Optimizing a piezometric network in the estimation of the groundwater budget: a case study from a crystalline-rock watershed in southern India

Faisal K. Zaidi · Shakeel Ahmed · Benoit Dewandel · Jean-Christophe Maréchal

Abstract An estimate of the groundwater budget at the catchment scale is extremely important for the sustainable management of available water resources. Water resources are generally subjected to over-exploitation for agricultural and domestic purposes in agrarian economies like India. The double water-table fluctuation method is a reliable method for calculating the water budget in semi-arid crystalline rock areas. Extensive measurements of water levels from a dense network before and after the monsoon rainfall were made in a 53 km^2 watershed in southern India and various components of the water balance were then calculated. Later, water level data underwent geostatistical analyses to determine the priority and/or redundancy of each measurement point using a cross-validation method. An optimal network evolved from these analyses. The network was then used in re-calculation of the water-balance components. It was established that such an optimized network provides far fewer measurement points without considerably changing the conclusions regarding groundwater budget. This exercise is helpful in reducing the time and expenditure involved in exhaustive piezometric surveys and also in determining the water budget for large watersheds (watersheds greater than 50 km^2).

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F. K. Zaidi (✉) · S. Ahmed · B. Dewandel
Indo-French Center for Groundwater Research,
National Geophysical Research Institute,
Hyderabad 500007, India
e-mail: fk.zaidi@gmail.com
e-mail: shakeelahmed@ngri.res.in

J.-C. Maréchal
IRD, Indo-French Cell for Water Science,
Indian Institute of Science,
Bangalore 560012, India
e-mail: marechal@civil.iisc.ernet.in

B. Dewandel
Discontinuous Aquifer Unit (Resource Assessment), BRGM,
1039 Rue de Pinville,
34000 Montpellier, France
e-mail: dewandel@ngri.res.in

Résumé L'estimation du bilan en eau à l'échelle du bassin versant est essentielle pour une gestion durable des ressources. Dans des économies agraires comme en Inde, les ressources en eau souterraine sont généralement surexploitées pour des usages agricoles et domestiques. La méthode de double fluctuation du niveau piézométrique, est une methode fiable pour calculer le bilan en eau en contexte cristallin semi-aride. Plusieurs campagnes piézométriques détaillées ont couvert un réseau dense sur un bassin versant de 53 km^2, au sud de l'Inde, avant et après la mousson, et ont permis de calculer plusieurs composantes du bilan en eau. Les données piézométriques ont ensuite été soumises à des analyses statistiques, afin de déterminer les priorités et redondances sur chaque point de mesure par une méthode de validation croisée. De ces analyses est né un réseau optimal, à partir duquel les composantes du bilan en eau ont été recalculées. Il a été mis en évidence qu'un tel réseau optimisé, s'il nécessitait beaucoup moins de points de mesure, ne changeait pas fondamentalement les conclusions sur le bilan en eau. Cet exercice est utile pour réduire le temps et le coût qu'impliquent la réalisation de campagnes piézométriques exhaustives, mais aussi pour déterminer le bilan en eau sur des bassins versants étendus (surface supérieure à 50 km^2).

Resumen Una estimación del balance de aguas subterráneas a escala de cuenca es muy importante para la gestión sostenible de los recursos disponibles de agua. Los recursos hídricos están generalmente sujetos a sobreexplotación para la agricultura y el uso doméstico en economías agrarias como es el caso de la India. El método de fluctuación doble del nivel piezométrico, es metodo fiable para el cálculo del balance hídrico en áreas semiáridas de rocas cristalinas. Se han llevado a cabo medidas extensivas de niveles de agua procedentes de una densa red de control antes y después de las lluvias monzónicas en una cuenca al sur de India y se han calculado varios componentes del balance de agua. Posteriormente, se llevaron a cabo análisis geoestadísticos con los datos de nivel de agua para determinar la prioridad y/o redundancia de cada punto de medida usando el método de validación cruzada. A partir de estos análisis se obtuvo una red de control óptima. La red de control fue entonces utilizada para recalcular los componentes del balance hídrico. Se ha establecido que una red de control optimizada da lugar a

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muchos menos puntos de medida sin cambiar considerablemente las conclusiones que tienen que ver con el balance hídrico. Este ejercicio ayuda a reducir el tiempo y el costo de campañas piezométricas exhaustivas y también a determinar el balance hídrico para grandes cuencas (cuencas mayores de 50 km^2).

