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Full Length Research Paper

Evaluation of mountain-front recharge estimation techniques for Southern New Mexico basins

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Technically sound water management practices in arid to semi-arid regions require effective quantification of model input parameters. Mountain-front recharge is one of the most uncertain parameters in groundwater flow models due to the complexity of estimation. This paper evaluated three mountain-front recharge estimation techniques using a numerical model developed for the Southern Jornada Del Muerto Basin, New Mexico. Digital elevation model (DEM) and distributed precipitation maps were used to delineate recharge zones in the study area on geographic information system (GIS) platform. Statistical and residual parameters were used to assess the reliability of the calibrated recharge. An estimated annual recharge of about 3,360 enters the basin through ephemeral streams. Simulated heads from the three estimation techniques had approximately equal mean, with different variance. Analysis of variance on the simulated piezometric heads revealed that all the three empirical methods were consistent with the observed data. Waltemeyer equation proved to be more efficient in estimating mountain-front recharge as it gave the closest match between the observed and simulated piezometric heads and other basin-specific climatic characteristics.

Key words: Mountain-front recharge, numerical model, Southern Jornada Del Muerto Basin, GIS.

INTRODUCTION

Reliable and accurate estimation of groundwater recharge in southwest United States is a challenging task due to complexities in measuring the extremely low fluxes which highly vary in time and space. Variations in topography, geology, geomorphology, and magnitude and form of precipitation also make recharge flux one of the most uncertain parameters of groundwater flow models in the region (Scanlon, 2004). Mountain-front recharge (MFR) is the process of aquifer recharge through infiltration of surface flow from streams with headwaters in mountains (Anderholm, 2001). Common water balance approaches used in estimating the recharge flux may not be so practicable in arid regions as most of the input and output parameters fall within the measurement errors (Flint et al., 2004). The Chloride balance method produces low recharge estimates in this region probably due to the presence of additional chlorides in the unsaturated and groundwater zones, and lengthy travel times resulting from the large sized drainage basins (Anderholm, 2001). Hence groundwater flow models developed for southern New Mexico basins rely on empirical techniques to estimate recharge fluxes that are originally derived for similar catchments. However, uncertainties in the estimated recharge fluxes have not been quantified in most of the modeling works due to: i) a very low magnitude of recharge compared to other fluxes and ii) the absence of calibration targets near the recharge zones. Hence selection of proper method for estimating recharge flux is vital for the effective simulation of groundwater availability in the region.

In the present study, MFR and other fluxes in the Southern Jornada Del Muerto (SJDM) Basin were assessed using a numerical model. Geographic information system

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(GIS) tools were used to process and analyze the geologic, hydraulic and storage characteristics of the basin. The model simulation was done on a seasonal basis from 1968 through 2007 using distributed recharge fluxes in proportion to precipitation. The model was calibrated against static monitoring well data from which basis, the hydraulic and storage characteristics of the basin were updated. The calibrated model was then tested with three empirical estimates of MFR so as to: i) select a method that best reflects the basin characteristics based on residual statistical analysis and ii) estimate sub-zone-based recharge distribution in the SJDM Basin.

STUDY AREA

Jornada Del Muerto Basin is in the northern portion of the Chihuahuan Desert, in the highlands of the basin and range province of Mexico (Hawley, 1975). The parallel north-south mountain ranges are separated by broad valleys, filled with alluvial deposits. The local climate is characterized by high solar radiation, large variations in diurnal temperature, low relative humidity, extremely variable precipitation, and high potential evapotranspiration. The study area is limited to southern part of the Jornada Del Muerto Basin existing within Doña Ana County, New Mexico. The study area is limited on the north by the point of rocks (POR) in that region. The hydrogeology to the north of POR is poorly understood (Hawley and Kennedy, 2004). There is also relatively less human activity and water used in this region. The aerial extent of study area and of the model domain is 576 mi^2 or 1,492 km^2 (Figure 1). In 2007, the SJDM Basin was reported an annual yield of 8,000 ac-ft (9.878×10^6 m^3). It is therefore a potentially important groundwater source for Las Cruces city (LCC).

