Development of a GIS-based model for extrapolating mesoscale groundwater recharge estimates using integrated geospatial data sets

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Abstract A geographic information systems (GIS)-based model was used to derive spatially explicit estimates of recharge using the elevation-dependent chloride mass-balance (EDCMB) approach in a 14-basin area in southwestern Nevada, USA. For each of the 14 basins, a non-linear regression equation was developed relating chloride enrichment to the elevation of spring watersheds. The ratio of chloride enrichment as a function of elevation was used in a GIS framework to transform continuous precipitation data to recharge. Spatial masks that represented two definitions of the lower limits of recharge—one definition based on alluvium/non-alluvium boundaries, the other based on both alluvium/non-alluvium boundaries and an elevation threshold—were applied to each basin. Resultant recharge estimates were then summed for each basin. When compared to summaries of previous recharge estimates for the study area, the EDCMB approach produced results that were within 14 and 3% of two studies, but were significantly greater (31%) than a third. GIS proved to be a very effective tool for combining large spatial data with widely different resolutions into an integrated data set, and also proved to be an efficient mechanism for implementing robust statistical models to estimate recharge.

Résumé Un modèle basé sur les systèmes d'informations géographiques (SIG) a été utilisé pour obtenir des estimations explicites de la recharge dans l'espace, en utilisant l'approche du bilan des chlorures en fonction de l'altitude (EDCMB en anglais) dans une zone de 14 bassins, dans le Sud-Ouest du Nevada aux Etats-Unis. Pour chacun des 14 bassins, une régression non-linéaire a été établie, reliant l'enrichissement des chlorures à l'altitude des bassins d'alimentation des sources. Le rapport d'enrichissement des chlorures en fonction de l'altitude a été utilisé dans une approche SIG pour transformer des données pluviométriques continues en terme de recharge. Des masques spatiaux représentant deux définitions des limites de recharge les plus basses ont été appliquées à chaque bassin ; l'une basée sur les limites alluvions/autres formations, l'autre sur ces mêmes limites ainsi que sur un seuil altitudinal. Les recharges estimées résultantes ont ensuite été additionnées pour chaque bassin. Comparée aux précédents bilans de recharge estimés dans la zone d'étude, l'approche EDCMB conduit à des résultats se situant entre 14 et 3% de ceux de deux autres études et largement supérieurs (31%) à ceux d'une troisième étude. Le SIG s'est révélé être un outil très efficace pour combiner dans une base de données intégrée, des données spatiales étendues avec des résolutions largement différentes, ainsi que pour implémenter des modèles statistiques conséquents permettant d'estimer la recharge.

Resumen Se utilizó un modelo basado en un Sistema de Información Geográfico (SIG) para derivar espacialmente estimados explícitos de recarga usando el enfoque de balance de masa de cloruro dependiente de elevación (EDCMB) en un área de 14 cuencas en el suroeste de Nevada, Estados Unidos. Para cada una de las 14 cuencas se desarrolló una ecuación de regresión no linear que relaciona el enriquecimiento de cloruro con la elevación de las cuencas con manantiales. La relación de enriquecimiento de cloruro en función de la elevación se usó en un marco SIG para transformar datos continuos de precipitación a recarga. Se aplicaron máscaras espaciales a cada cuenca las cuales representaron dos definiciones de los límites inferiores de recarga, una definición basada en límites de aluvión/sin aluvión, el otro basado en ambos límites aluvión/sin aluvión y una elevación normal de fondo. Los estimados resultantes de recarga fueron sumados para cada cuenca. Al compararse con estimados de recarga previos para el área de estudio se encontró que el enfoque EDCMB produjo resultados que estaban entre el 14 y 3% de dos estudios pero fueron significativamente

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mayores (31%) que un tercer estudio. El SIG ha demostrado ser una herramienta muy efectiva para combinar datos espaciales grandes con resoluciones muy distintas en un grupo integrado de datos y también ha mostrado ser un mecanismo eficiente para implementar modelos estadísticos robustos para estimar recarga.

Keywords Geographic information systems · Groundwater recharge/water budget · Statistical modeling · Chloride mass-balance

Introduction

Long-term sustainability of groundwater resources, based on estimates of the renewable water supply, is often a critical objective of proactive water management in the arid western United States. Knowing the amount of available water is essential to optimizing use while ensuring sustainability of water supplies. The renewable water supply is often approximated by estimates of average total discharge or average total recharge. Being able to quantify recharge spatially is essential for effective water management. Accurate spatial estimates of recharge support development of groundwater flow models for evaluating contaminant transport. The southwestern Nevada study area was selected so that results would provide estimates of recharge in support of groundwater flow and transport models that simulate the movement of radionuclides from underground test areas on the Nevada Test Site (NTS).

This work is based on an elevation-dependent chloride mass-balance (EDCMB) approach first developed for an original study area that included the NTS and adjacent areas in southern Nevada, but did not focus on individual basins (Russell and Minor 2002). The authors of this previous work decided to prepare two journal articles based on these results; the first article, Russell et al. (personal observations, 2006), details the development of the EDCMB approach for the original study area, including a description and review of the assumptions made in the EDCMB method, and the incorporation of parametric uncertainty in all variables using Monte-Carlo analysis. The second article, presented herein, focuses on the application of geographic information systems (GIS) data integration and modeling techniques to extrapolate the EDCMB method to an expanded 14-basin study area centered on the NTS in southern Nevada, developing specific recharge estimates for each basin.

The chloride mass balance approach utilizes annual precipitation, chloride flux, and chloride enrichment in groundwater to quantify the amount of recharge that has occurred spatially over a given area. The elevation-dependent modification determines chloride enrichment for numerous springs at various elevations in and around the study area, and develops a relationship between enrichment and elevation. Chloride enrichment, as a function of mean elevation, and precipitation, is then used to predict continuous spatial variation in recharge and sum the amount of recharge for each of 14 hydrographic basins located in the study area. Lower limits of recharge were established using both an elevation threshold and alluvium/non-alluvium geologic boundaries. For each of the 14 basins, 1,000 realizations of the non-linear regression equation, parameterized via Monte Carlo type sampling of simple parameter distributions, were run in a GIS framework, using two definitions of the lower limits of recharge. Resultant recharge estimates for each basin, for two definitions of the lower limits of recharge, were summed in $m^3\ yr^{-1}$.

The methods and analysis presented here provide an assessment of the utility of GIS for constructing and integrating data layers and performing subsequent modeling and analysis to generate spatially explicit values of recharge at mesoscales useful for resource monitoring and assessment. Results developed within the GIS framework can then be compared and contrasted to previously published recharge results for the same area and basins, providing for a semi-independent assessment of recharge calculated for the study area.

