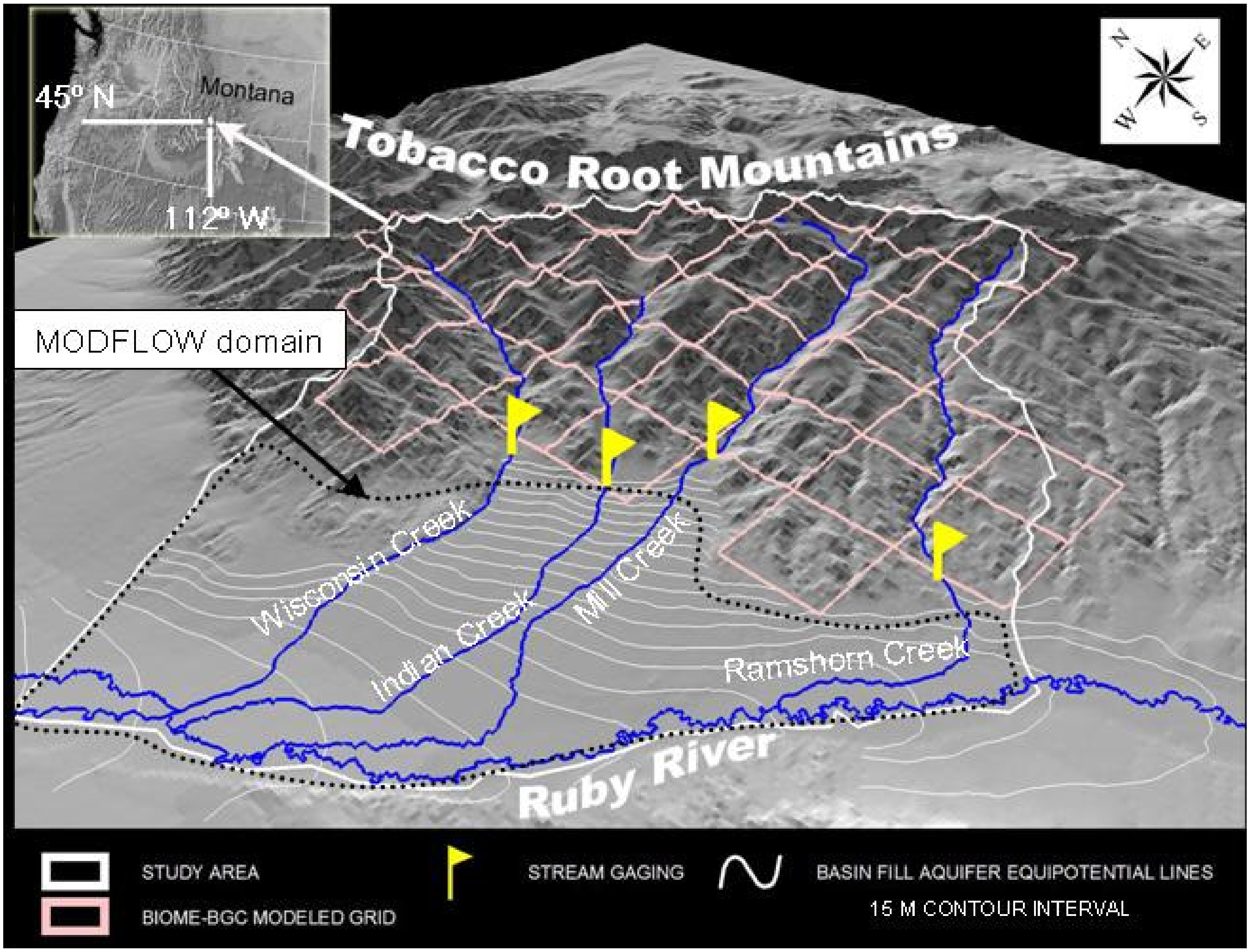

Figure 2: Ramshorn Creek example hydrograph.

