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Hydrology and Earth System Sciences Discussions

Interactive comment on "Water-balance and groundwater-flow estimation for an arid environment: San Diego region, California" *by* L. E. Flint et al.

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Hydrol. Earth Syst. Sci. Discuss., Responses to reviewer comments on "Water-balance and groundwater-flow estimation for an arid environment: San Diego region, California" by L. E. Flint et al.

All review comments from multiple reviewers are addressed in this document. Written comments are duplicated and responded to in italics. All electronic editorial comments in pdf on the documents are directly incorporated or referred to directly below.

Anonymous Referee #2:

All editorial suggestions and commentsfrom the manuscript mark-upthat were accepted were incorporated or addressed directly in the manuscript. Those suggestions or comments not incorporated or accepted or that required explanation follow.

Page 4, number 3. The reviewer comments that soil properties are the most uncertain, yet the focus of the review was on the uncertainty in recharge due to PET/precip. A sentence was added to the text noting that bedrock permeability was used in a calibration process, so uncertainty in permeability is not addressed, yet the mapped estimate of geologic type is relied on without uncertainty. We believe the soils dataset is relatively robust at the spatial scale of SSURGO, and we do not attribute the most uncertainty to this dataset. However, comments with regard to uncertainty of all input datasets were added to the descriptions.

Page 4, number 5. The issues of partitioning the recharge and runoff into subsurface and surface flows is described later in the paper.

Page 4, number 6.The San Diego basin has very few truly unimpaired streamgages, and possibly none at all, but the calibration of the model makes this assumption for upstream gages that have no documented diversions or reservoirs, and assumes that other losses are insignificant. Basins with impairments such as urban runoff are readily obvious in the record when compared to simulated flows, and the calibration process de-emphasizes these when changes are made to bedrock permeability.

Page 5, number 1.GWshallow and GWdeep are described in the text, and the schematic illustrates them as different processes.

Page 5, number 3. Mass balance is preserved exactly.

Page 5, number 7. They are a problem, and they are addressed directly in the San Diego River basin in the reconstruction of streamflow, which relies on measured reservoir levels, diversions, and imports. This allows for the direct comparison of the BCM results with the measured gage data.

Page 5, number 9. Agreed, this will happen in subsequent model refinements as additional data are available.

Page 7, number 4. Disagree that this is contradictory. It is a different approach/methodology/model to partitioning the BCM rch and run into subsurface and surface flows to estimate groundwater recharge. MODFLOW is a completely different approach that relies on a physical subsurface configuration and equations that are actually independent of the equations used in post-processing the BCM. The physical MODFLOW conceptualization assisted in the development of the BCM post-processing equations and the schematic in figure 5.

Page 7, number 13. This paragraph was rewritten to better reflect the contents of the results section.

Page 8, numbers 1 and 3.I can't believe the calibration results were so far back in this section. Moved them to the front and softened the language about results, estimates, facts etc. according to the suggestions.

Page 8, number 12.Explained in sentences following the comment.

Page 8, number 21. The amount of water recharged from low flow streams is very small in comparison to the volume of water recharged where the precipitation dominates over much larger areas than the 1-dimensional stream channel. The rivers in the coastal plain are all generally losing because there is little rain and deep soils. That doesn't mean there aren't shallow gains in some locations (see schematic) or subsurface water that moves from the higher elevations deeper to the coast.

General comment:It has been common knowledge in hydrology that estimates of groundwater recharge based on precipitation, runoff and actual ET (AET) are uncertain to the point of infeasibility because of uncertainty in AET that is far greater than the recharge. In other words, estimation of recharge through water balance calculations has been mostly impractical because the thus far irreducible uncertainty in AET

is much greater than magnitude of the recharge term. The main exception is in the case of agricultural crops, for which decades of monitoring and research have helped adequately constrain the AET term. From the title and conclusions of this paper, one might construe that the above-stated problem has been partially or substantially solved. Unfortunately, this problem persists and is as nasty as ever, and I believe the authors should include more direct discussion of this shortcoming.

In concept, the recharge uncertainty problem can be better constrained through the combined approach of integrated hydrologic analysis that includes a bona fide, calibrated groundwater model. The authors have taken a small step in that direction, but the groundwater model appears highly preliminary, has questionable boundary conditions, and is apparently not calibrated. Moreover, the recharge forcing in the groundwater model was apparently taken from the water balance model, removing the possibility of using the groundwater model to constrain the water balance calculations.

Response:The major issue posed in this review is with regard to the relative proportions of the water balance components and the magnitude of errors of each, leading to unacceptable uncertainty in the recharge estimate.The issue is ill-posed in arid and semiarid environments because of the mismatch in where and when the water balance components occur. What the reviewer refers to as common knowledge has been disputed in the literature and disproved over the last 20 years with advancements of understanding of arid and semiarid hydrology. We have addressed this concern in several ways, including the addition of a section in the introduction describing the episodic nature of recharge in arid and semiarid environments including references, the calculation of the percentage of months over the entire simulation that resulted in recharge, a sensitivity analysis of the change in recharge given assumed errors in PET, and discussions of uncertainty in each of the input variables, including precipitation, PET, and soils.