Background

Multiple studies have been conducted in the state of Nevada, through a variety of techniques, in an attempt to quantify recharge. The most commonly used recharge estimation technique is the Maxey-Eakin Method (Maxey and Eakin 1949), which utilized 21 basins in eastern Nevada from which groundwater discharge could be reasonably constrained. Uniform sets of recharge coefficients were developed for different precipitation zones in each of the 21 basins in an attempt to balance basin recharge with the estimated discharge. The total amount of precipitation occurring within each zone was summed and recharge for that zone was determined via multiplication of the summed precipitation by the appropriate recharge coefficient. Calculated recharge for each zone was then summed to determine total recharge for a given basin. Nichols (2000) conducted a similar analysis in which updated estimates of discharge were related to precipitation via calculated recharge coefficients. The study used field measurements to estimate evapotranspiration rates at five sites in Nevada and seven sites in Owens Valley, California. Data from these sites were used to develop equations relating evapotranspiration as a function of phreatophytic plant coverage and depth to groundwater. The areal coverage of phreatophytes was then mapped in 16 valleys in eastern Nevada using satellite imagery. Evapotranspiration was estimated based upon analysis of the imagery and application of the previously discussed equations. Recharge coefficients were derived through multiple linear regression of precipitation zones (Daly et al. 1994) as a function of the previously described estimates of discharge for the 16 valleys. Multiplication of the summed precipitation within each zone by the relevant recharge coefficient yielded estimates of total recharge occurring within each zone. Recharge within each zone was summed to determine total recharge within a given basin. US DOE (1997) used the Maxey Eakin coefficients along with a revised Hardman (1965) precipitation map and an algorithm for redistributing recharge along surface-water runoff channels. D'Agnese et al. (1997) modified Maxey and Eakin (1949) to make it more sensitive to critical factors affecting recharge by using potential recharge indicators and their spatial distribution. The four potential recharge indicators used were: (1) altitude, (2) slope-aspect, (3) relative rock and soil permeability, and (4) vegetation. Each class of indicators were subdivided into categories and assigned an integer value ranging from 0 to 5, with zero representing no recharge and five representing a high recharge potential. The subcategories were mapped across the area of interest, using a GIS platform, and the spatial distribution of the subcategories was evaluated. The spatial distribution of all four subcategories was reclassified into six recharge potential zones. The percentages associated with each recharge potential zone were multiplied with precipitation flux rates to determine the rate and spatial distribution of recharge.

Regardless of the estimation method employed, assessment of groundwater recharge often depends on the precise integration of spatial data such as topography, precipitation, geology, and hydraulic characteristics (Alley et al. 1999), and for this reason, GIS has proved to be a valuable tool for estimating recharge. GIS have proven to be a relatively new, powerful tool for effectively quantifying groundwater recharge (Cherkauer 2004), predicting spatial variation in potential subsurface water flux (Baker et al. 2003), and providing a geographic modeling framework for assessing groundwater potential (Murray et al. 2003). A detailed review of GIS applications in modeling hydrologic and transport processes, including the application of GIS to the modeling of non-point source pollutants in the vadose zone, can be found in Corwin and Loague (1996). This collection of papers describes how cost-effective GIS methods can be utilized to collate remotely sensed soil and landscape data and organize them at the landscape scale. GIS is shown to be useful when combined with models that simulate processes at landscape scales in order to produce spatial characterizations of interactive parameters, like precipitation and elevation, in an entire watershed. Corwin and Loague (1996) also include detailed descriptions of uncertainty analysis in regional-scale assessments of non-point source pollutants, and sensitivity analysis for regional solute transport modeling.

Study area

Groundwater recharge was assessed for 14 basins within a large region of southwestern Nevada centered on the NTS (Fig. 1). The modeling area occupies approximately 14,000 km^2. The study area lies within the Basin and Range physiographic province, and is bordered by Kawich Valley on the north and the Amargosa Valley on the south. The area lies between the Great Basin Desert and the Mojave Desert as defined by Jaeger (1957). Transitional areas between the two desert types are also present having been created by gradients in precipitation, temperature, and soils.

The study area's climate is characteristic of high deserts, with little precipitation, warm, dry summers, cold, dry winters, and large diurnal temperature ranges. Precipitation in the area is influenced by two distinct storm patterns affecting the desert climate (D'Agnese et al. 2002). Winter precipitation frequently occurs as snow, especially in the northern portions of the study area, and tends to be low in intensity and long in duration. Higher elevations commonly are covered with snow throughout the winter. Snow seldom persists for more than a few hours in the southern, lower portions of the study area. Summer rains result from localized convective thunderstorms of high intensity and short duration (Hales 1974). The mean annual precipitation over the study site ranges from 9.8 cm yr^{-1} in Amargosa Valley to 42.3 cm yr^{-1} in the Spring Mountains at the lower edge of the Indian Springs Valley basin (precipitation-elevation regressions on independent slopes model (PRISM): Climate Source PRISM version 2000). Precipitation in the study area resulting from both winter and summer events are influenced by major orographic and topographic controls, thus some of the study region receives a precipitation excess, while other areas within the 14 basins receive a precipitation deficit relative to mean annual precipitation (French 1983).

The geologic setting of the study area consists of clastic and crystalline rocks of the Middle Proterozoic to Early Cambrian; Paleozoic carbonate and clastic rocks; Mesozoic clastic, volcanic, and intrusive rocks; Pliocene fluvial, paludal, and playa sedimentary deposits; Tertiary volcanic, volcaniclastic, and sedimentary units; and alluvium and colluvium and eolian deposits of Quaternary age (Waddell 1982).

The hydrology of the 14-basin study area is a complex groundwater flow system. Although there are very few perennial stream systems in the study area, the region has been delineated on the basis of topographic divides into hydrographic basins that have been used for descriptive and summary purposes in many surface-water and groundwater studies (D'Agnese et al. 2002; Eakin et al. 1976; Winograd and Thordarson 1975). Interbasin flow controls most of the regional groundwater system. Hydraulic compartmentalization may occur throughout the study area due to the complex nature of the geology. Most groundwater recharge results from infiltration of precipitation and runoff from the higher elevations (Bedinger et al. 1989). Natural discharge is by flow to springs and by evapotranspiration (ET) in areas where the water table is near the surface. Regional groundwater flow patterns do not coincide with topographic basins, but flow generally follows the regional topographic gradient (north to south), and ultimately moves toward Amargosa Valley and on to Death Valley.