Keywords Groundwater budget · India · Granitic watershed · Geostatistics · Piezometric survey

Introduction

Quantification of the available groundwater resources of an area is important for evolving a sustainable development strategy for these resources. Calculating the groundwater budget is an important step in developing a strategy. In over-exploited aquifers such as the granitic aquifer in the present study, and others found in agrarian economies such as India, a precise and reliable estimate of the groundwater budget is extremely important. The double water-table fluctuation (DWTF) method (Maréchal et al. 2006) is an appropriate and robust method for estimating the recharge and specific capacity in crystalline rock aquifers. Due to the accuracy, ease, and application in semiarid areas (Beekman and Xu 2003), this method is considered to be reliable and cost-effective. Based on this method, the changes in the groundwater storage are a combined effect of the resulting water-table fluctuation and the storage parameter. In the case of unconfined aquifers such as in this case study, this parameter is the specific yield.

The key to a successful budget estimation using this method depends on the representativeness of the piezometric maps of the area from which the water-table fluctuations are calculated. The accuracy and reliability of any estimate greatly depends on the quality and quantity of the measurable parameter. Water level, which is the only directly measurable parameter, is not problematic as related to data quality if careful measurements are taken. Thus, the measurement density is of utmost interests. A very high measurement density will increase the time and cost of field measurement and on the other hand, a very low measurement density can result in losing vital information.

The objective of the present study was to develop a methodology for the optimization of the piezometric network using geostatistics so that it adequately represents hydrologic conditions in a given area and does not affect the sensitivity of the water-budget calculations. This methodology will greatly help in reducing the cost and time associated with exhaustive piezometric surveys because budget calculation is required for many time periods, even in a single hydrological year. In the present study, the hydrological year has been defined as the beginning of June to the end of May in the next calendar year.

Study area

The study was carried out in the Maheshwaram watershed about 35 km south of Hyderabad in the Ranga Reddy district of Andhra Pradesh covering an area of about 53 km^2 (Fig. 1); elevation in the watershed ranges from