The reviewer acknowledges that the uncertainty in recharge can be constrained through the incorporation of multiple approaches, which in our case includes a mechanistic distributed parameter water balance model constrained by the use of a reconnaissance-level groundwater model. The use of the groundwater model was unintentionally emphasized in the manuscript on the basis of the amount of text necessary to describe the methodology. Rewrites have reduced that emphasis to include the reconnaissance-level groundwater model only as a means to support the partitioning of accumulated recharge and runoff by the BCM into streamflow, baseflow, and deep recharge components. In fact, the results of the paper and the estimates of recharge to the coastal plain do not rely on the groundwater model at all. The use of the groundwater model was to rely on the mode of distributing groundwater in the subsurface by MODFLOW, which is physically based, to determine if the equations developed to partition the BCMrch and run into streamflow and baseflow components, which were then compared to measured streamflow, were well conceived.

Review from T. Rasmussen

General comments: 1. This article provides a comprehensive overview of the hydrologic conditions in the Greater San Diego watershed. A great diversity of hydrologic information from multiple sources is compiled and assimilated in the form of a watershed model. Results from the model provide a means for understanding and predicting hydrologic changes due to alternate management and climatic scenarios. 2. While the article is a excellent compilation of data and modeling results, it has little in terms of scientific merit. There are no new ideas or hypotheses presented, nor independent checks of model results. Possible independent checks might include environmental tracers (e.g., 14C) to check for water ages and residence times, or geochemical tracers to show the evolution of water along a flowpath.

Response:The introduction has been rewritten to more explicitly indicate the intent of the paper and to justify its scientificcontribution to the field of arid land hydrology and the conceptualization of hydrologic processes in a data-scarce region. The advancements offered by this investigation include 1) expansion of BCM capability that allows direct comparison of model output to gaged streamflow data toallow for the constraint

or authentication of the spatially distributed model results, 2) outlining a reasonable approach for quantifying a first-order water budget estimate for areas with sparse hydrologic data, and 3) describing the episodic nature of groundwater recharge in a semi-arid environment. The episodic nature of semi-arid recharge cannot be over-emphasized and is reiterated in this document. These tools and approaches provide a pathway for development of conceptual models to frame hydrologic and hydro-geologic problems in data sparse regions to identify data gaps and model weaknesses and this application is the first step in a long endeavor to quantify the water resources in the coastal plain of the San Diego area by stepping back to consider the entire contributing water balance.

Specific Comments 1. The water budget considers many natural sources of water, such as precipitation. Yet, it is my understanding that substantial volumes of water are imported into the watershed from the Colorado River and other sources. It is not clear whether these volumes are important to the overall water budget. An additional statement related to the magnitude of these imports (as well as desalination inputs?) would be helpful. Response:information on imports included, and elaborations on the streamflow reconstruction using these values for the San Diego River basin

2. Natural groundwater flow can be influenced by local additions from agricultural and landscape irrigation, stormwater retention, and leaking sewer and water lines in urban areas. Are there any data related to the magnitude of fugitive flows from urban systems? Response:There are insufficient data for these local additions to incorporate them into a water balance calculation for the entire basin contributing to the coastal plain. It is assumed they are insignificant, and this is stated in the text.

3. Do stormflows from impervious surfaces in urban areas substantially affect the surface-water budget? I would assume that recharge at lower elevations would be small, with most of the water evapotranspirating under natural conditions. Yet, this evapotranspiration might be reduced in areas with substantial impervious surface, thus increasing stormwater runoff. Response:Stormflows are evident in the streamgage data for several of the gages, specifically two gages in the San Diego River basin,

Los Coches and Forester Creeks. Although originally considered, these two gages were not eventually used in the model calibration. Additionally, the gage at Fashion Valley has evidence of urban runoff, but the total monthly volumes were used in the unimpaired streamflow reconstruction with the upstream Mast Rd gage record. These stormflows are part of the surface-water budget. The actual evapotranspiration is calculated as part of the water balance and the low precipitation, deeper soils and lower PET result in estimates of negligible recharge on the low elevation coastal plain under all but very wet years when precipitation can episodically overcome winter PET to provide enough excess water for penetration through the soil column. The specific identification of urban surfaces in the water balance is not incorporated directly into this version of the BCM, although sensitivity analyses have been done using the model resulting in increases of runoff and decreases in recharge. In this region, the predominant locations with large urban footprints are on the lower elevation plain where the precipitation is low, and thus this factor was not considered for this preliminary conceptualization and quantification of recharge. A brief discussion of this factor has been added to the text for completeness.

4. It appears that the study does not address groundwater pumping. Does this mean that groundwater withdrawals do not alter hydrologic conditions? Are there any aquifer recharge efforts, and if so, are they substantial? As an ancillary issue, does groundwater pumping affect coastal saltwater intrusion or brackish water upconing? Response:Groundwater pumping is a common use of water in the region, but there is not data available to quantify it and relate it locally to a water balance. In this model, pumping was not considered as a significant source of loss to the aquifer in the areas under consideration above the coastal plain.

Suggested Changes 1. Unitsof million m3/yr are used in the paper. An equivalent unit is GL/yr, which is more compact and uses a standard metric prefix. Response:We prefer the use of million m3/yr as more frequently used in the literature. 2. Page 2721, Line 10. You say that precipitation increases with distance inland. While true, would it not