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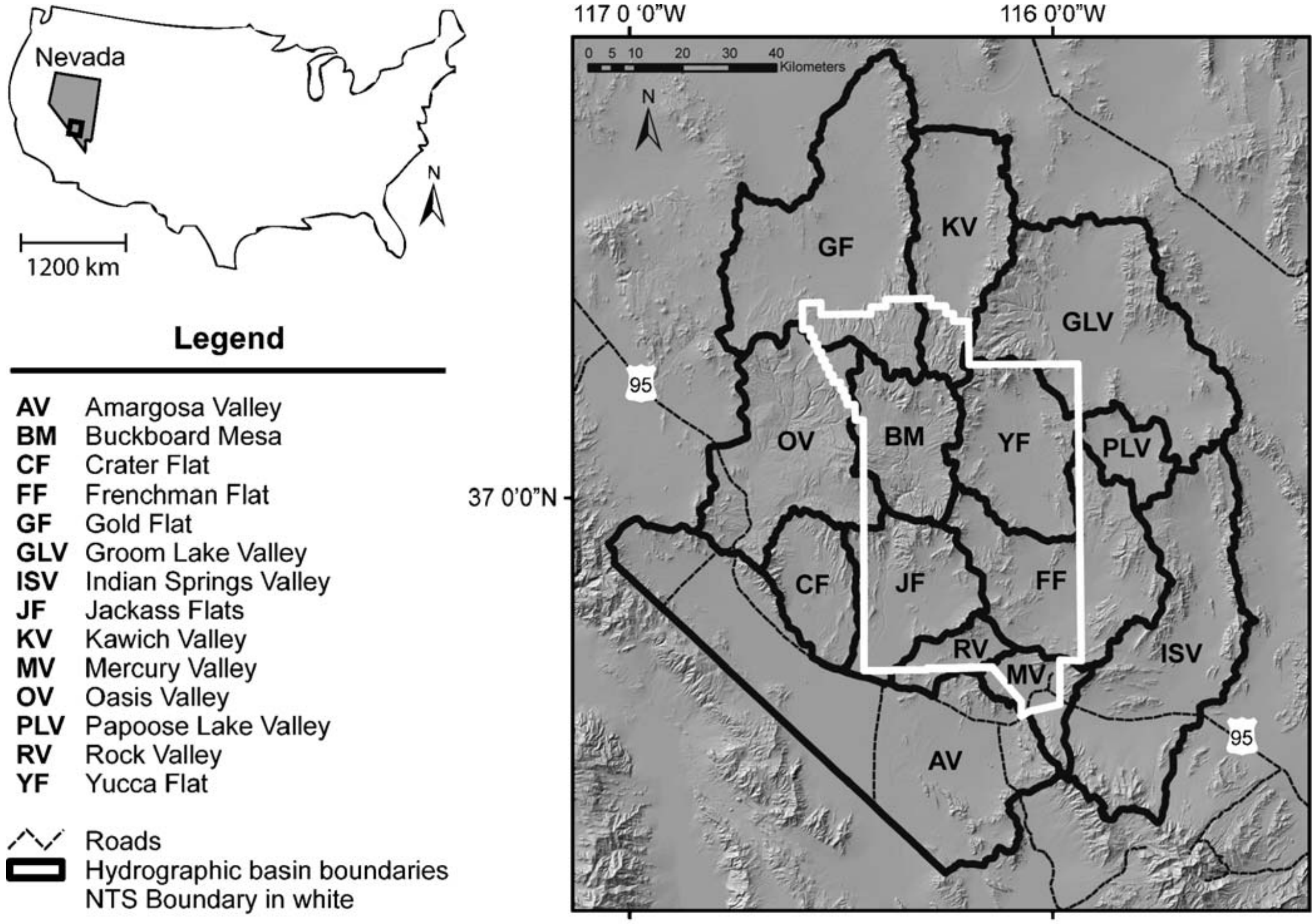

Fig. 1 Location of 14 hydrographic basin study area in southwestern Nevada, USA. Data overlaid on a *shaded relief* digital elevation model of the study area

Methods

Data acquisition and data construction

Geologic data

The geology of the study area was derived from the 1:500,000 geologic map of the state of Nevada (Stewart and Carlson 1978a). A digital version of the Stewart and Carlson state geologic map was obtained from the USGS (2003) in Arc shapefile format, and entered into a geographic information system using ArcView v3.3 software. Alluvial and non-alluvial units were reselected from the data set and converted into separate shapefiles (Fig. 2). The non-alluvial units shapefile was converted to a raster (Arc/Info GRID format) with a cell resolution of 30 m and its spatial extent was used to define the first of two alternate definitions of the lower limit of recharge in subsequent modeling steps.

Precipitation data

Precipitation studies in central Nevada are hampered by the lack of high altitude gauging stations, a lack in the overall number and distribution of stations, and a lack of lengthy records from many of the existing stations. As a result, estimates of precipitation rates and their distribution are underlain by a considerable degree of uncertainty. For this study, the PRISM model was utilized to describe the distribution of precipitation across the study area. The PRISM data set was developed from precipitation data collected from 1961 to 1999, and integrates the influence of slope, aspect and elevation. Mean monthly values for stations that had at least 27 years of data were used without modification. Data sets for those with at least 15 years but less than 27 years of data were modified by applying a least-squares fit to data from a representative nearby station, yielding a 30-year average. PRISM was run for each month and the months summed to obtain an annual estimate. The spatial resolution of the PRISM data used in this study is 2.06 km (4.24 km^2).

Elevation data

A 30-m digital elevation model (DEM) of the entire study area was developed by mosaicking individual 1° blocks of one arc second United States Geological Survey (USGS) National Elevation Dataset (NED) data into one Arc raster. The DEM was used for several applications in the study.

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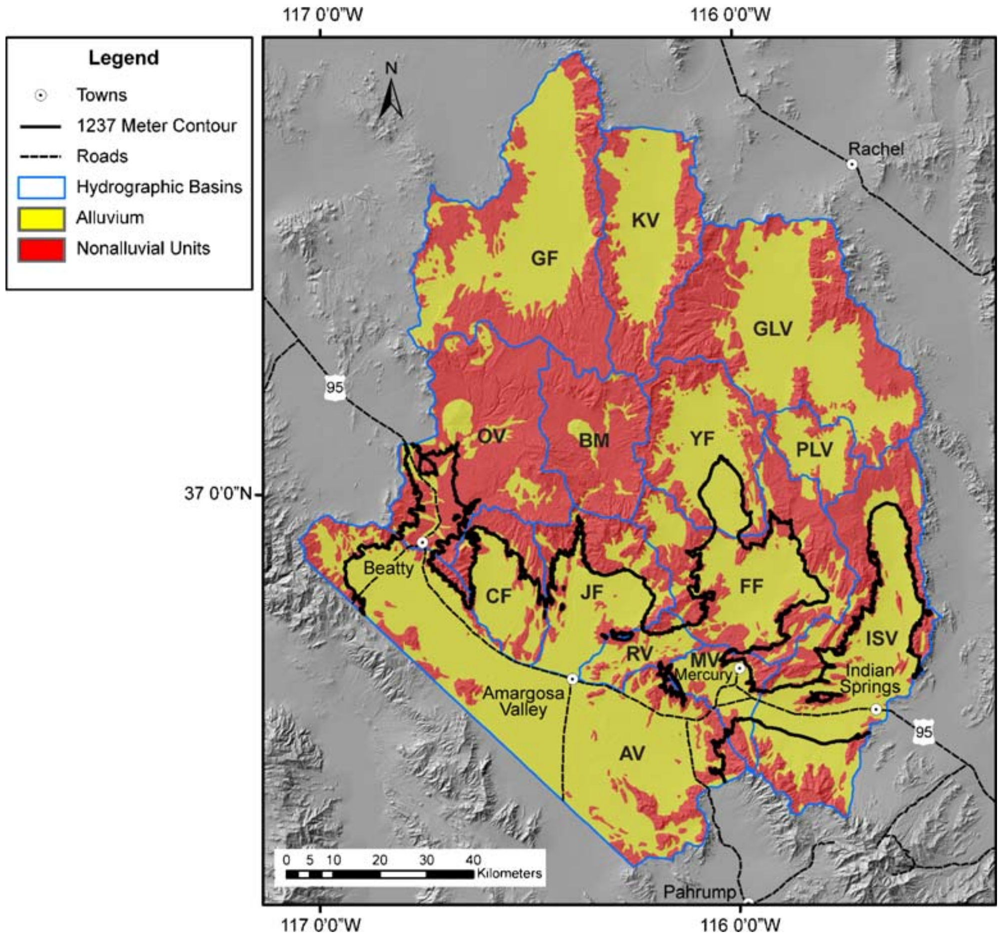

Fig. 2 Alluvium and non-alluvial rock units in the 14 basin study area, southwestern Nevada, with the 1,237-m elevation contour. Data overlaid on a *shaded relief* digital elevation model of the study area

First, area and elevation of spring catchments were derived using a multi-step process that incorporated interactive analysis of the 30-m DEM data using a GIS. Secondly, the DEM was resampled to a coarser resolution and used to define mean elevation in the spatial extrapolation of the EDCMB method to the 14-basin study area. Finally, the data set was used to identify the elevation threshold value for the second of two definitions of the lower limit of recharge (Fig. 2).