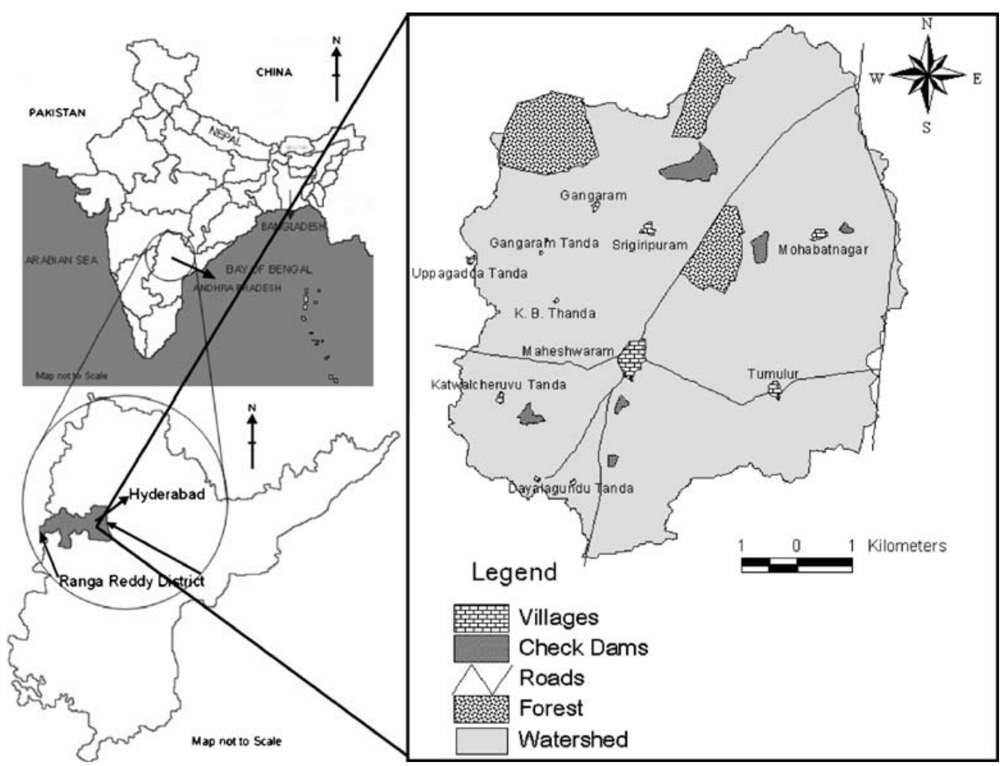

Fig. 1 Location map of the Maheshwaram watershed, southern India

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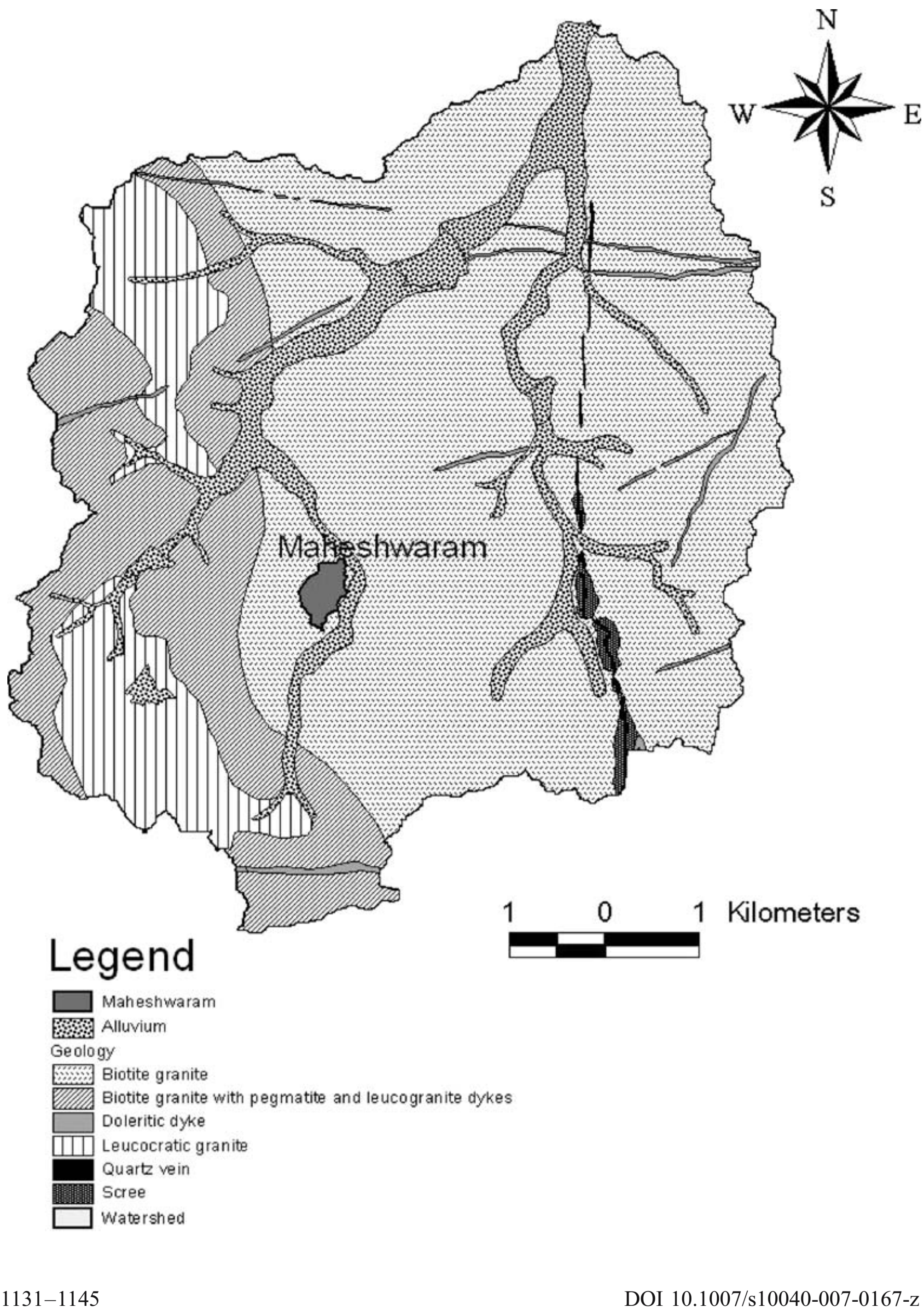
590 to 670 m above mean sea level with the higher elevations in the southern part of the basin with land surface gently sloping towards the north. The watershed is of a semi-arid climate type with a distinctive rainy season known as the monsoon. The monsoon occurs from July to October. The mean annual rainfall in the study area is 750 mm. More than 90% of the precipitation falls during the monsoon season. The mean annual range of temperature varies from 22 to 44°C. The absence of any perennial streams in the watershed has resulted in groundwater as the main source of water supply for irrigation and domestic purposes.

Geologically, the watershed is composed of Archean granites (Fig. 2), which forms a part of the larger, 2,500 million-year-old peninsular gneissic complex of the eastern Dharwar craton with a multiphase weathering profile (Dewandel et al. 2007).

Because of the over-exploitation of groundwater, the weathered layer is dry and water is present in the fissured layer only. The Maheshwaram watershed is typical of rural Indian watersheds with its agricultural practices and over-exploitation of the groundwater resources (more than 700 wells in use).