be more accurate to say that it increases with elevation. Elevation and distance inland are highly correlated. Is the fact that it decreases from north to south due to a change in elevation, or are the elevations similar? Response:The correlation with elevation has been added to the text. 3. Table 1. It would be helpful to add the elevation of the USGS stations. Response:good idea, elevation added 4. Table 2. The discharge is called "Runoff" in this table. Does this mean Stormwater Runoff, or should it be Discharge. Is this the total discharge or the incremental discharge for the segment between the stations? Response:the table correctly identifies the variable as BCMrun, which is the gridded calculation of runoff from the model, accumulated for all grid cells contributing to each stream segment. Changed to runoff in the table heading. 5. Table 8. The method by which the sum of squares weighted residuals is calculated is not defined. Because streamflow is highly heteroscedastic (i.e., the error in measurement is highly correlated to the magnitude of the observation), we normally fit the log10 transform of discharge instead of the simple, untransformed discharge. The logarithmic transforms implies an error that is proportional to the magnitude of the observation, e.g., five percent, which is what is usually expected. Is this what was done? If so, this should be indicated. Response:This is now indicated. 6. Figure 5. The figure indicates that the coast drops precipitously - i.e., there is no continental shelf. Is there a saline water wedge (halocline) along the Pacific Ocean? How was the boundary condition handled here? Response:This is a conceptual model representing a groundwater domain that also doesn't include the mountains, preferring to highlight the direction and general volume of the water balance partitioning. There is a continental shelf as well as a saline halocline that has been developed using a SUTRO model in a parallel effort to constrain the direction of flow in the coastal plain and the general volume of recharge. 7. Figure 7. Would it be possible to indicate the reservoir locations? Do they receive imported water?Response:The reservoir locations are noted on figure 1, added to figure 7. The imported water to the reservoirs is included in the streamflow reconstruction, which is noted in the text. 8. Figure 8. Are the decadal averages significantly different? Would a Kruskal- Wallis (homogeneity) test show a difference? Response:The 1940-1989 population of precipitation values are not significantly different than the 1990-2009 population of precipitation values, although the variance is about 30 % higher in the last 2 decades. However, regardless of significance, we believe that the illustration serves to point out that ranges in precipitation, with more frequent low precipitation and more frequent high precipitation dominates the recharge calculation. 9. Figure 9. Would it be possible to indicate the recharge and runoff efficiencies (i.e., divided by the precipitation)? Is there a correlation between these efficiencies and elevation? Response:We added a precipitation map, along with the seasonality of water balance components. The pet/ppt/rch/run maps provide the indication of recharge at high elevations with high excess winter water. 10. Figure 10. It might be helpful to plot this using a log-log scale because the regression lines are linear on that plot. Response:You're right about this, but leaving it arithmetic makes it more visual and easier to explain. 11. Figure 11. It would be helpful to show discharge using a logarithmic scale (GL/mo) in order to resolve lower flows. Also, the grey shading for the background is not helpful. Response:redid this figure for clarity, but in the grand scheme of things, although the log view was used during calibration, the low flows are an insignificant part of the whole water balance.

Review from T. Durbin

Specific comments related to manuscript sections: Abstract:Flint et al. estimated recharge from precipitation for the San Diego region using a water-balance model. A fundamental problem with the application of the model to the San Diego region is that in a semiarid climate annual evapotranspiration nearly equals the precipitation. Uncertainty in the evapotranspiration and precipitation is on the same order of magnitude as the difference between those quantities. The uncertaintyin the model recharge estimate can be assessed by considering the essential inputs to the model, the sensitivity of the resulting water-yield estimates to uncertainty in those inputs, and the uncertainty in the inputs. Such an exercise indicates that moderate uncertainty in the model inputs leads to large uncertainty in the estimate of the watershed-scale recharge. The coeffi-

cient of variation of the recharge estimate is about 100 percent, which means that the uncertainty is of the same order of magnitude as the recharge estimate itself.

Response:In fact, in semiarid environments annual PET far exceeds precipitation. However, the mechanisms responsible for recharge in the southwest result in recharge estimates that are quite robust. This comment results from a lack of knowledge regarding the episodic nature of recharge in arid and semiarid environments. As noted in a response to the previous reviewer, the notion of the inability of water balance approaches to address recharge in arid lands has been disputed in the literature following advances in methods and understanding over the last 20 years. A section was added to the introduction that describes the nature of recharge in arid lands, and how transient water balance approaches have been shown to successfully capture the relative components. Additional references that provide evidence regarding episodic recharge that aren't explicitly discussed in the manuscript are:

Nishikawa, T., Izbicki, J.A., Hevesi, J.A., Stamos, C.L., and Martin, P., 2005, Evaluation of geohydrologic framework, recharge estimates, and groundwater flow of the Joshua tree area, San Bernardino County, CA: USGS Scientific Investigations Report 2004-5267

Izbicki, J.A., Radyk, J., and Michel, R.L., 2002, Movement of water through the thick unsaturated zone underlying Oro Grande and Sheep Creek Washes in the western Mojave Desert, USA: Hydrogeology Journal 10:409-427.

Izbicki, J.A., Johnson, U.U., Kulongoski, J., and Predmore, S., 2007, Groundwater recharge from small intermittent streams in the western Mojave Desert, CA, USGS Professional Paper 1703-G.

1 Introduction: R=P-ET-RO (Eq. 3) where R is the average annual recharge for the watershed Flint et al. (2012) estimated for the San Diego River watershed that the recharge is about 54x106 m3/yr (or 48 mm/yr) and runoff is about 19x106 m3/yr (or 17 mm/yr). The average annual precipitation within the watershed is about 530x106

m3/yr or 470 mm/yr. Correspondingly, the watershed yield equals 13 percent of the precipitation,and the recharge equals about 10 percent of the precipitation. Flint et al. (2012) report that the BCM relation between point recharge and precipitation can be approximated for the San Diego River watershed by a power function such that the recharge as a percentage of precipitation is 7 percent for precipitation of 300 mm/yr, 12 percent for precipitation of 500 mm/yr, and 26 percent for precipitation of 700 mm/yr. Flint et al. (2012) discuss the uncertainty in the recharge estimate, but they do not offer a quantification.