Hydrographic basins

The 1:100,000 scale USGS digital line graph (DLG) Nevada state hydrographic basin data set was used to define the 14 hydrographic basins evaluated in the southwestern Nevada study area (Fig. 1). The individual basins, with their respective areas, are listed in Table 1. The vector representations of each of the basins were reselected and converted to individual shapefiles, then converted to rasters. These raster representations of each basin were used to constrain the spatial extent of the recharge models developed using the EDCMB approach.

Spring measurements

Discharge rates, chloride and bromide concentration measurements were collected for all 17 springs within and in proximity to the 14-basin study area (Fig. 3). Springs were selected to ensure that discharge was derived from localized recharge and not from regional flow. Therefore, only non-thermal springs located on the flanks of topographic highlands were selected. A number of springs used in the analysis had to be drawn from outside the study area (see Fig. 3), due to the complete lack of springs associated with higher elevations within the study area.

Discharge rates were measured using a variety of standard techniques, primarily volumetric measurements for springs with low discharge rates and channels or orifices that facilitated such measurements. The alternative technique utilized was the velocity area method for assessing stream flow. Published measures of discharge were used to augment field-measured discharge rates for most of the 17 springs. Chloride concentrations were measured using groundwater samples collected from the

Table 1 Fourteen hydrographic basins in the study area, with area in km^2

Basin and corresponding area	
Amargosa Valley (2,334.55)	Jackass Flats (715.09)
Buckboard Mesa (613.33)	Kawich Valley (906.86)
Crater Flat (469.01)	Mercury Valley (289.18)
Frenchman Flat (1,184.01)	Oasis Valley (1,192.85)
Gold Flat (1,766.17)	Papoose Lake Valley (264.37)
Groom Lake Valley (1,698.33)	Rock Valley (211.32)
Indian Springs Valley (1,594.81)	Yucca Flat (786.19)

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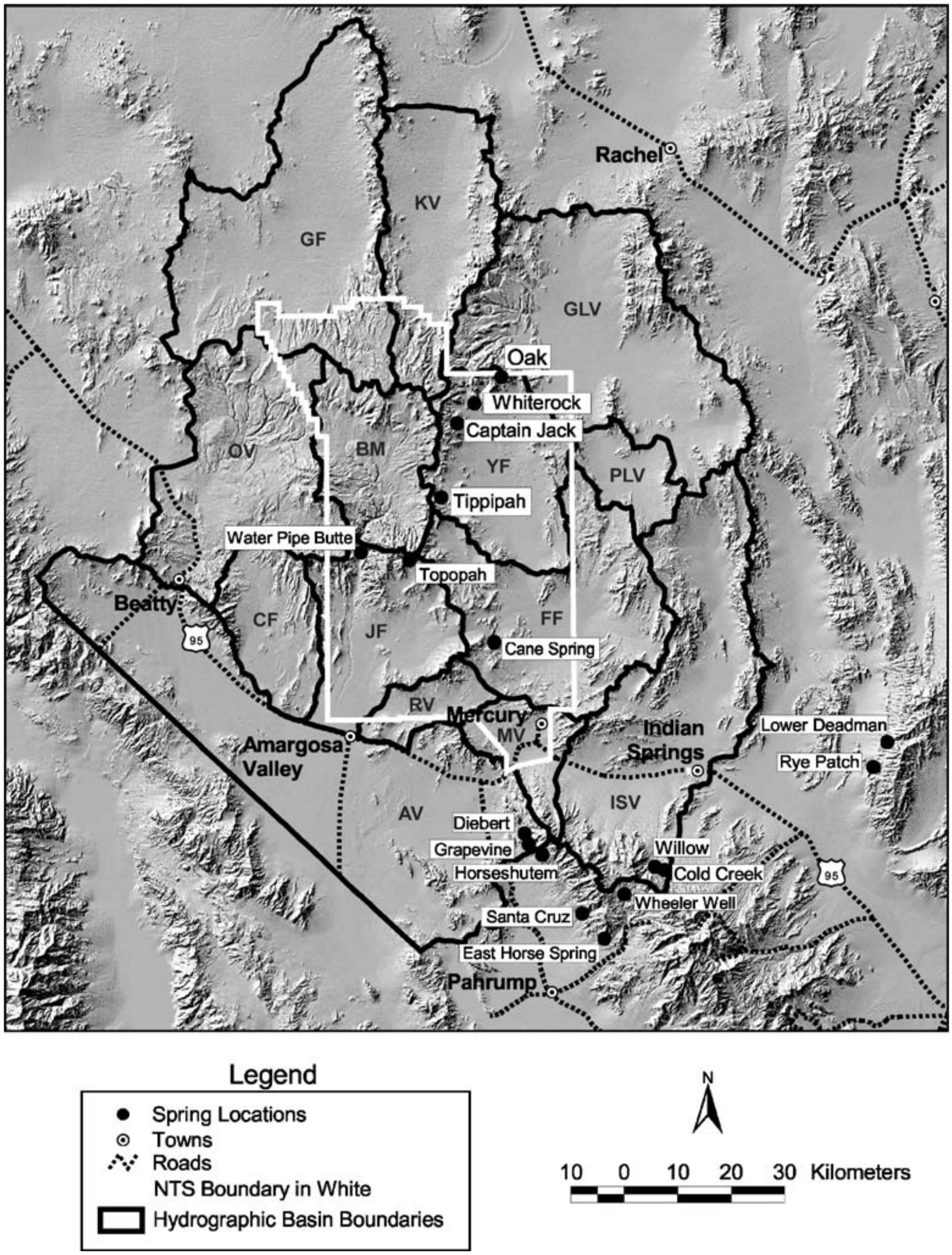

Fig. 3 Location of 17 springs used in the analysis. Data overlaid on a *shaded relief* digital elevation model of the study area

spring discharge. Bromide concentrations were collected to support analysis of authigenic contribution of chloride to the chemical signatures of groundwater.