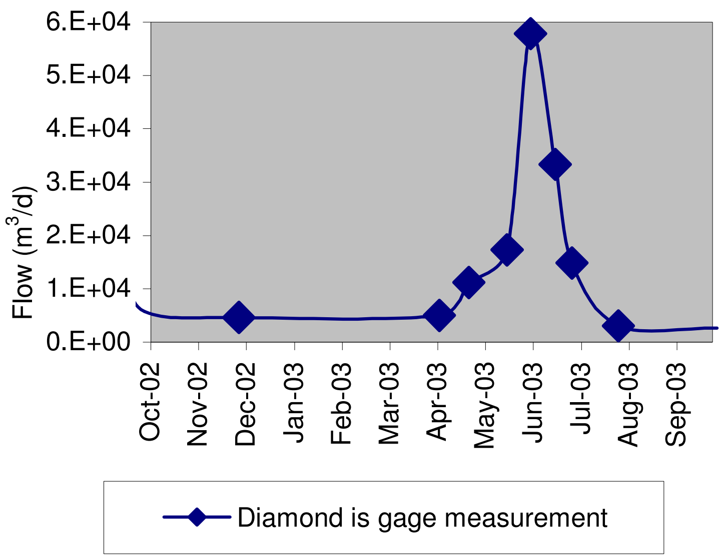

Figure 3: Biome-BGC modeled annual water flux and mean temperature.