Response:The use of average annual values in water balance estimates has been discussed as erroneous and is included in the manuscript with additional detail. Error analyses were done and a section on uncertainty in PET and the resulting changes to estimates of recharge have been added.

The stated purpose of the BCM application is to facilitate groundwater management within the San Diego region, but the uncertainty in the BCM recharge estimate is so large that the purpose is not achieved. Our comments on this application of the BCM to the San Diego region address the overall uncertainty in the estimate of recharge. The fundamental issue with the recharge estimate is that it is derived from the subtraction of two nearly equal uncertain quantities where the uncertainty is of the same order as the difference. Furthermore, the available data do not facilitate reducing the uncertainty through a model calibration. Finally, comments address mostly the recharge estimate for the San Diego River watershed within the BCM model area because Flint et al. (2012) provide the most complete information on that subarea.

Response:The water budget, Eq. 3, is not solved on an annual basis but rather a monthly basis. The estimate of recharge is not derived from the subtraction of two nearly equal uncertain quantities as the reviewer suggests. Additional text was added to better express the concepts of recharge in arid and semi-arid regions because the conceptualization of recharge in the arid and semi-arid southwest is complicated. Aridity is defined as the ratio of annual precipitation to potential evapotranspiration (UN-

ESCO, Flint and Flint 2004). The San Diego area is semi-arid (Flint and Flint 2004) which means average annual precipitation is between 20 and 50 percent of potential evapotranspiration which suggests little potential for recharge. However recharge in a basin does not occur based on average annual conditions. In certain areas of a basin (in particular, for the higher elevations), precipitation in some months can exceed potential evapotranspiration and soil storage and net infiltration (defined as infiltration that reach depths below where it can be removed evapotranspiration processes) and/or runoff may occur, depending on the rate of rainfall or snowmelt, soil properties (including permeability, thickness, field capacity, and porosity), and bedrock permeability (Flint et al., 2001). For many basins, snow accumulated for several months provides enough moisture to exceed the soil storage capacity and exceed potential evapotranspiration for the month or months during which snowmelt occurs (Flint and Flint, 2007c). This leads to sporadic and sometimes spatially limited occurrences of net infiltration but may lead to the majority of recharge in a basin. Net infiltration is the precursor to recharge, which can occur months to decades after the net infiltration event and is dependent on the properties and thickness of the unsaturated zone. For the San Diego area winter precipitation and spring snow melt can well exceed the storage capacity of the soils and either enters the bedrock to become net infiltration or becomes runoff and enters the stream. With shallow soils this can occur over several days where little of the larger volume of water can be removed by evapotranspiration. The approach taken to represent this is a monthly numerical model that incorporates the conceptual model, the physical system (soils and geology), and the climate parameters of precipitation, air temperature and potential evapotranspiration defined on a monthly basis. Errors in these parameters introduce uncertainty into the estimates of recharge, but there is still a robust estimate of recharge in certain locations in certain years. For instance, in the 114 year simulation of the San Diego area, 10 percent of the total recharge occurred in just 3 of the 1232 months (0.2 percent of the time). The amount of precipitation so overwhelmed the soil storage capacity the recharge occurred and errors in potential evapotranspiration would be minor compared to the large volume of recharge. Fifty percent of the recharge occurred in just 27 months of the 1232 month simulation (2% of the time). Taken further 95 percent of the recharge occurred in 128 months of the 1232 month simulation (10 % of the time). Given this it seems that summing the potential evapotranspiration for the other 90 percent of the months to count against average annual precipitation doesn't provide much insight into the water balance that actually leads to recharge in the San Diego area. In the upper Sweetwater Basin the ratio of precipitation to PET in the largest recharge months are over 10:1, not the 0.50:1 (for a semi-arid climate). Over half the recharge occurs the when the ratio is between 10:1 and 5:1 so it is clearly not subtraction of two equal numbers. Point data, rather than averages would certainly have much higher ratios of precipitation to PET.

2 Overall Uncertainty in Recharge Estimates The recharge within the BCM area is a small percentage of the precipitation. Based ontables within Flint et al. (2012), the average annual runoff volume equals about 3 percentof the precipitation volume within the San Diego River watershed. The rechargeequals about 10 percent of the precipitation. Correspondingly, the average annualevapotranspiration equals about 87 percent of the precipitation. The model area evapotranspirationis only slightly smaller than the precipitation, which leads to an exaggerateduncertainty in the water yield (Gee and Hillel, 1988). That uncertainty can bederived from the relation (Benjamin and Cornell, 1970)

Var[R]=Var[P]+Var[ET]+Var[RO] (Eq. 4)

This relational form assumes no correlation among errors in the independent variables,which probably is a reasonable representation of actual conditions. Equation 4 expressesthe recharge uncertainty at the watershed scale, and that uncertainty can bederived by first assessing the recharge uncertainty at a point and then upscaling theuncertainty at a point to the watershed scale.The uncertainty in point recharge was assessed by making simulations using a soilwatermodel to quantify the sensitivities of the simulated recharge to the model inputs.For that purpose, the soil-water module was extracted from the FEMFLOW3Dgroundwater-modeling program (Durbin and