The SJDM Basin is characterized by the Santa Fe group deposit. This deposit is generally divided into three stratigraphic units on the basis of lithology, depositional environment and age (Hawley and Kennedy, 2004). The lower Santa Fe (LSF) unit consists primarily of fine-grained and partly consolidated sediments. The middle Santa Fe (MSF) unit consists of clean fluvial eolian sand, interbedded with silty clay on the basin floor. The upper Santa Fe (USF) consists of sand and gravel deposits from the ancestral Rio Grande River. This deposit forms the most productive aquifer system in the Santa Fe sequence.

MATERIALS AND METHODS

Model design

A three layer conceptual groundwater flow model that was developed for the study area is used in the present study (Kambhammettu et al., 2010). A digital elevation model (DEM) was used to delineate study area and the hydrogeologic boundaries on GIS platform. Using spatial and geostatistical analyst tools of GIS, continuous surfaces of hydrologic and storage properties of the study area were generated from the measured values. To account for the geologic faults, the elevation profile of each layer was manually mapped from the scanned contours. The initial water table profile was based on 1968 water table elevation data derived from 51 monitoring wells (King et al., 1971; Wilson et al., 1981). Pumping from domestic, stock and multi-utility wells, mountain-front recharge, and shallow groundwater evapotranspiration were modeled as head dependant boundary condition. All GIS files were projected into New Mexico State Plane Central FIPS coordinate system on North American Datum (NAD, 1983). The model was grided into 180 rows and 105 columns at a uniform cell size of 402.3 m. The model was run for 1968 through 2007 in 79 stress periods. The model grid was oriented at 24° in counter clockwise direction to optimize the number of active cells and to align the grids with the general flow direction in the Rincon-Mesilla Basin. The model was calibrated by comparing the simulated groundwater head with piezometric data from 72 monitoring wells.

Sensitivity analysis showed that the model was sensitive to hydraulic conductivity in the upper unconfined aquifer and to storativity in the central, eastern and north-eastern regions of the confined aquifer.

Empirical methods

The three empirical methods used in the present study to estimate the mountain-front recharge fluxes based on spatially distributed precipitation fluxes are: Maxey-Eakin (1949), Hearne-Dewey (1988), and Waltemeyer (1993). Average monthly precipitation was obtained from the Oregon State University's Parameter-elevation Regressions on Independent Slopes Model (PRISM) data. ArcHydro tool in GIS was used to delineate the sub-basins from a 30-m DEM of the region. The area outside the model boundary and up to the groundwater divide was divided into several sub-basins with designated areas. These sub-basins were intersected with precipitation and slope maps, resulting in multiple sub-polygons within each recharge zone with designated recharge parameters.

Maxey-Eakin method

Maxey-Eakin (1949) developed a method for estimating precipitation recharge based on water balance studies in many river basins in Nevada. After adjusting for surface runoff and evapotranspiration losses, recharge along the model boundary was estimated as a function of precipitation:

$$P_e = P \times C_{me} \qquad (1)$$

Where P_e is average annual recharge depth; P is average annual precipitation depth; and C_{me} is Maxey-Eakin coefficient, which is exclusively a function of annual precipitation.

Hearne-Dewey method

Hearne-Dewey (1988) developed a regression equation based on data from 16 basins in northern New Mexico. This method assumes that aquifer recharge occurs through ephemeral streams in response to snowmelt runoff and local storms:

$$Q = (1.074 \times 10^{-5}) \times A^{1.216} \times P^{2.749} \times S^{0.536} \qquad (2)$$