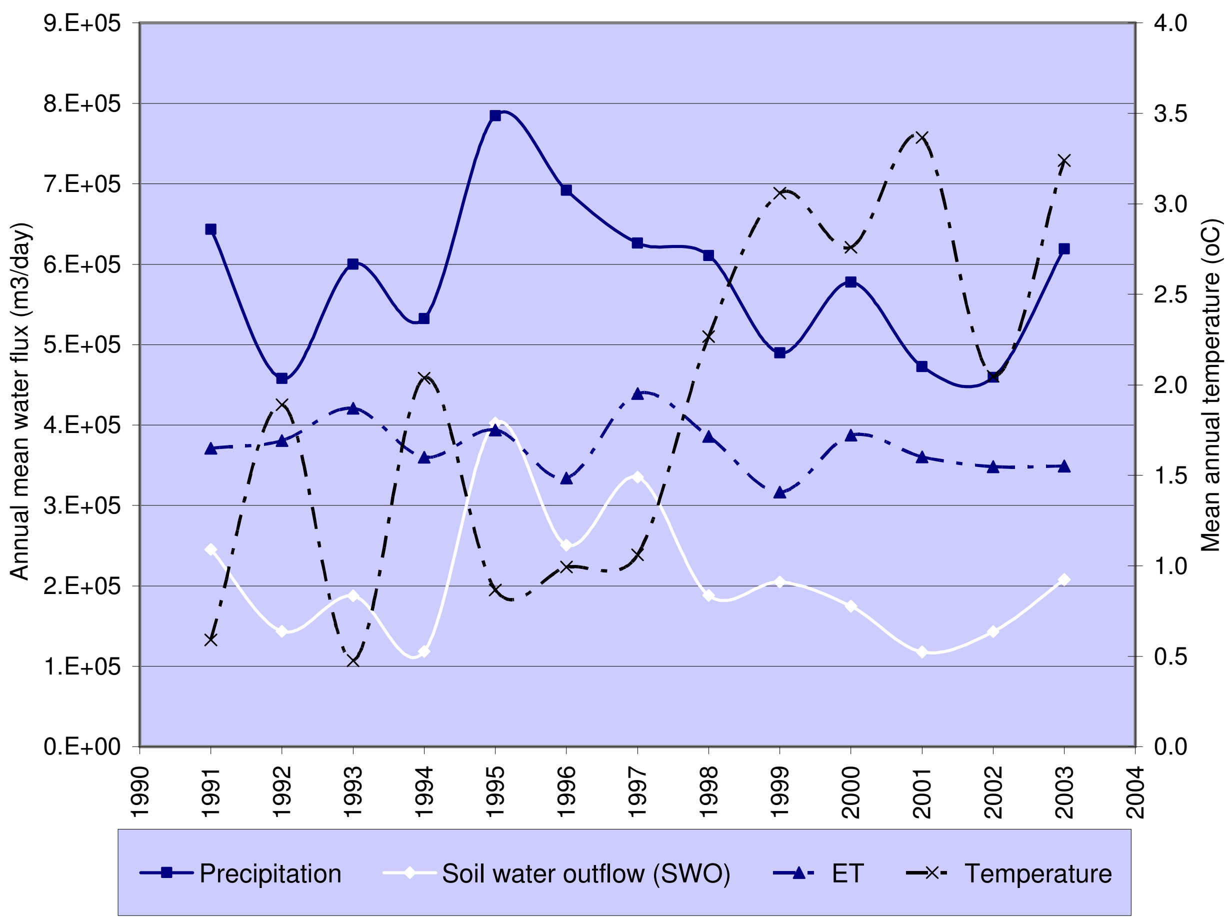

Figure 4: Example daily hydrologic response of a temperate mountain biome.

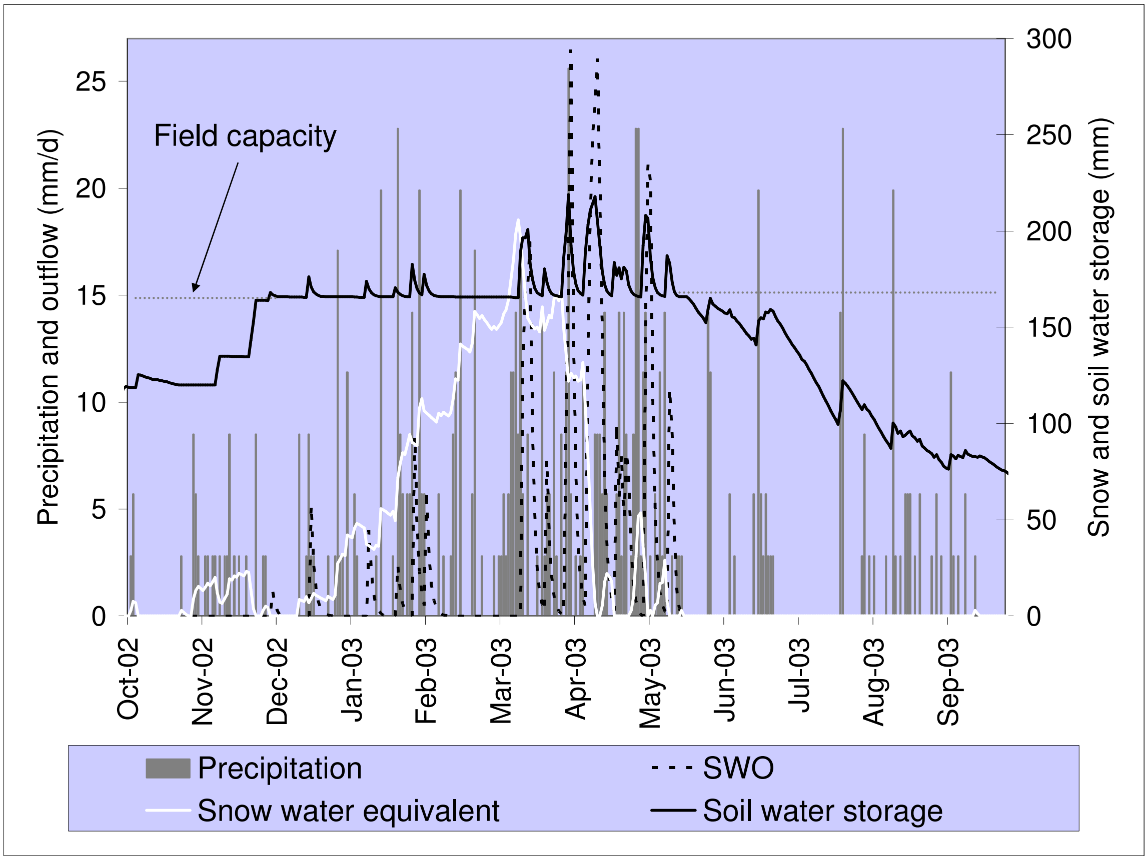

Figure 5: Soil water outflow sensitivity to modeled biome type.