Processing and analysis of data

GIS data integration

ArcView version 3.3 and Arc/Info Workstation version 8.3 software were used to integrate the required data sets for the study and perform the subsequent modeling and analysis of recharge parameters. Using both raster and vector modes of GIS, spring locations, hydrographic basins, DEMs, precipitation, and geology were developed as integrated spatial data layers. All data layers were converted to a common coordinate frame system, the Universal Transverse Mercator (UTM) grid system, based on the Transverse Mercator projection and the North American 1927 horizontal datum. A minimum mapping unit (MMU) of 1,000 m (1 km) was established for the study, based on an assessment of the scales of the various inputs and the mesoscale recharge output requirements.

Elevation-dependent chloride mass-balance approach applied in a GIS framework

The chloride mass-balance approach utilizes annual precipitation and chloride to estimate the amount of

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recharge per unit area, based on the assumption that the sole source of chloride is combined wet-fall and dry-fall atmospheric deposition, and the sole recipient of chloride is groundwater. The general form of the conceptual model used in the approach is defined as:

$$R = C_p \times P / C_r \tag{1}$$

where R is the mean annual recharge per unit area ($m^3\ yr^{-1}$), C_p is the spatially averaged mean annual chloride concentration in precipitation ($g\ m^{-3}$), P is the mean annual precipitation ($m^3\ yr^{-1}$), and C_r is the chloride concentration in recharged groundwater ($g\ m^{-3}$).

Several assumptions are associated with this equation (Russell et al., personal observations, 2006): measured chloride is solely from atmospheric deposition; chloride is in a mobile form and there are no significant chloride sinks; flow from other basins does not affect the sample springs; measured spring chloride concentrations are representative of mesoscale, spatially varied processes that affect recharge; and surface-water runoff from recharge areas is negligible.

Modifying the chloride mass-balance approach for elevation dependency involves the determination of chloride enrichment for springs in the study area at various elevations, calculating mean spring catchment area and elevation using knowledge of the local geology and manual interpretation of topography (utilizing DEMs). These measurements were used to develop a relationship between enrichment and elevation.

Recharge estimates were based on the chloride concentration measurements taken at the 17 springs described above. Monte Carlo sampling of the parameter distributions were used to generate 1,000 realizations of the mean elevation of each spring watershed and chloride concentrations of spring discharge for each spring (C_r), the effective concentration of chloride in precipitation (C_p), and the precipitation flux within the study area. Non-linear regression was used to develop an equation describing chloride enrichment as a function of mean elevation for each of the 17 spring watersheds. Non-linear regression of $C_{r(n,i)}/C_{p(i)}$ versus elevation, $El_{(n,i)}$, where n is an incremental counter for each of the 17 spring watersheds and i is the i^{th} regression, were obtained using the Gauss-Newton Method for non-linear regression. One thousand non-linear regression realizations were performed, with each exponential regression equation having the form

$$C_{r(n,i)} \Big/ C_{p(i)} = 1.0 + \left\{ c1_{(i)} \times e^{[c2(i)\,El(n,i)]} \right\} \tag{2}$$

where $c1_{(i)}$ and $c2_{(i)}$ are regression coefficients for i^{th} regression.

Equation (2) was then used to spatially extrapolate the relationship of C_r/C_p as a function of mean elevation to all 14 basins in the study area using resampled values (1 km^2 cells) of elevation derived from the NED DEM data described above. Realization-specific estimates of precipitation flux—PRISM precipitation data modified by a precipitation multiplier ($Pmult_{(i)}$)—were divided by the realization and elevation specific interpolated values of $C_{r(n,i)}/C_{p(i)}$, resulting in 1,000 estimates of recharge for each hydrographic basin. This algorithm was implemented in Arc Macro Language (AML), Arc/Info Workstation version 8.3, where the cell by cell recharge for a given hydrographic basin was calculated with the equation

$$\text{Recharge}_{(x,y,i)} = \{[P_{(prism,x,y)} \times \text{Pmult}_{(i)}] / [1.0 + (c1_{(i)} \times e^{[c2(i)\,El(x,y)]})]\} \times K \tag{3}$$

where $\text{Recharge}_{(x,y,i)}$ is the mean annual recharge flux ($m^3\ yr^{-1}$) to an individual model cell with coordinate pair x,y for a single realization i, $P_{(prism,\ x,y)}$ is the mean annual precipitation flux for an individual cell of the PRISM precipitation model ($mm\ yr^{-1}$), $Pmult_{(i)}$ is the precipitation multiplier, $El_{(x,y)}$ is the NED DEM resampled elevation value for an individual cell (m), and K is a factor for converting the base PRISM precipitation data ($mm\ yr^{-1}$ for a 1 km^2 area) to units of $m^3\ yr^{-1}$.

Total recharge for a given realization was determined by

$$\text{TotalRecharge}_{(i)} = \Sigma \text{Recharge}_{(x,y,i)} \tag{4}$$

where $\text{TotalRecharge}_{(i)}$ is the summed mean annual recharge flux ($m^3\ yr^{-1}$) for a given basin for a single realization.

Recharge for each of the 14 basins, for all 1,000 realizations, was calculated using masking functions in the AML code that only performed the evaluation of the equations in areas defined by the mask definition. Two variations of masks were used to calculate the recharge for each basin based on two definitions of the lower limit of recharge for the study area. Each of the hydrographic basin raster representations that were constructed was modified by one of two masks that defined these lower limits.

The first definition of the lower limit was the boundary between alluvium and non-alluvium geologic units. This assumption is based on an analysis of 33 soil chloride profiles obtained from vegetated alluvial formations (Russell and Minor 2002) that indicated that alluvial soils within the original study area incurred little or no recharge. In this definition all alluvium was excluded from the analysis by using the raster representation of all non-alluvium geologic units as a mask.

The second definition of the lower limit of recharge included both the non-alluvial mask and an elevation threshold. The use of an elevation threshold to further define the lower limit of recharge is based on observed climatic and hydrologic processes in the 14-basin study area; recharge rates in the lower elevations of these basins are negligible due to the relatively small amount of precipitation received, coupled with high rates of evapotranspiration. This second definition extended the first and

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is based on an elevation threshold of 1,237 m because this is the elevation of the lowest spring used in the study that is fed by local precipitation. In this definition, all alluvium and any DEM cells found below the 1,237-m-elevation threshold were excluded from analysis. A total of 28 alluvium and non-alluvium elevation masks were created for the 14 hydrographic basins; the GIS model was run 1,000 times for each of the 28 conditions.

For each realization and each lower limit condition for each basin, a raster was created with cells representing annual recharge flux. Each of these rasters, in turn, was summed and the resulting values were exported to ASCII text files containing the 1,000 summed total recharge values for each of the 28 conditions. These operations were performed using an AML routine in Arc/Info Workstation version 8.3.

The 1,000 realizations run on each individual basin were used to generate a recharge mean and variance for each watershed. The two parameters were used, in conjunction with the integral that describes the probability of the standard normal distribution, to determine the 5th, 50th, and 95th percentile recharge rates for each basin. Subsequent examination of the 1,000 realizations for each basin identified the three cases that generated the amount of recharge closest to these probabilities. The total recharge for the three cases, for each hydrologic basin, for both of the lower limits of recharge, was recorded. Thus a set of 84 rasters was created (three percentile distributions × two lower limits of recharge × 14 hydrographic basins = 84 raster representations) in Arc/Info Grid format. These rasters were subsequently converted to x, y, z ASCII files, where the x and y coordinates, respectively, are the UTM eastings and northings for each cell center point in the raster, and the z value is the calculated recharge for each cell.