Where Q is mean annual recharge (cfs); A is drainage basin are

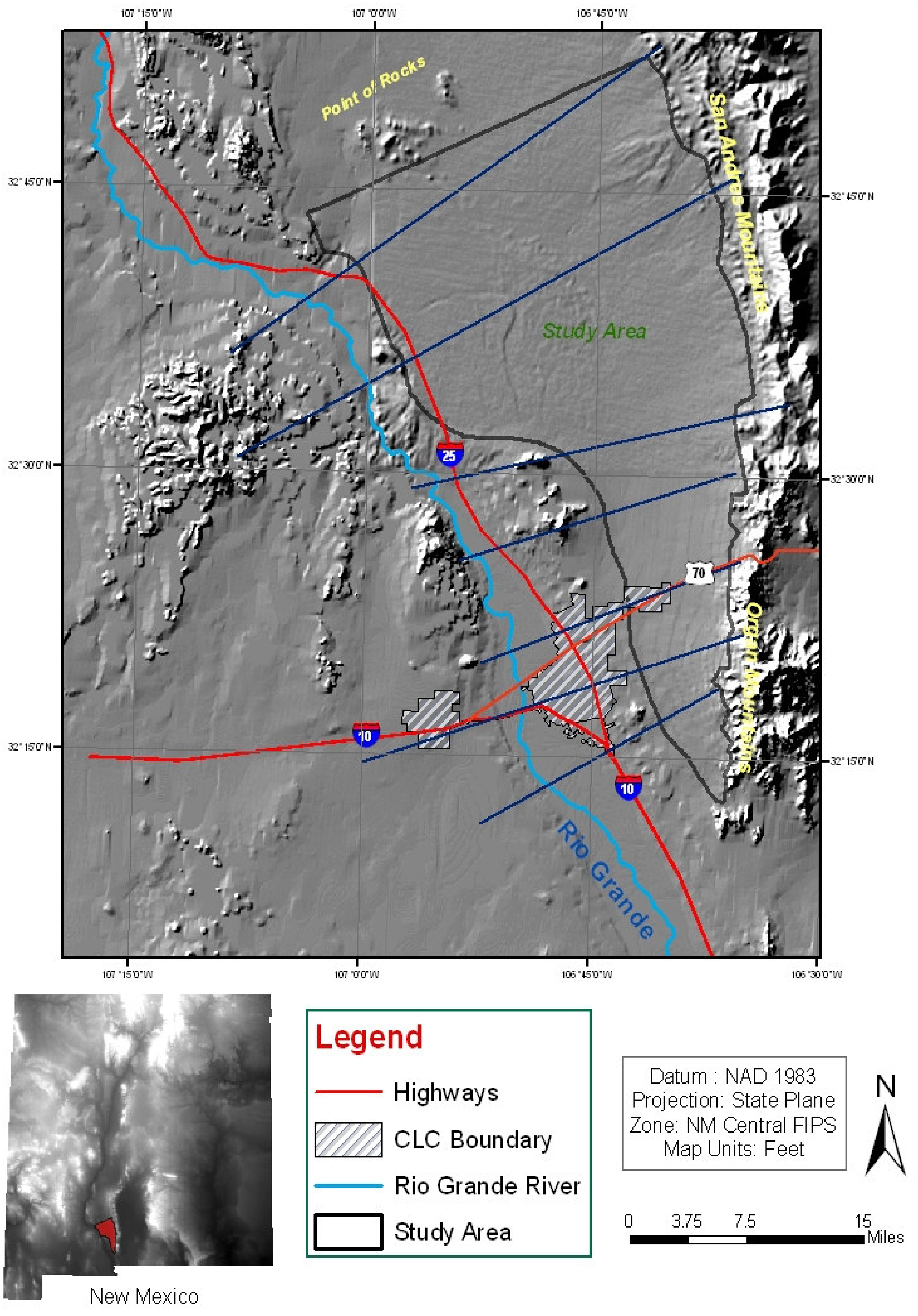

Figure 1. Location of study area showing hydrogeologic cross-sections.