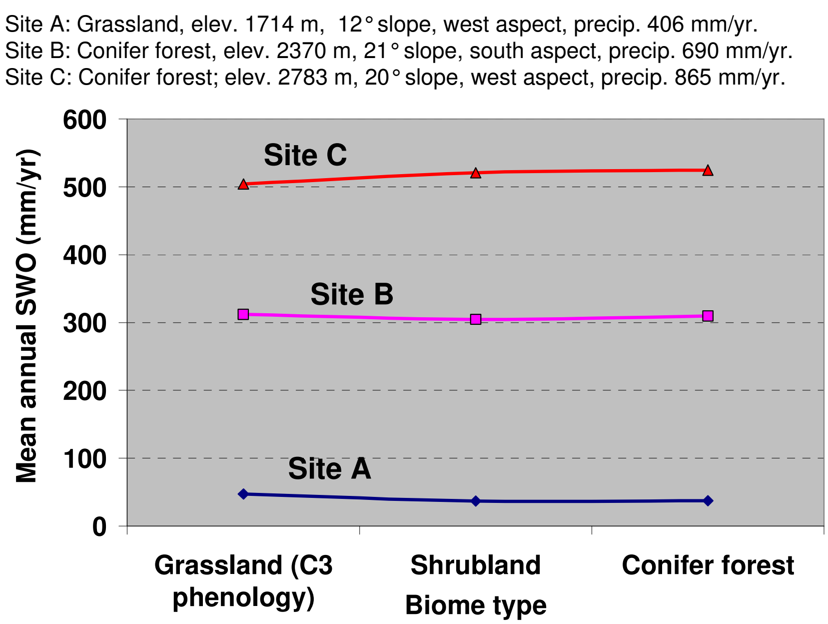

Figure 6: Soil water outflow sensitivity to modeled soil depth.

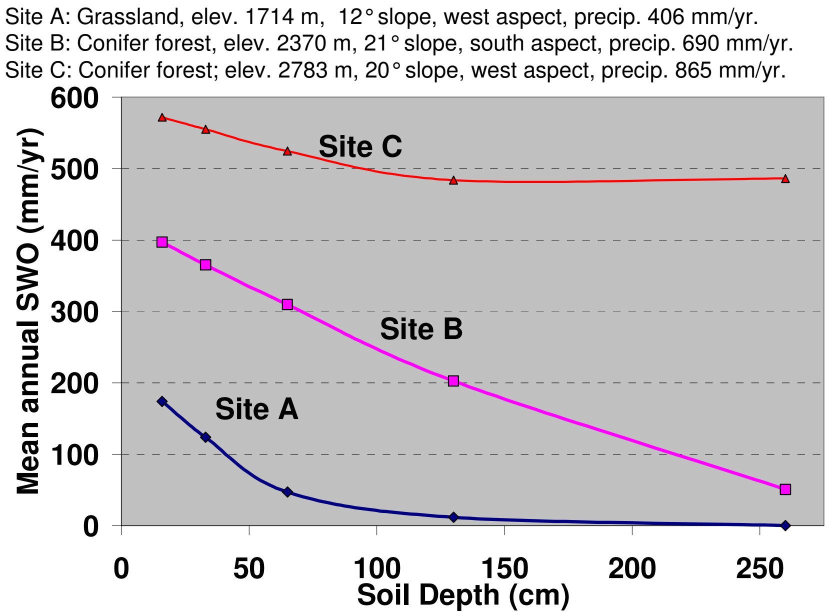

Figure 7: Comparison of modeled monthly soil water outflow and sum of measured runoff.