Results

Individual results for all 14 basins in the study, applying the 1,000 non-linear regression equations (Eqs. 2 and 3) in a GIS-based framework using continuous grids of precipitation and elevation with a spatial extent defined by the boundary between alluvium and non-alluvium geologic units, yielded the estimates of recharge presented in Table 2. Table 2 displays the minimum, maximum, mean, and standard deviation estimates of recharge in $m^3\ yr^{-1}$ for each of the 14 basins. Table 3 presents the results of the GIS-based model runs for the 1,000 realizations using the spatial extent defined by the second definition of the lower limit of recharge, i.e. both the alluvium/non-alluvium boundary and the 1,237-m-elevation threshold.

Figure 4 shows a graphical representation of one of the results, the spatial extent of recharge estimates ($m^3\ yr^{-1}\ km^{-2}$) for all 14 basins using the realization for each basin that is closest to the 50th percentile (mean), calculated by Monte Carlo simulation using 1,000 realizations, and constrained by the first lower limit of recharge, the alluvium/non-alluvium boundary. The recharge raster for all basins in the study area was created by mosaicking the 14 individual basin recharge rasters in ArcView version 3.3, using a cell size of 1,000 m. Figure 4 shows that the greatest recharge estimates can be found in the higher elevations, i.e., the Belted Range, the Groom Range south of Rachel, the northern edge of the Spring Mountains, the Kawich Range, and on Pahute Mesa. Figure 4 also shows those regions in the study area where no recharge was calculated (areas where no color is present indicates no recharge).

Discussion

Comparison of Tables 2 and 3 indicate that regardless of which definition of the lower limit of recharge was applied in the GIS modeling process, the same two basins, Gold Flat and Groom Lake Valley, yielded the greatest amount of estimated recharge, with means of 8,350,311 and 7,375,170 $m^3\ yr^{-1}$, respectively. Both of these basins have relatively higher mean elevations (1,759 and 1,637 m, respectively, second and fourth highest) than the rest of the basins in the study, and are two of the larger

Table 2 Minimum, maximum, mean, and standard deviation recharge ($m^3\ yr^{-1}$) to each of the 14 basins in the study area by Monte Carlo analysis of the elevation-dependent chloride mass-balance method, based on the boundary between alluvium and non-alluvium geologic units as the definition of the lower limit of recharge

Basins	Minimum	Maximum	Mean	Standard deviation
Amargosa Valley	323,274.47	2,601,764.39	1,250,591.68	306,148.60
Buckboard Mesa	1,486,263.15	14,031,935.09	5,951,377.32	1,647,735.62
Crater Flat	152,222.76	1,254,267.76	661,380.33	161,659.84
Frenchman Flat	662,637.32	4,340,734.36	2,506,157.89	575,306.95
Gold Flat	1,716,632.22	24,054,599.56	8,350,311.94	2,712,377.08
Groom Lake Valley	1,755,116.46	19,096,672.37	7,375,170.04	2,170,467.44
Indian Springs Valley	1,550,140.81	12,025,775.51	5,012,961.32	1,320,109.69
Jackass Flats	498,445.46	2,376,198.70	1,425,884.31	310,003.28
Kawich Valley	901,608.99	17,139,995	5,176,132.28	1,892,605.11
Mercury Valley	160,487.99	812,707.53	480,635.89	105,195.49
Oasis Valley	2,139,285.80	10,515,870.63	6,148,923.54	1,387,843.10
Papoose Lake Valley	183,960.87	918,899.21	552,772.02	121,551.66
Rock Valley	34,263.66	437,022.88	193,175.18	54,620.55
Yucca Flat	740,423.40	4,950,778.53	2,464,923.19	606,753.97

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Table 3 Minimum, maximum, mean, and standard deviation recharge ($m^3\ yr^{-1}$) to each of the 14 basins in the study area by Monte Carlo analysis of the elevation-dependent chloride mass-balance method, based on the boundary between alluvium and non-alluvium geologic units and the 1,237-m-elevation threshold as the definition of the lower limit of recharge

Basins	Minimum	Maximum	Mean	Standard deviation
Amargosa Valley	274,630.41	1,226,612.08	743,101.16	162,339.76
Buckboard Mesa	1,486,263.15	14,031,935.09	5,951,377.32	1,647,735.62
Crater Flat	139,079.39	937,511.23	540,298.88	124,577.47
Frenchman Flat	628,073.93	3,811,361.01	2,224,178.48	498,412.28
Gold Flat	1,716,632.22	24,054,599.56	8,350,311.94	2,712,377.08
Groom Lake Valley	1,755,116.46	19,096,672.37	7,375,170.04	2,170,467.44
Indian Springs Valley	1,353,817.11	11,961,246.99	4,771,832.41	1,314,442.99
Jackass Flats	484,361.67	2,143,281.24	1,302,535.68	285,644.45
Kawich Valley	901,608.99	17,139,995	5,176,132.28	1,892,605.11
Mercury Valley	140,368.49	606,231.68	370,735.84	81,585.43
Oasis Valley	1,918,253.14	10,255,045.36	5,860,156.06	1,348,639.53
Papoose Lake Valley	183,960.87	918,899.21	552,772.02	121,551.66
Rock Valley	23,588.53	165,419.70	94,936.76	22,150.23
Yucca Flat	733,918.66	4,947,314.35	2,455,943.87	605,977.16

basins in the study by area (second and third largest, respectively). Comparing the two tables again, the most pronounced differences in recharge estimates between the two definitions are found in lowering-lying basins, where the application of the alternative definition of the lower limit of recharge can significantly reduce the amount of recharge in a basin. For example, Rock Valley and Amargosa Valley recharge estimates are reduced 49 and 59%, respectively, when constrained by the alluvium/non-alluvium-elevation threshold definition of the lower limit of recharge versus the alluvium/non-alluvium only lower limit. Not surprisingly, Amargosa Valley and Rock Valley are the two lowest basins in the study area, with mean elevations of 906 and 1,088 m, respectively.