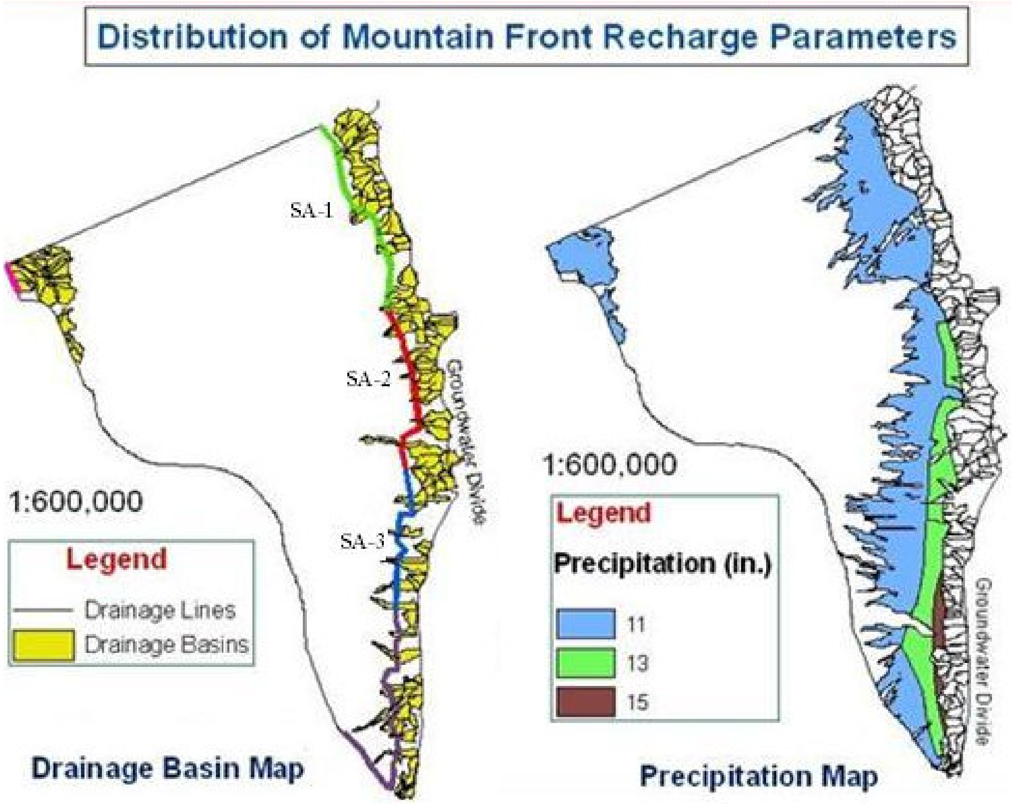

Figure 2. Maps of distributed precipitation and recharge parameters in the study area.

(mi^2); P is mean winter (October to April) precipitation (in); and S is basin average slope (ft/mi).

Waltemeyer method

Waltemeyer (2001) developed a regression equation based on basin climatic characteristics using data from 13 streamflow gage stations in Tularosa Basin in central New Mexico:

$$Q = (1.7 \times 10^{-4}) \times A^{1.35} \times P^{1.65} \tag{3}$$

Where Q is mean annual recharge (cfs); A is drainage basin area (mi^2); and P is mean annual precipitation (in).

RESULTS AND DISCUSSION

Recharge distribution within the basin along the mountain region was divided into three zones (San Andres, Organ, and Caballo) based on the delineated drainage sub-basins. The San Andres zone was further divided into three sub-zones (San Andres-1, 2 and 3) due to high variability in mean annual precipitation (Figure 2). A total of 216 finite difference cells (53 for San Andres-1, 46 forSan Andres-2, 39 for San Andres-3, 69 for Organ, and 9 for Caballo) were built along the basin boundaries for inputting recharge flux. Recharge rate for each stress period was estimated as the ratio of the fraction of mean annual recharge in a zonal area, which was equally distributed over the cells in a zone. Zone-wise distributed MFR, estimated by the three empirical precipitation recharge methods is given in Table 1. Due to the high coefficients, Maxey-Eakin estimated MFR was higher than that of the Waltemeyer method at high precipitations (San Andres-3, Organ), irrespective of the drainage area. The Hearne-Dewey method underestimated recharge flux. This was probably due to the low coefficient of proportionality (Equation 2) and use of mean winter precipitation instead of mean annual precipitation. Estimates of recharge by all the three methods showed that San Andres Basin is the major contributor of recharge in the region. It accounted for over 70% of the estimated basin recharge. This is primarily due to the higher precipitation index and the large drainage area.