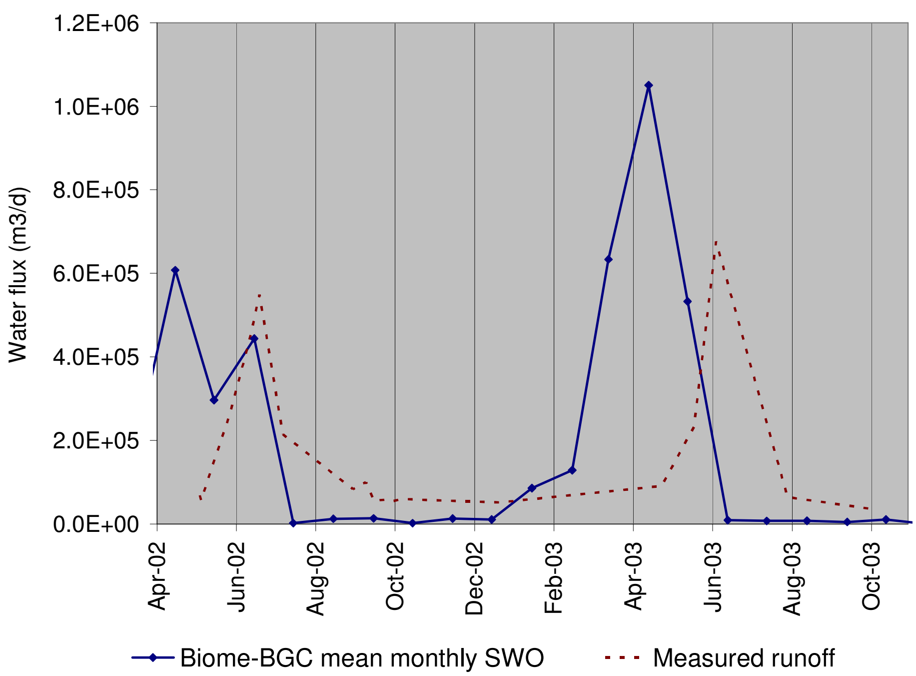

Figure 8: Stream gain sensitivity to DMBR at 7/7/03 time step.

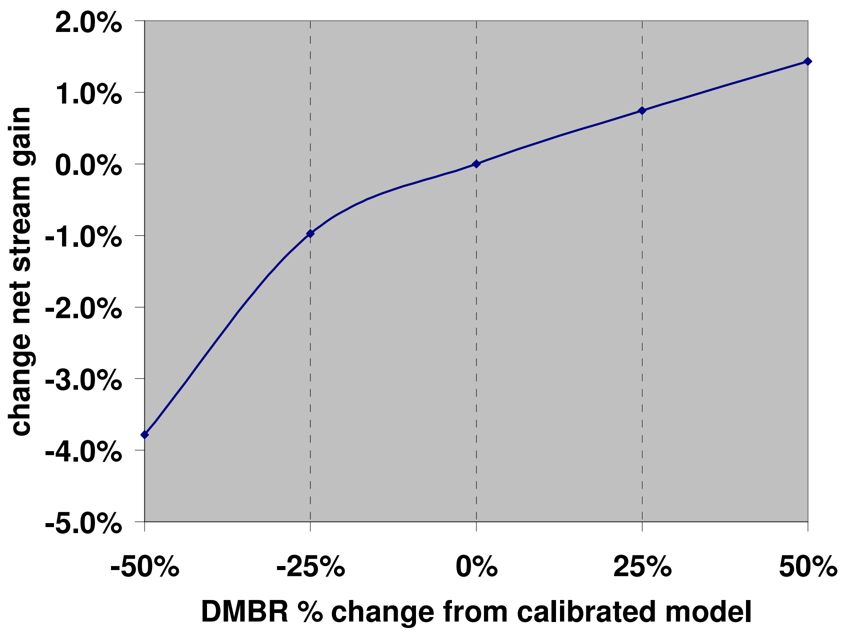

Figure 9: Stream gain sensitivity to K at 7/7/03 time step.