Bond, 1998). The module structure hassimilarities to the BCM structure. As in the BCM, the module is based on the waterbudget for a soil column, and it contains a relation for constraining evapotranspirationwhen the available soil moisture is limiting. The module dependencies are representedby

r=f(x_1,x_2,x_3,x_4,x_5,x_6) (Eq. 5)

where x_1 is the local infiltration of precipitation, x_2 is the local potential evapotranspiration,x_3 is the vegetation rooting depth, x_4 is a parameter related to the dependence of evapotranspiration on soil moisture (Durbin and Bond, 1998), x_5 is the soilavailable water capacity, and x_6 is the vegetation cover. Given the functional relationexpressed in Equation 5, the variance of the uncertainty in the recharge estimate isgiven by (Benjamin and Cornell, 1970)

Var[r]=P_(i = 1)_6(@r/(@x_i))ËĘ2 Var[x_i] ãËŸA°U(Eq. 6)

where the uncertainties in independent variables are assumed to be uncorrelated.The partial differentials are approximated with finite differences derived from the soilwatermodule, where the partial differentials represent the sensitivities of the simulatedrecharge to the respective module inputs.Equation 6 was applied to average annual infiltrations of 300, 500, and 700 mm.Monthly recharge was simulated for a 12-year period. Precipitation and potential evapotranspirationwere derived from a California Irrigation Management Information System(CIMIS) (California Department of Water Resources, 2011) station within the SanDiego region. The simulation results are summarized in Table 1 with respect to the coefficientof variation for point recharge. The coefficients are 1100 percent for averageprecipitation of 300 mm/yr, 360 percent for precipitation of 500 mm/yr, and 160 percentfor precipitation of 700 mm/yr. The uncertainty in the point recharge estimates is basedon the underlying uncertainty in the inputs to the simulations as listed in Table 2.

Response:See above for response to comments regarding annual averages.

2.1 Uncertainty in Point Precipitation The uncertainty in the point precipitation is based on comparisons between the PRISMmaps (Daly et al., 2004) of monthly, annual, and average annual precipitation for theSan Diego region. The precipitation input to the BCM was derived from monthly PRISMmaps. The PRISM maps are a gridded representation of monthly precipitation basedupon a regression of station precipitation data against variables describing orographiceffects. Based on calendar year 2001, the comparison to monthly and annual precipitationwith station data indicates monthly coefficients of variation that range from 20to 300 percent for individual months. The coefficient of variation for the annual precipitation is about 20 percent. That is consistent with a comparison of PRISM mapsof average annual precipitation in Nevada with station data (Jeton et al., 2005). Thecoefficient of variation for that comparison was about 15 percent, depending on thestation set considered, but it tended to be larger with higher elevation.

Response:The analysis of Jeton, et al., 2005 was based on the 4 km transient PRISM data and is a different data set than the 800 m transient data from PRISM used in this study. It's generally agreed that maps of precipitation made from point data are not necessarily accurate away from the point data, however PRISM appears have improved the estimates for precipitation when going from the 4 km maps to the 800 m maps (Curtis, et al., 2011; Stern, et al., 2011) in some cases showing a 27 percent improvement in estimate of precipitation. There is also uncertainty in the point data as well, particularly with RAWS data. And we did find that precipitation stations from RAWS averaged 11 percent lower than PRISM with a standard deviation of 23 percent (PRISM was both high and low). We excluded the precipitation estimate of 2043 mm in November, 2000 from the Potrero station, (we also excluded about 15 other dates from other stations that were obvious errors). The other active RAWS stations for November, 2000, ranged from 9 mm to 37 mm. The Potrero station had a minimum daily air temperature of -27 C for July, 1990, which leads one to have less trust in web based RAWS data. We did a sensitivity analysis of errors in precipitation and added that information to the paper. A 10 percent error in precipitation causes a 20 percent variation

in recharge, however the uncertainty in recharge could be higher or lower depending on the location of recharge versus the location of the errors, either higher or lower, than the station data. Because this is a scoping paper and not intended to definitively quantify recharge we wanted a consistent data for reference so we chose to use the better 800 m data over the 4 km data without an attempt to correct the PRISM data to uncertain station data.

2.2 Uncertainty in Point Evapotranspiration Flint et al. (2012) used the Priestly-Taylor equation (Flint and Childs, 1991) for calculatinghourly potential evapotranspiration, which was aggregated into monthly potentialevapotranspiration. The approach requires measurements or estimates of net radiation,soil heat flux, air temperature, and atmospheric vapor density. The BCM was calibratedto monthly potential evapotranspiration derived from CIMIS climatic measurementsat stations located within the northern coastal part of the model area (Figure 2).

Nearly all the CIMIS stations are located within 4 km of the ocean, while the upper watershedboundary is about 80 km from the ocean. The average annual precipitation isabout 300 mm within the region containing the stations, while the precipitation near theupper watershed boundary is as much as 900 mm/yr. Flint et al. (2012) indicate thatmost of the watershed recharge is generated within areas of higher elevation and precipitation.However, the BCM evapotranspiration functions were calibrated to stationswithin areas of lower precipitation and elevation, which are climatically distinct fromareas of higher precipitation. Based on data compiled for Remote Automatic WeatherStations (RAWS) (Western Regional Climatic Center, 2011) for the San Diego region(Figure 2), the average annual relative humidity decreases from about 70 percent nearthe coast to about 45 percent at the upper watershed boundary. The coastal areastend to be windier than mountain areas, but winds display high geographic variability.The RAWS dataset includes information on potential evapotranspiration computed usingthe Kimberly-Penman equation (Wright, 1982). Those estimates of potential evapotranspirationcharacterize the general geographic distribution of potential evapotranspirationwithin the BCM area. Firstly, as shown on Figure 3, the RAWS data indicate alinear relation between average annual potential evapotranspiration and elevation overthe range of elevation within the BCM area. Secondly, the geographic application ofthat relation to the BCM area yields the map of average annual potential evapotranspirationshown on Figure 4. That map is significantly different than the correspondingmap produced by Flint et al. (2012, Figure 3a). Their map indicates that average annualpotential evapotranspiration is about 700 mm/yr within coastal areas, about 1,700mm/yr within middle watershed areas, and about 800 mm/yr within upper watershedareas. In contrast, Figures 3 and 4 indicate that the average annual potential evapotranspirationis about 900 mm/yr within coastal areas, about 1,050 mm/yr within middlewatershed areas, and about 1,150 mm/yr within upper watershed areas. While Flintet al. (2012) conclude that the highest potential evapotranspiration occurs within themiddle watershed areas, the RAWS data indicates that the highest potential evapotranspirationoccurs within the upper watershed areas. These differences suggest thatthe potential evapotranspiration maps generated by Flint et al. (2012) may containconsiderable uncertainty.