To determine the best method for estimating MFR in the SJDM Basin, the model was re-calibrated with varying recharge fluxes against the data from 72 monitoring wells that were uniformly distributed across the study area. The residual statistics were evaluated in terms of mean error (ME), sum of squared errors (SSE) and root mean square error (RMSE). Zonal variations in the residual statistical parameters were estimated using the three empirical methods (Table 2). The Waltemeyer estimated recharge was noted to be in close agreement

Table 1. Estimated mountain-front recharge by three empirical methods.

Method	Zone wise Recharge distribution in ac.ft/yr (cfs)					Basin recharge in ac.ft/yr (cfs)
	San Andres-1	San Andres-2	San Andres-3	Organ mountains	Rincon - Caballo	
Maxey-Eakin	588.19 (0.81)	1381.44 (1.91)	1143.93 (1.58)	1128.44 (1.56)	240.77 (0.33)	4482.77 (6.19)
Hearne-Dewey	270.62 (0.37)	466.35 (0.64)	338.10 (0.47)	133.84 (0.18)	91.71 (0.13)	1300.62 (1.79)
Waltemeyer	734.90 (1.01)	1198.58 (1.65)	604.07 (0.83)	606.37 (0.84)	220.06 (0.30)	3363.98 (4.63)

Table 2. Residual statistics on recharge estimates using three empirical methods.

Recharge zone	Target wells	Method used	ME (ft)	SSE (ft^2)	RMS (ft)
San Andres – 1	4	Maxey-Eakin	-8.30	592.83	12.17
		Hearne-Dewey	-8.24	582.92	12.07
		Waltemeyer	8.33	596.38	12.21
San Andres – 2	2	Maxey-Eakin	-1.31	97.53	6.99
		Hearne-Dewey	-1.21	95.27	6.92
		Waltemeyer	-1.31	97.42	6.99
San Andres – 3	34	Maxey-Eakin	-3.45	1981.83	7.64
		Hearne-Dewey	0.89	1323.34	6.23
		Waltemeyer	-1.12	1429.48	6.50
Organ mountains	15	Maxey-Eakin	3.25	1712.49	10.70
		Hearne-Dewey	6.82	2150.30	11.98
		Waltemeyer	5.22	1328.72	9.42
Caballo mountains	0	---	---	---	---
Study area	72	Maxey-Eakin	-1.71	5256.42	8.53
		Hearne-Dewey	1.35	5404.87	8.66
		Waltemeyer	-0.07	5075.36	8.40

with the measured groundwater levels in the 72 monitoring wells. This is particularly true for the San Andres-3 and the Organ zones, where most of the target wells are in the vicinities of the recharge zones. Pumping in the southern part of the study area near San Andres-3 and Organ had a greater influence on budget flows and simulated heads. Hence an accurate estimation of recharge in this zone is essential for effective management of groundwater resources of the region. The calibrated models showed that Maxey-Eakin and Waltemeyer equations better estimated recharge in the SJDM Basin. This was primarily due to the increased amounts of recharge flux in the central and eastern parts of study area. Groundwater gradient in the region is primarily towards the west/northwest, but is apparently flattening out with time. The best agreement between the observed and simulated heads was produced by the Waltemeyer equation (Figure 3).

