IAMG'06 Int. Assoc. for Mathematical Geology
XI[th] International Congress
Université de Liège – Belgium

Stochastic analysis of the recharge uncertainty of a regional aquifer in extreme arid conditions

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ABSTRACT: The Pampa del Tamarugal Aquifer (PTA) is an important source of groundwater in northern Chile. Since the study area is situated in the Atacama Desert, the estimation of groundwater recharge based on conventional hydrological methods is subject to large uncertainties. To account for variations in the groundwater balance, caused by uncertainties in the average recharge rates, randomly generated recharge values with different levels of uncertainty are simulated using a groundwater flow model. Results show that evaporation and groundwater outflows are insensitive to the recharge uncertainty, while the storage terms can vary considerably. Considering current groundwater abstraction and random recharge rates, it is unlikely that the cumulative discharged volume from the aquifer, after a 45 years simulation period, will be larger than 12% of the estimated groundwater reserve. Simulated groundwater heads fluctuations due to uncertainties in the average recharge rates are more noticeable in certain areas. These fluctuations could explain anomalies in the observed groundwater heads in these areas.

KEYWORDS: Atacama Desert, numerical modelling, random recharge.

1. Introduction

Due to extreme arid conditions, groundwater in northern Chile is a vital resource. A particularly important groundwater reserve is the *Pampa del Tamarugal* Aquifer (PTA) located in the I Region of Chile (Fig. 1). Efforts to numerically model the groundwater flow have been reported in DGA-UChile (1988), JICA-DGA-PCI (1995) and Rojas (2005). Although these numerical models are able to approach the observed groundwater flow pattern, they are based on conceptually and quantitatively dissimilar recharge processes. In addition, due to the arid nature of the study area, estimations of the groundwater recharge derived from traditional hydrological approaches are dominated by a large uncertainty. As an example, Houston (2002) estimated a recharge value approximately 20% larger than the value reported in JICA-DGA-PCI (1995) for the same sub-basin. Although the estimation of Houston (2002) is in the same order of magnitude than the estimation reported in JICA-DGA-PCI (1995), revisions in groundwater recharge estimations maintain the debate very much alive, especially in this region, where a marginal increase of groundwater availability brings the possibility of large mining economical revenues.
In this study, the groundwater recharge is treated as a random variable and a groundwater flow model for the PTA is run for a large number of stochastically generated random recharge values. In this way, the influence of the uncertainty in the groundwater recharge on the water balance components and groundwater heads is analysed for the PTA.

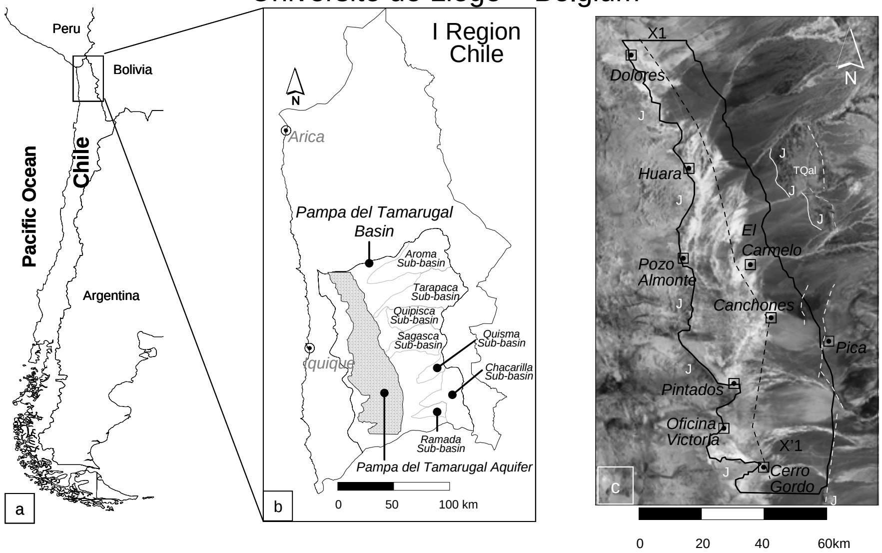

Fig. 1. Location of the study area. a) General location in Chile, b) Pampa del Tamarugal Basin and sub-basins delimitation (shaded area is PTA), c) Modelled domain.