The basin recharge estimates developed in this study were compared to three previous estimates of recharge:

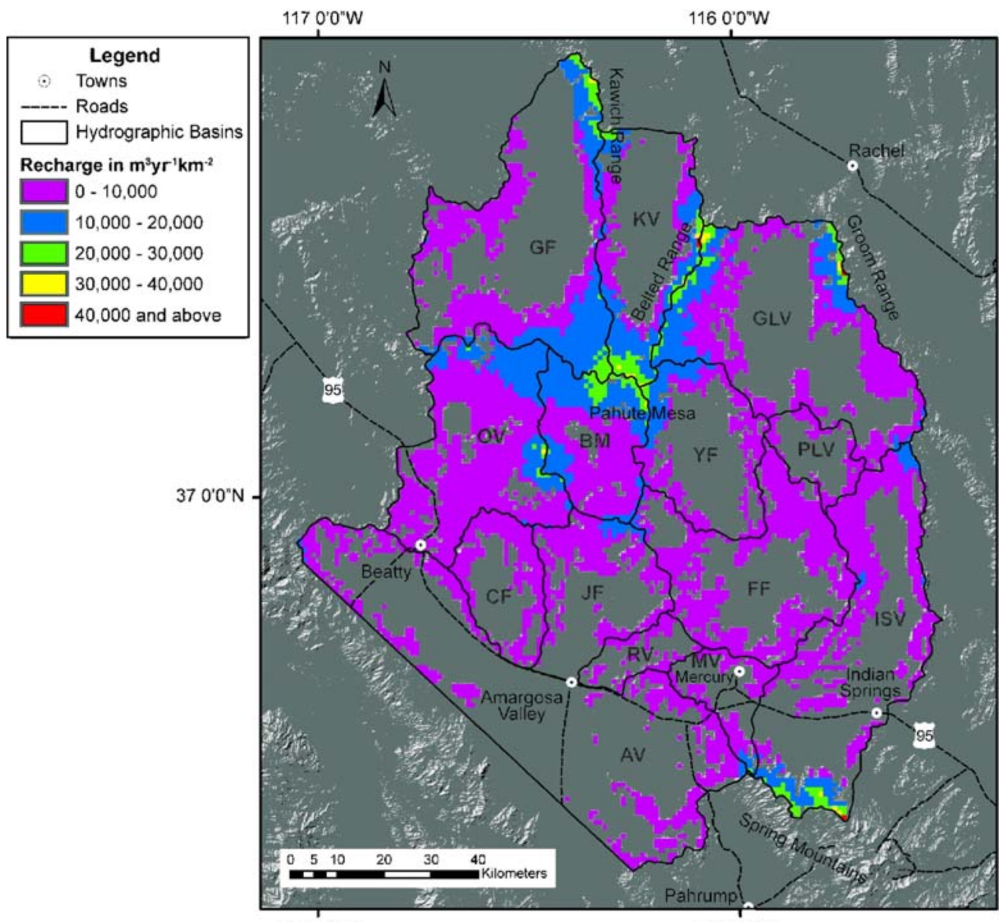

Fig. 4 Combined recharge results for all 14 basins, in $m^3\ yr^{-1}\ km^{-2}$, using the 50th percentile estimate based on the first definition of the lower limit of recharge, the alluvium/non-alluvium boundary. Data overlaid on a *shaded relief* digital elevation model of the study area (areas where no color is present indicates no recharge)

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The Maxey and Eakin (1949) estimates—these estimates were derived from several variations of the original Maxey and Eakin (1949) calculations, including those published by Rush (1970), and were compiled and tabulated in LVVWD (1997)—the D'Agnese et al. (1997) estimates, and those estimates calculated by US DOE (1997). Table 4 tabulates these previous estimates and the 5th, 50th and 95th percentile distributions of recharge calculated with the EDCMB approach using the two definitions of the lower limit of recharge. The Amargosa Valley basin is not included in Table 4 because the EDCMB estimates were only calculated for the Nevada side of the basin, due to the spatial constraints of the Nevada geology data layer used in the study. The three previous estimates are incomplete for three of the basins in the current study area: Buckboard Mesa, Papoose Lake Valley, and Rock Valley. In all three previous studies, Papoose Lake Valley estimates were included in the Groom Lake Valley estimates, Buckboard Mesa estimates were included in the Jackass Flat calculations, and the Rock Valley estimates were included in the Mercury Valley calculations.

The 50th percentile EDCMB results using the second definition of the lower limit of recharge are much greater than those estimates derived using the Maxey and Eakin (1949) method (31% greater), but are much closer in agreement with the D'Agnese et al. (1997; 14% less) and US DOE (1997) results (3% greater). The greater discrepancy between the EDCMB estimates and Maxey and Eakin (1949) estimates may be explained in part by the differences in how the elevation-precipitation relationship was calculated in the two methods. In the extrapolated EDCMB approach utilized in this study, the elevation-precipitation relationship utilized was consistent across all 14 basins in the study area. In the Rush (1970) variation of the Maxey and Eakin (1949) method, which contributed to the recharge estimates reported in LVVWD (1997), several different elevation-precipitation relationships were established for individual basins in the study area. The use of lower elevation-precipitation relationships in some basins like Groom Lake Valley may have contributed to an overall lower estimate of recharge for the entire area.

The range in recharge estimate given in Tables 2 and 3 appear to be quite large as are the associated standard deviations. In perspective, inter-model standard deviations (based on recharge estimates from Maxey and Eakin 1949; D'Agnese et al. 1997; US DOE 1997; and either of the two EDCMB models) are, in the majority of cases, larger than the standard deviations associated with the EDCMB models. The EDCMB models incorporate full uncertainty in the input parameters. The other models are deterministic models. The range in uncertainty associated with an inter-model comparison is greater than that associated with either of the two EDCMB models. This comparison reveals that the range in recharge estimates predicted by the EDCMB model fall well within the uncertainty associated with previously published recharge estimates.

Figure 5 graphically compares results for 10 basins in the study area for the three previous estimates and the results from the EDCMB approach using the 50th

Table 4 Comparison of recharge estimates derived from the elevation-dependent chloride mass-balance approach to previously determined estimates of recharge for basins in the study area. Values are in $\times 10^6 m^3 yr^{-1}$

Hydrographic basin	Maxey and Eakin (1949)[a]	D'Agnese et al. (1997)	US DOE (1997)	Elevation-dependent chloride mass-balance (EDCMB)					
				5%[e]	50%[e]	95%[e]	5%[f]	50%[f]	95%[f]
Buckboard Mesa				3.24	5.96	8.66	3.24	5.95	8.66
Crater Flat	0.27	0.15	0.98	0.40	0.66	0.93	0.34	0.54	0.75
Frenchman Flat	0.12	1.21	0.63	1.56	2.51	3.45	1.40	2.22	3.04
Gold Flat	4.69	8.18	5.04	3.89	8.35	12.81	3.89	8.35	12.81
Groom Lake Valley	4.00[b]	16.03[b]	9.81[b]	3.81	7.38	10.95	3.81	7.38	10.95
Indian Springs Valley	12.33	10.08	6.65	2.84	5.01	7.18	2.61	4.77	6.93
Jackass Flat	2.81[c]	0.84[c]	4.75[c]	0.92	1.43	1.94	0.83	1.30	1.77
Kawich Valley	4.32	9.31	8.35	2.06	5.18	8.29	2.06	5.18	8.29
Mercury Valley	0.35[d]	0.47[d]	0.03[d]	0.31	0.48	0.65	0.24	0.37	0.50
Oasis Valley	1.23	3.76	4.37	3.87	6.15	8.43	3.64	5.87	8.08
Papoose Lake Valley				0.35	0.55	0.75	0.35	0.55	0.75
Rock Valley				0.10	0.19	0.28	0.06	0.09	0.13
Yucca Flat	0.86	2.30	2.96	1.47	2.46	3.46	1.46	2.46	3.45
Summary	30.98	52.33	43.57	24.82	46.31	67.78	23.93	45.03	66.11

[a] As compiled in LVVWD (1997)

[b] Includes Papoose Lake Valley estimates

[c] Includes Buckboard Mesa estimates

[d] Includes Rock Valley estimates

[e] Alluvium/non-alluvium boundary defines the lower limit of recharge.