A higher discrepancy in groundwater elevations along the adjacent wells in the south central part of the study area resulted in poor residual statistics for the other models. To test the consistence of the estimated recharge by the three methods with the basin characteristics, one-way analysis of variance (ANOVA) was performed on the simulated heads. A graph of cluster averages of the simulated heads for the 49 monitoring wells near San Andres-3 and Organ zones is plotted in Figure 4. The null hypothesis (H_0) used in the ANOVA test assumed that the simulated heads resulting from the three empirical methods were consistent with the

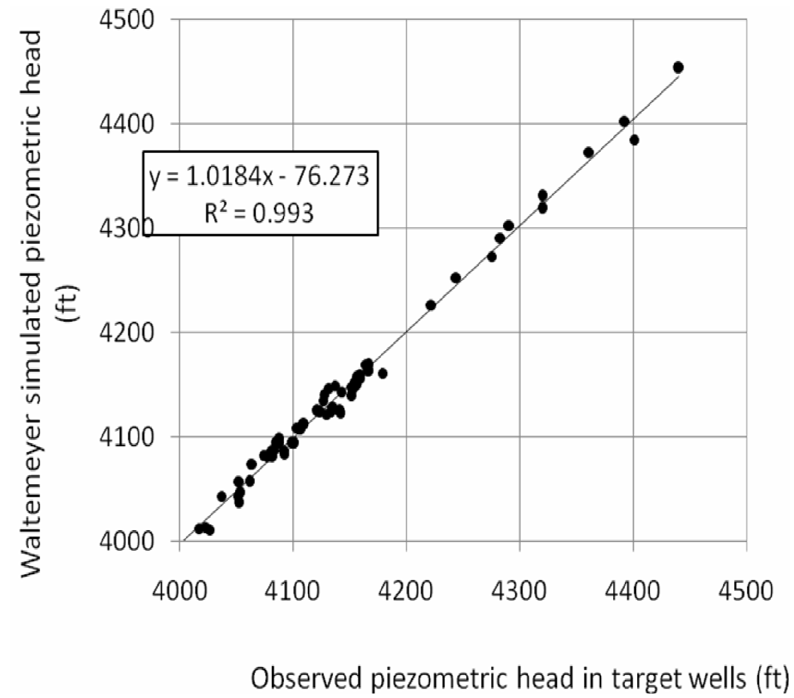

Figure 3. Comparison of observed and simulated heads by the Waltemeyer method.