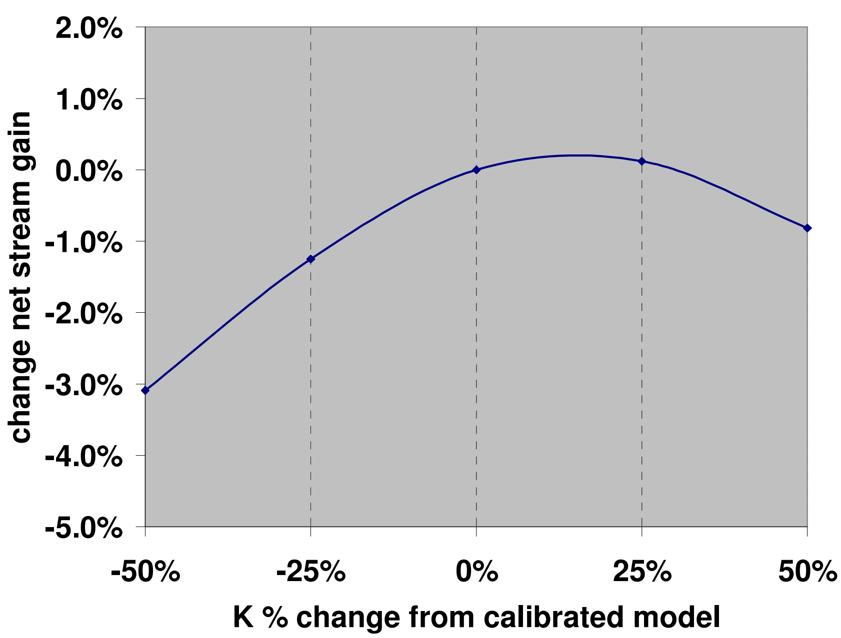

Figure 10: Head calibration sensitivity to DMBR.

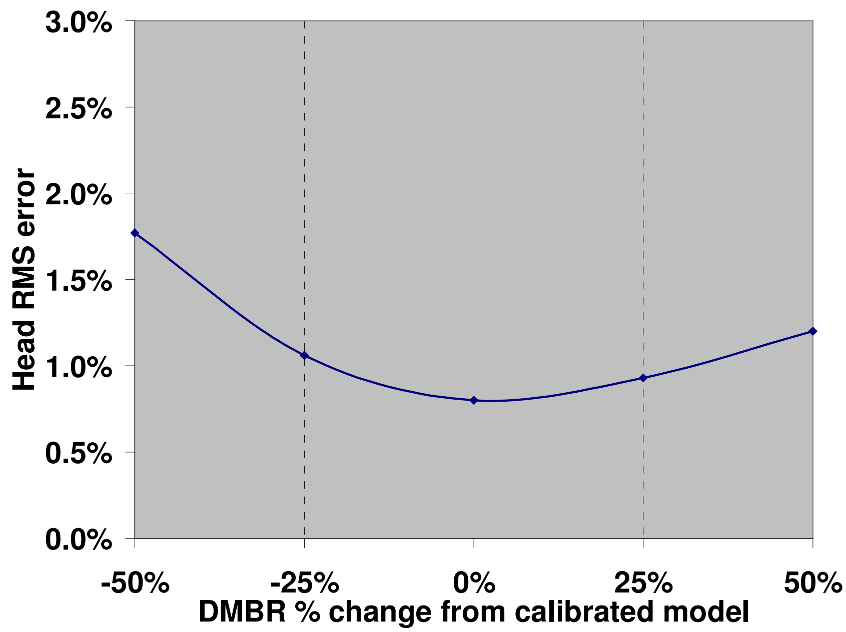

Figure 11: Head calibration sensitivity to K.