Response:The Priestley-Taylor model was calibrated using CIMIS and AZMET stations in California and Arizona (Flint and Flint, 2004) using over 100 station estimates of reference evapotranspiration not just the stations within the San Diego Area. An analysis of the CIMIS zone map provides further insight into potential evapotranspiration. The PET from the BCM is shown below as figure 1 and 2 with the zonal areas from the CIMIS website (http://wwwcimis.water.ca.gov/cimis/info.jsp).

Figure 1.Cimis zone map overlaying the San Diego study area used in the PET analysis.

Figure 2. PET for the San Diego area overlain by the CIMIS zonal areas, CIMIS stations and RAWS stations.

Figure 3.PET versus elevation for the CIMIS, RAWS (from Durbin review), and BCM

(solpetsubmodel).

The CIMIS zone map and the CIMIS stations are in general agreement with the BCM PET estimates for the CIMIS stations as well as the CIMIS zones (fig 3). These data suggest that there is not a linear relation between elevation and PET as suggested by the reviewer. The RAWS PET estimates from the Durbin review are considerably underestimating PET relative to the State of California's state wide analysis which is in general agreement with the BCM estimate therefore we believe our estimate of PET is valid.

2.3 Uncertainty in Point Land-Surface Characterizations The land-surface characterizations include the vegetation cover density, vegetationrooting depth, and soil available water capacity. Flint et al. (2012) presumably usedas a BCM input the U. S Geological Survey (2011) vegetation mapping, or similarmapping, to assess cover type, density, and rooting depth, which was the case for aprevious BCM application (Flint et al., 2007a). For the San Diego River watershed,the U. S. Geological Survey mapping delineates general vegetation classes, such aslive oak woodland and savanna, chaparral, coastal scrub, and coastal grass land. Themapping system is such that particular classifications include broad variations in vegetationcomposition, such as the oak woodland-savanna classification, which rangesfrom closed-canopy woodlands to mostly grasslands. The diversity within that particularclassification represents different cover densities, rooting depths, and water use,which leaves the characterization at a point within the area delineated for the classificationvery uncertain. The same uncertainty exists within other vegetation classifications.Flint et al. (2012) used as a BCM input a generalized soil map produced by the NationalResources Conservation Service (2006). The map was created by generalizingmore detailed soil survey maps. Where more detailed soil survey maps were not available,data on geology, topography, vegetation, and climate were assembled. The soilsmapping was used to compile soil depth, field capacity, wilting point, porosity, and otherparameters for BCM inputs. As for the vegetation map, the soil-map classifications includesoils with different characteristics, which leaves the point characterization veryuncertain.

Response:Vegetation is not used in the BCM and is not discussed in this paper, so this comment is not relevant. This manuscript specifies that county level SSURGO maps were used in this model, unlike the STATSGO generalized maps that were used in previous models and referred to by the reviewer. The exercise of using STATSGO wherever SSURGO is unavailable was practiced for this model and the location of this is evident in Figure 3d, where there is a small square of approximately 2.5 m deep soil in the upper elevations of the watershed spanning across the divide between the San Diego River and Sweetwater River basins. Other than this small location the entire domain of the San Diego watershed is SSURGO. This dataset provides a scale of detail that is finer in most cases than our 270-m scale grids and offers estimates of hydraulic properties that are suitable for direct use by the BCM. I attribute little uncertainty in the final estimates of recharge to this input data.

2.4 Uncertainty in Watershed-Scale Recharge The uncertainty in point process can be translated into watershed-scale processesusing the variance-reduction method developed by Vanmarcke (2010). The watersheduncertainty is smaller than the point uncertainty because the point uncertaintyis smoothed in the summation from the point recharge to the watershed recharge. Themagnitude of the reduction depends on the correlation structure for the uncertainty inthe recharge estimates as described by the relations