2. Study area

The PTA is located in the *Pampa del Tamarugal* basin and it covers an area of ca. 5000 km² (Fig. 1b). Direct precipitation on the PTA is nil and thus no recharge through this process is expected. On the other hand, the eastern sub-basins receive precipitation produced at high altitudes and it is accepted that part of this water is recharging the aquifer through infiltration and lateral groundwater flows (Aravena, 1995). As described in Houston (2002), the basin is a complex asymmetric graben bounded in the west and in the east by N-S regional fault zones. JICA-DGA-PCI (1995) showed that the main aquifer system is composed of the upper units of *Altos de Pica Formation* (**Q4** and **Q3**) with depths ranging from 50 m up to 300 m.

2.1. Water balance

The water balance for the PTA is shown in Table 1. According to JICA-DGA-PCI (1995) the groundwater recharge coming from the eastern sub-basins for the period 1960-1993 is estimated to be 976 l/s.

Tab. 1. Water balance (l/s) for years 1960, 1987, 1993

Flow Components	1960		1987		1993	
	In	Out	In	Out	In	Out
Recharge from sub-basins	976		976		976	
Transpiration *Tamarugo* areas		210		690		904
Evaporation from *Salares*		410-602		286		145
Groundwater Outflow		164-356		164-356		164-356
Pumping Discharge		0		716		730
TOTAL	976	976	976	1856-2048	976	1943-2135

Transpiration from forested areas increases from 210 l/s in 1960 up to 904 l/s in 1993 due to reforestation strategies (FAO, 1989). Evaporation decreases from 542 l/s in 1960 up to 145 l/s in 1993 due to the steady decrease observed in the groundwater heads in the PTA (Rojas, 2005). The groundwater outflows are estimated between 164 l/s and 356 l/s (Rojas, 2005). Pumping discharges increases from nil values in 1960 up to 730 l/s in 1993 due to rises in the groundwater demand for public water supply and mining activities.

2.2. Groundwater flow model

A groundwater flow model considering the modelled domain depicted in Fig. 1c was developed. The model combined upper units of *Altos de Pica Formation* in one hydrostratigraphic unit. In order to implement and solve numerically the groundwater flow equation subject to the respective boundary conditions, MODFLOW (McDonald and Harbaugh, 1988) was used. The groundwater model was calibrated for steady (1960) and transient (1983-2004) conditions. Subsequently, series of 100 purely random realizations of average recharge values were generated for three levels of uncertainty expressed as a percentage of the average recharge (R) values. Each of these recharge values was used in order to simulate a 45 years period (2005-2050). The level of uncertainty was set arbitrarily in σ_1=0.05R, σ_2=0.15R and σ_3=0.35R. Random recharge flow rates were generated for each sub-basin using a random number generator honouring a log-normal distribution to avoid negative values. Spatio-temporal structure of correlation for the recharge values were not considered in the synthetic generation.

3. Results

Results for the random recharge are presented in Fig. 2. Fluctuations in the evaporation flow and groundwater outflows are insensitive to σ_1, σ_2 and σ_3 and they are not included in the figure. Results for the loss of groundwater storage for σ3 and 100 recharge realizations are shown in Fig. 2a (bold line represents the average recharge flow rate - 976 l/s). Fluctuations of the average and standard deviation of the cumulative loss of groundwater storage vs. number of realization, for the last year of simulation (2050), are shown in Fig. 2b and Fig. 2c, respectively. From these figures, the cumulative loss of groundwater storage is in the order of 2060 l/s ± 23 l/s, 2085 l/s ± 65 l/s and 2100 l/s ± 110 l/s for σ_1, σ_2 and σ_3, respectively.