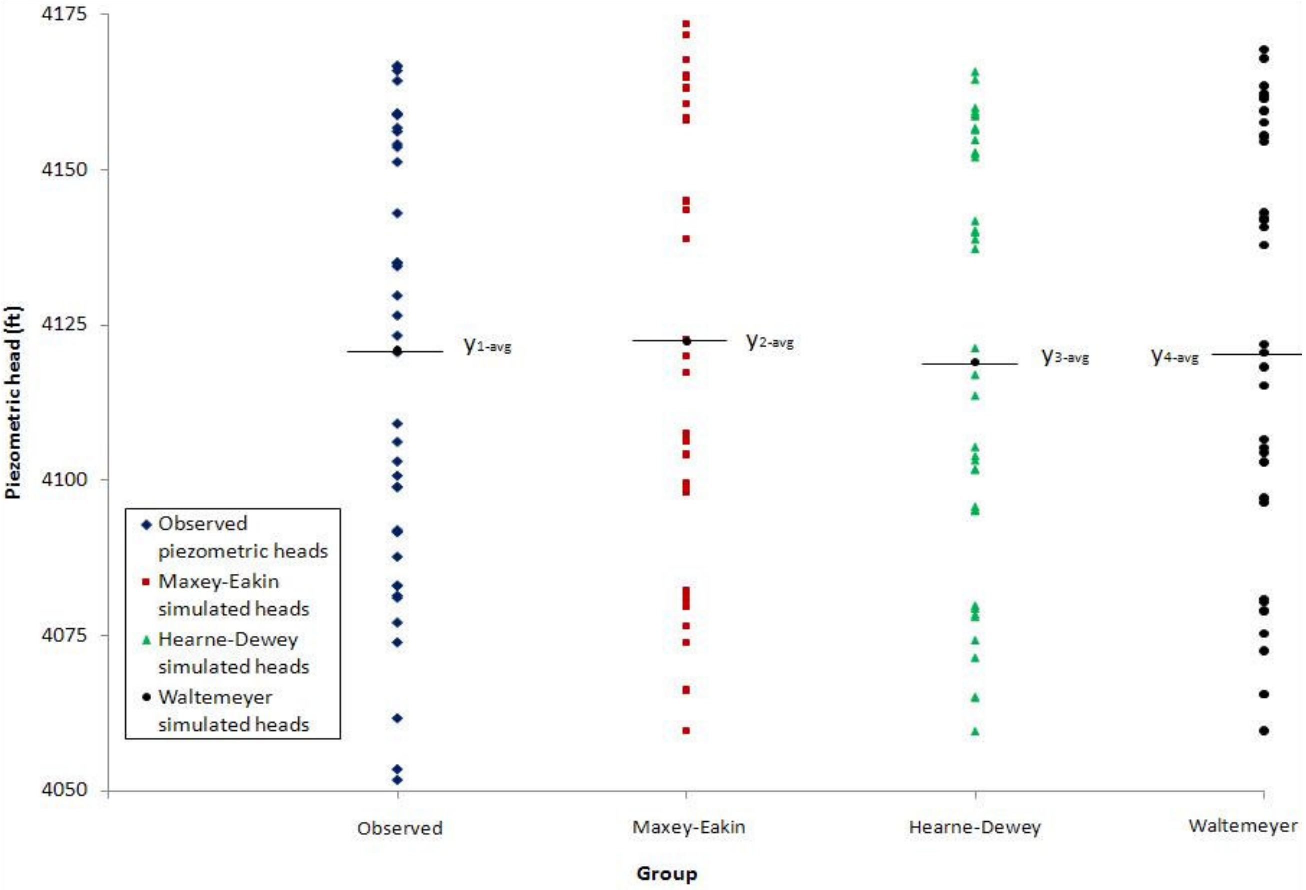

Figure 4. Deviation of piezometric heads among clusters (San Andres-3 and Organ zone data).

observed values, with probably based on a unique population. Results of the ANOVA test suggested that the null hypothesis was acceptable at all confidence levels. However, the Waltemeyer equation, which was originally developed for the Tularosa Basin in central New Mexico, seemed to be more appropriate for the SJDM Basin. This was mainly due to the strong similarities between the two basins in terms of climate and hydrogeologic characteristics.

Conclusions

A three-layer numerical groundwater recharge for the Southern Jornada Del Muerto Basin in New Mexico was used to assess current MFR distribution techniques in the region. The model was grided into 180 rows and 105 columns, and run for 1968 through 2007 on seasonal time scale. The hydrogeologic parameters of the upper aquifer were most sensitive in the simulation (Kambhammettu et al., 2010). Three empirical estimates of mountain-front recharge were evaluated via inverse modeling and residual statistics analysis. The Maxey-Eakin and Waltemeyer equations yielded approximately same amount of recharge because both use annual precipitation instead of average winter precipitation. The Maxey-Eakin method slightly overestimated recharge due to the high coefficients resulting from high precipitation in the southern recharge zones. The Hearne-Dewey equation appeared to underestimate recharge in the basin. Most of the target wells considered in the model calibration were in the vicinity of the San Andres-3 and Organ zones. The estimated recharge via the three methods differed significantly for these zones.

The Waltemeyer equation, which was originally developed for a basin with similar hydrogeologic characteristics to the study area, produced the least residual statistics. Analysis of variance on the simulated heads suggested that all the three empirical methods were consistent and reliable in terms of the estimated recharge. However, the Waltemeyer simulated heads were in the strongest agreement with measured groundwater elevations in the region. This close agreement was attributed to the strong similarities in the hydro-climatic characteristics of the basin. Based on the results, the Waltemeyer method was recommended for use in estimating recharge in the SJDM Basin.

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