Var[R]=(A)Var[r] (Eq. 7)

where

[A]=_/A (Eq. 8)

and_=R_A(a)da(Eq.9)

where is the variance-reduction factor, is the correlation function, and _ is the characteristicarea. These relations indicate that the variance reduction is smaller for high-

erspatial correlations. The correlation distance for the point-recharge uncertainty is probably large. A largecorrelation distance most likely characterizes the PRISM precipitation maps becauseof the geographical sparsity of station data, especially for the early years included inthe BCM simulations. A large correlation distance most likely also characterizes thegeographic distribution of potential evapotranspiration because of bias suggested bythe comparison between the BCM simulations and RAWS data. Finally, large correlationdistances apply also to the land-surface characterizations. The BCM incorporatesgeneralized rooting depth, available water capacity, and vegetation-cover density. Fora particular soil or vegetation class, the same parameter value is assigned throughoutthe BCM area. Concomitantly, errors occurring in the parameterization of a soilor vegetation class will be highly correlated across the BCM area. Assuming a linearcorrelation function for the uncertainty in the point recharge and a correlation distanceof 15 km, the variance reduction factor is 20 percent, which means that the variancefor the watershed-scale recharge is 20 percent of the variance for the point recharge.The watershed-scale uncertainty is the composite of the point recharge uncertainty fordifferent precipitation zones, which is characterized by a decrease in the coefficient ofvariation with an increase in precipitation. The result is a coefficient of variation for theSan Diego River watershed recharge of about 100 percent. The recharge estimatedby Flint et al. (2012) is 54x106 with an uncertainty of $\pm$ 54x106 m3/yr.The uncertainty in recharge estimates produced by the BCM is described by Masbruchet al. (2011) for an application to a regional groundwater system within the Great Basin,Nevada and Utah. The BCM was applied much as it was for the San Diego region.However, for the Great Basin groundwater system, estimates were available regardingdischarges from the groundwater system, which would be the equivalent to knowingthe underflow to the ocean prior to applying the BCM to the San Diego region. For theGreat Basin groundwater system, local adjustments were made to the BCM rechargeestimates to match better the recharge implied by the discharge estimates. While theBCM recharge estimates were reduced by a specified factor in some subareas, theestimates were increased in other subareas. The adjustment factors ranged from 0.20to 2.25, which indicates considerable disparity between the BCM recharge estimatesand the prior discharge estimates.

Response:It seems good news that the uncertainty in the accumulated recharge estimates can be reduced below the gridcell-based calculations. However, the uncertainty the reviewer describes is what he has based on faulty conclusions regarding the uncertainty of soil or vegetation layers as input (vegetation not used), or annual estimates of the water balance (annual time steps not used). He refers to the Masbruch et al. (2011) paper that includes an uncertainty analysis. This analysis was conducted because the BCM was used for the region using only one iteration to reduce the mismatches between measured and calculated streamflow over a huge region, and prior to the development of the equations now implemented to improve the partitioning of the accumulated recharge and runoff into basin discharge estimates for comparison to streamflow measurements. The reviewer notes that local adjustments were made to the calculated BCM recharge estimates to accommodate the occurrence of basin underflow in this very permeable carbonate dominated region, and that this is a case for error in the BCM. The BCM calculates recharge on the basis of the surface water balance and doesn't claim and has never claimed to account for subsurface flows that extend across surface hydrologicboundaries. In the San Diego model, this was not done, and the application of the post-processing equations to partition the BCMrch and run into streamflow components assumes that the spatial extent of influence does not extend across hydrologic divides.

2.5 Uncertainty in Bedrock Hydraulic Conductivity Flint et al. (2012) developed a groundwater model for the San Diego River watershedto partition the water yield between streamflow and underflow at the coast. Streamaquiferinteractions occur such that both streamflow and underflow comprise somemixture of point runoff and recharge. Using recharge and runoff generated by theBCM, the groundwater model was used to simulate streamflow at a streamgaging siteon the San Diego River near the coast. Simulations were made assuming differenthydraulic conductivity to charac-

terize the deep groundwater system. The simulationsrespectively used conductivities of 8 and 1 m/d, but the higher conductivity produceda better fit of the groundwater model to the measured streamflow. The transmissivitiescorresponding to these conductivities respectively are about 4,000 and 500 m2/d. Fromthe simulation results, Flint et al. (2012) conclude that the underflow at the coast mayequal about 40 percent of the point recharge within the San Diego River watershed, orabout 22x106 m3/yr.

The underflow at the coast depends on the hydraulic characterization of the deepgroundwater system. Different combinations of BCM recharge and groundwatermodelhydraulic conductivity can fit the streamgaging measurements with correspondinglydifferent quantities of BCM recharge and partition between streamflow and underflow.Correspondingly, the uncertainty in the recharge and partitioning is tied ultimately tothe uncertainty in the hydraulic characteristics of the deep groundwater system. Thatuncertainty unfortunately, is large. Furthermore, the hydraulic conductivities used inthe groundwater model probably are much larger than actually exists.The most extensive information on the hydraulic conductivity of the deep aquifer systemis a collection of specific-capacity tests reported by well drillers to the CaliforniaDepartment of Water Resources. About 150 wells are located within middle and upperwatershed areaswhere the crystalline rocks comprising the deep aquifer system cropout. The geometric mean of the hydraulic conductivity derived from tests on these wellis about 2x10-2 m/d, which is about two orders of magnitude less than the conductivityused in the groundwater model. Kaehler and Hsieh (1994) evaluated the hydraulicconductivity of fractured rock within a subarea of the BCM area, and they derived aconductivity of about 10-3 m/d.The specific-capacity data suggest a decay of conductivity with depth, which is similarto the findings of Page et al. (1984), Borchers (1996), and Boutt et al. (2010). Forthe San Diego region specific-capacity data, the depth decay is such that the aquifertransmissivity is 10 m2/d, which is two and three orders of magnitude smaller thanthe aquifer transmissivity used in the two separate groundwater model formulations.If the transmissivity derived from the specific-capacity tests were to be used in thegroundwater model, the BCM recharge would need to be reduced substantially in orderto fit the groundwater model to the streamgaging data, and the groundwater modelwould have simulated at least an order of magnitude less underflow at the coast.