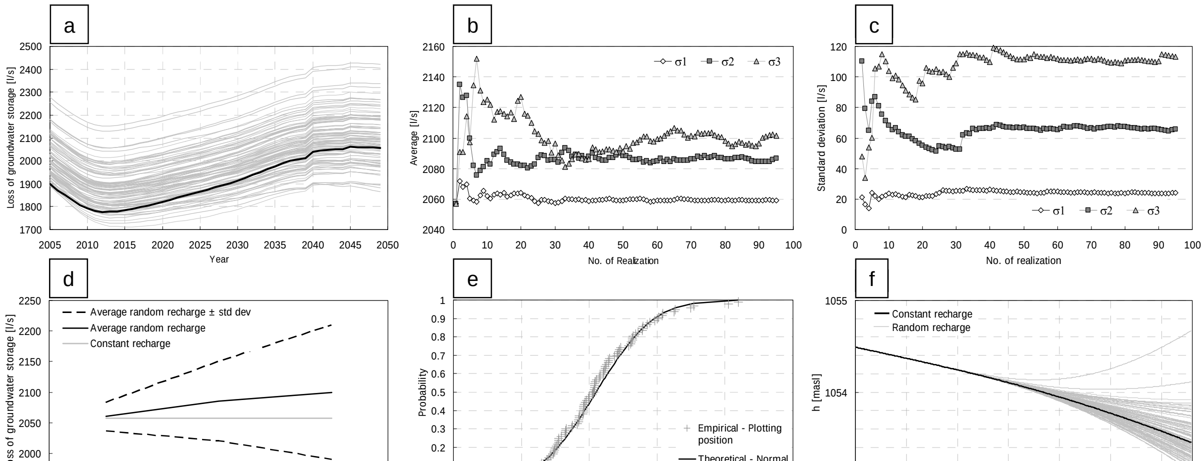

Fig. 2. Results for the random recharge analysis: a) loss of groundwater storage for PTA vs. time, b) average loss of groundwater storage for year 2050 vs. number of recharge realization, c) standard deviation of the loss of groundwater storage for year 2050 vs. number of recharge realization, d) loss of groundwater storage vs. level of uncertainty in recharge values, e) probability distribution for the cumulative loss of groundwater storage (45 years), f) groundwater head fluctuation for an artificial piezometer located in *Aroma* creek (North).

Fig. 2d shows a comparison between the cumulative loss of storage for the average recharge case and the random recharge case. From this figure, it is possible to see that the cumulative loss of groundwater storage deviates significantly from the average recharge case when increasing the uncertainty in the recharge values. In Fig. 2e the probability distribution of the cumulative loss of groundwater storage for σ3 is depicted. Based on the groundwater storage reserve estimated in JICA-DGA-PCI (1995), it is unlikely that the cumulative loss of storage for a 45 years simulation period will be larger than 12% of the known reserves. Fig. 2f shows the groundwater head variation in an artificial piezometer located in the north of the modelled domain for σ3. This area presents the largest variation in groundwater heads (1.7 m) and it is located in the confluence of the two most northern sub-basins, which jointly generate ca. 50 % of the total incoming groundwater recharges. Therefore, it is clear that the northern sub-basins influence the groundwater heads in the north sector of the study area.

4. Conclusions

Using the projection of the current groundwater abstraction and including random recharge values in a simulation period of 45 years, evaporation flow rates from *Salares* and groundwater outflows are insensitive to all uncertainty levels in recharge (σ_1, σ_2 and σ_3). This could be related to: a) the time span (45 years) used to evaluate the flow components which could suggest that the simulation period might be too short to observe more pronounced effects, or b) since evaporation and transpiration are strong compared to the recharge in the modelled domain, the insensitivity might also be due to the evaporation and transpiration overpowering the recharge effect.

The cumulative loss of groundwater storage for supplying the system demand increases when the uncertainty in the recharge increases. Despite of this, the cumulative loss of groundwater storage represents less than 12% of the known groundwater total reserves for the most uncertain case (σ_3).

Uncertainties in the simulated groundwater heads due to uncertainties in average recharge values are more noticeable in the north area of the modelled domain. Although these fluctuations in groundwater head are minors, they certainly could explain observed anomalies in wells located in this area, where some local recharge events could be expected.

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