[f] Alluvium/non-alluvium boundary and 1,237-m-elevation threshold defines the lower limit of recharge.

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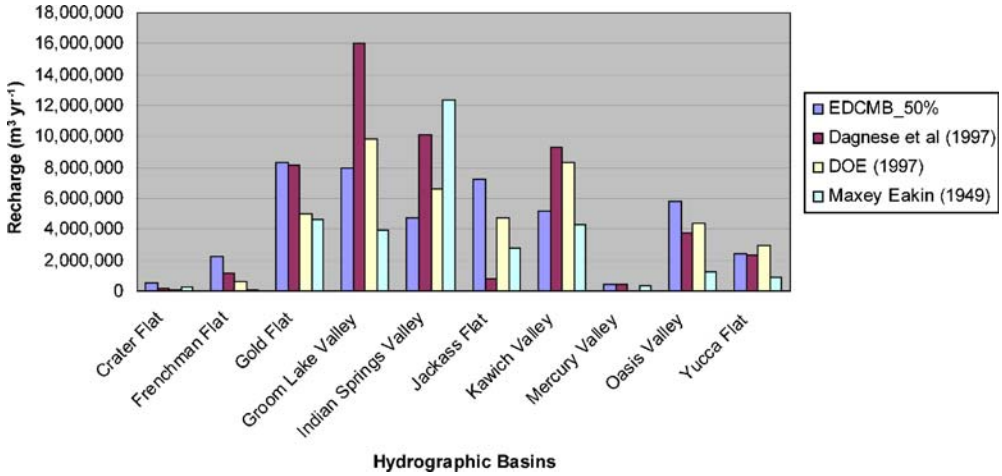

Fig. 5 Comparison of summarized recharge estimates from previous studies (Maxey and Eakin 1949; D'Agnese et al. 1997; US DOE 1997) and the EDCMB approach using the 50th percentile and the second definition of the lower limit of recharge, for 10 hydrographic basins in the study area

percentile and the second definition of the lower limit of recharge, both the alluvium/non-alluvium boundary and the 1,237 m elevation threshold. The EDCMB estimates for Groom Lake Valley, Jackass Flat, and Mercury Valley were properly adjusted so that a meaningful comparison could be made with the basin estimates from the previous studies. For most of the basins, the EDCMB approach produced results that were in close agreement with the previous studies, the greatest differences being in Groom Lake Valley, Indian Springs Valley, Jackass Flat, and Kawich Valley. This could be explained, in part, by the locations of the spring calibration sites from the Russell et al. (personal observations, 2006) original study area, which were used in this study to extrapolate the EDCMB approach to the expanded 14 basin study area. The original study area was much smaller and centered closer to the south, thus the locational bias of the spring calibration sites. The use of these springs probably led to underestimates in the amount of recharge calculated for basins in the northern portion of the expanded study area. Estimates for the northern basins would have been more accurate given available spring calibration sites in the north, but collection of new spring data in these areas was not feasible in the current study. The lower EDCMB estimates in the four basins could also be explained by the different precipitation models used in each study; the EDCMB, D'Agnese et al. (1997), and US DOE (1997) approaches all used different interpretations or variations of the PRISM model, whereas the Maxey and Eakin (1949) method used a modified Hardman (1965) precipitation model.

Russell et al. (personal observations, 2006) performed a sensitivity analysis of the EDCMB approach and determined that the model was most sensitive to chloride chemistry of the springs, followed by the area-weighted precipitation, the spring watershed elevations, and the effective chloride concentration in precipitation. With respect to data quality issues and the application of spatial data sets with large differences in spatial resolutions, results must be analyzed with the awareness that resampling of spatial data to fit a MMU such as the PRISM and DEM data in this study, will lead to errors in the model results. Sensitivity to potential data quality issues such as interpolation techniques used to develop the PRISM and USGS DEM data must be maintained when evaluating the accuracy of spatially explicit models.

When applying a spatially continuous model in a GIS framework using integrated data sets with different spatial resolutions, it is critical when determining the MMU and performing the subsequent masking and modeling that the spatial extent be explicitly defined with a fixed set of boundary coordinates. This is especially true when combining spatial data sets with large differences in cell resolution, as in this study where relatively coarse PRISM cells (2.06 km) were being integrated with 30-m DEM cells and raster masks were being developed from relatively detailed geologic polygon boundaries. The initial registration of data sets and the determination of the extent and size of the masks, if not performed properly, will propagate serious spatial errors that will eventually create inaccurate results. In this study, it was imperative that the individual masks for each basin be constructed based on the same MMU and the same spatial extent for the entire study area, that way the basin rasters would fit together much like a puzzle. If this had not been done correctly, subsequent recharge estimates calculated for each basin could have possibly included cells found in adjacent basins, leading to overestimation errors in the recharge calculations for each basin and for the entire 14-basin study area.

GIS provided a useful set of tools for rapidly integrating spatial data sets for a relatively large area, providing a capability to overlay and integrate vector and raster data at a wide range of scales. The GIS framework developed in this study facilitated the use of large, continuous data sets, in real and integer format, as variables in a significant number of non-linear regression equations combined with numerical coefficients. Macro language tools facilitated the rapid generation of the regression results, as well as the summation of recharge estimates for each of the 1,000 realizations for each of the 14 basins, for two different spatial constraints (two definitions of the lower limit of recharge). A large number of rasters representing the spatial distribution of recharge

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across each of the 14 basins in the study area were quickly produced using GIS.

Conclusions

A GIS-based model was successfully developed to estimate spatially explicit estimates of recharge using the elevation-dependent chloride mass-balance approach. This approach was based on precipitation, elevation and recharge water chemistry from an original study (Russell et al., personal observations, 2006), extrapolated to an expanded 14 hydrographic basin study area in southwestern Nevada. Spatially continuous raster data sets of precipitation and elevation and discrete vector representations of geology were converted and integrated in a GIS framework to facilitate modeling of 1,000 realizations of a non-linear regression equation developed using a Monte Carlo simulation. Recharge estimates were calculated as spatially continuous raster data sets, then total recharge was summed for each hydrographic basin in the study area. The raster data sets for each individual basin were then combined to show the spatial distribution of recharge estimates across the entire study area. When compared to summaries of previous estimates for the entire study area, the EDCMB approach produced estimates of recharge flux that were in close agreement with two studies, but were significantly greater than a third. The differences with the third estimate, recharge calculated using the Maxey and Eakin (1949) method, may be due to differences in the modeling parameters used in the respective approaches, specifically the elevation-precipitation relationship. When individual basins in the study area were evaluated, the EDCMB results were in close agreement with the previous studies in seven of ten basins evaluated.

In this study, GIS proved to be a very effective, efficient tool for combining spatial data at widely different scales into an integrated data set, and it provided the mechanism for implementing robust statistical models to estimate recharge. Spatially explicit recharge estimates are critical for supporting groundwater flow and transport models, and can prove valuable for contaminant transport analysis and groundwater assessments related to development of potential water supplies in arid environments.

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