Response:The calculation of the ratio of total calculated BCMrch + BCMrun to the reconstructed streamflow at Fashion Valley that concluded approximately 40% of the BCMrch+run becomes underflow does not include any use of the groundwater model or any of the subsurface hydraulic characterization. The intended use of the groundwater model was SOLELY to provide some confirmation on the basis of the rigorous and physically-based MODFLOW algorithms that our depiction of partitioning on the basis of the post-processing equations was valid. The uncertainties in the deep groundwater system that is currently poorly characterized may only influence the outcome of the ratio calculation in terms of what happens to the underflow once it passes Fashion Valley, or if it has variable directions of flow and doesn't actually make it to the ocean. In any case, this water is concluded to be present in the coastal plain aquifer.

3 Lack of Documentation Flint et al. (2012) do not provide a citation that adequately describes formulation of theBCM simulator. Elements of the formulation appear in Hevesi et al. (2003), Flint andFlint (2007b), and U. S. Geological Survey (2008). However, Flint et al. (2012) do notidentify where a comprehensive description of the BCM simulator can be found. TheBCM appears to have evolved from the U. S. Geological Survey simulator INFIL (U.S. Geological Survey, 2008), based on comparisons among the INFIL documentation and various BCM narratives that appear in subsequent papers and reports (Flint et al.,2001a, Flint et al., 2001b, Flint et al., 2002, Flint et al., 2004, Flint and Flint, 2007a,and Flint and Flint, 2007b). The first specific reference to the BCM is in Flint et al.(2007b), but that report contains only a diagram of the BCM structure. Subsequentpapers provide little additional information. Consequently, little information is availableto judge the adequacy of the BCM structure.

Response:The reviewer is correct, the BCM evolved from the simulator INFIL, prior to the inclusion of streamflow routing in INFILv3. The development of the BCM and subsequent refinements has been documented in numerous papers. This most recent

manuscript describes the refinement of the post-processing equations to partition the model outputs into streamflow components to facilitate calibration to streamflow. The reviewer cites several reports, omitting the report earlier referred to by Masbruch (actually, Flint, Flint, and Masbruch 2011), that describes the operation of the BCM, details all the input and output files, and describes how the model is run. There is also a paper by Thorne et al. that has recently been released that further describes the details of all the input and output files, and what it takes to operate the model. These additional reports have been added to the text in the methods section for readers to pursue if they choose to run the model. The code is freely available and archived at the California Water Science Center in Sacramento.

4 Conclusions A fundamental problem with the application of the BCM to the San Diego region is thatin a semiarid climate annual evapotranspiration nearly equals the precipitation. Uncertaintyin the evapotranspiration and precipitation is on the same order of magnitude asthe difference between those quantities. The result is an exaggerated uncertainty in therecharge estimate. A second problem with the application is that the model requirescalibration, because direct measures of model parameters are unavailable or incomplete.Correspondingly, the model development was based on generalized informationof highly uncertain specificity. Were the model to be calibrated, the calibration targetshould be the water yield from the BCM area or a subarea.The water yield of the BCM area ultimately discharges to the ocean as either streamflowsor underflow. While streamgaging data allow a reasonable estimate of thestreamflow discharge to the ocean from the San Diego River watershed, the availabledata facilitate only an order of magnitude estimate of underflow, which means thatthe water yield from the BCM area is essentially unknown, and no basis exists for amodel calibration. Nevertheless, the uncertainty in the BCM recharge estimate can beassessed by considering the essential inputs to the BCM, the sensitivity of the resultingwater-yield estimates to uncertainty in those inputs, and the uncertainty in the inputs.Such an exercise indicates that moderate uncertainty in the BCM inputs leads to largeuncertainty in the estimate of the watershed-scale recharge. The coefficient of variationof the recharge

estimate is about 100 percent, which means that the uncertaintyis of the same order of magnitude as the recharge estimate itself. This is the expectedresult of applying a soil water-budget with an arid or semiarid environment (Gee andHillel, 1988).

Response: The conclusions of the paper rely on several notions and assumptions that have been discussed in all the above comment responses. First of all, The use of water balance approaches to estimate recharge in arid and semiarid environments has been disputed in the literature over the last two decades partially in response to Gee and Hillel (1988), who reported that the volumes of recharge in arid environments were too small to measure or estimate using anything other than approaches that integrated recharge over long time periods, such as lysimetry or chloride mass balance methods. Since then, major advances have been made in the understanding of how recharge occurs in arid and semiarid environments, as described above, and discussed and scrutinized by numerous authors (Lerner et al., 1990; Hendrickx and Walker, 1997; Zhang and Walker, 1998; Kinzelbach et al., 2002; Scanlon et al., 2002; Flint et al., 2002). In addition, the BCM calibration process, which partitions the BCMrch and run into streamflow components for comparison to measured streamflow in upstream, mostly unimpaired basins, provides some confirmation that the partitioning of spatially distributed excess water into recharge and runoff due to differences in bedrock permeability are reasonable. When reconstructions of unimpaired streamflow are subtracted from the sum of the upstream spatially distributed recharge and runoff, the remainder is groundwater that didn't make it through the gage. This is a very simple notion and calculation, and we believe that the review version of the document clouded the simplicity and introduced a complexity that made the paper confusing. We believe we have rewritten the manuscript to quell the concerns of the reviewer, clarify the processes and associated uncertainties and assumptions, and make the intent of the research clear.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 9, 2717, 2012.