Fig. 2 Geology of the study area



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Estimation of water budget

Changes in the groundwater storage are a combined effect of the recharge, irrigation return flow, and the horizontal groundwater inflows into the aquifer minus the base flow, evapotranspiration from groundwater, pumping, and horizontal groundwater outflows, and is given as (Schicht and Walton 1961)

$$(R + RF + Q_{in}) - (ET + PG + Q_{out} + Q_{bf}) = \Delta S, \quad (1)$$

where R is the groundwater recharge due to rainfall, RF is the irrigation return flow, Q_{in} and Q_{out} are the horizontal inflows and outflows to the basin, respectively, ET is the evapotranspiration from vegetation, PG is the groundwater abstraction by pumping, and Q_{bf} is the base flow or the groundwater discharge to the springs. The presence of a deep water table in the study area does not facilitate the presence of springs and there is no groundwater contribution to the streams; hence, the term base flow in Eq. (1) can be neglected. Also, because of the deep water table, vegetation is not able to consume any water; hence, the term evapotranspiration can be replaced by evaporation in Eq. (1). Thus, Eq. (1) can be reduced to

$$(R + RF + Q_{in}) - (E + PG + Q_{out}) = \Delta S \quad (2)$$

The DWTF method is used for calculating the recharge, which links the changes in groundwater storage, ΔS, with the resulting water-table fluctuation Δh:

$$\Delta S = \mathrm{Sy}\Delta h, \quad (3)$$

where Sy is the specific yield of the unconfined aquifer. A brief discussion of the individual components of the groundwater budget calculation using the DWTF method is given below.

Pumping flows

Absence of perennial-surface water supply and free electricity has resulted in the development of tube wells as the main source of irrigation for the numerous paddy fields, vegetables, and fruit orchards present in the watershed. All these crops are irrigated round the year. The annual pumping rate was estimated using the wells inventory, supported by the land-use map derived from remote-sensing techniques (Galeazzi 2002).

Table 1 Seasonal groundwater abstraction for the hydrological year June 2003 to May 2004, according to usage

Usage	Kharif (mm)	Rabi (mm)
Rice	62.5	108.7
Vegetables and flowers	1.2	1.6
Fruit (including grapes)	3.8	9.4
Domestic use and chickens	3.3	4.1

Kharif is the wet season; Rabi is the dry season

Table 2 Seasonal horizontal flow across the aquifer boundaries for the hydrological year June 2003 to May 2004

Flow component	Kharif (mm)	Rabi (mm)
Q_{in}	0.7	1.6
Q_{out}	1.8	0.5
Q_{in}-Q_{out}	−1.1	1.1

Kharif is the wet season, Rabi is the dry season

Using a hand-held global positioning system, 929 wells were located, and the discharge rates of the 707 wells in use were measured using a graduated bucket (Maréchal et al. 2003). The discharge rates varied from 5 to 700 l/min. Information about daily duration of pumping, annual number of pumping days, and use resulted in the calculation of the annual pumped volume of water. Water-level fluctuations in response to pumping were recorded by automatic water-level recorders installed during the Indo-French Project (IFP) in five wells (IFP wells serve as piezometers without any pump fittings and these wells were specially drilled for the project) and this helped in computing the monthly evaluation of the rate of pumping at the watershed scale (Maréchal et al. 2006). Table 1 shows the pumping for the hydrological year 2003–2004. Kharif is the wet season (beginning of June to end of November) and Rabi is the dry season (beginning of December to end of May).

Horizontal flow across the boundaries

Due the absence of any groundwater movement in the weathered layer of the geological profile and extremely low permeability of the fresh basement, groundwater movement in these layers can be neglected. Thus, flow in the aquifer only occurs in the fissured zone. These flows are, in turn, dependant on the horizontal permeability, thickness of the saturated zone, and local hydraulic gradient. These flows were computed using a finite-difference model in order to obtain a spatial distribution on a grid of squared cells. The inflow and outflow values are given in Table 2 (Maréchal et al. 2003).

Evaporation from the water table

Coudrain-Ribstein et al. (1998) has demonstrated that evaporation from aquifers in arid zones is independent of the soil characteristics. According to them, the annual

Table 3 Seasonal and annual evaporation from the water table for the hydrological year June 2003 to May 2004 (after Maréchal et al. 2006)

	Kharif	Rabi
Seasonal evaporation (mm/season)	1.0	1.3
Annual evaporation (mm/year)	2.3	

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Table 4 Seasonal-irrigation return flow for the hydrological year June 2003 to May 2004

	Kharif	Rabi
Return flow per season (mm)	32.6	53.7

evaporation flux is expressed as an inverse power function of the water-table depth below the surface, independently of the soil properties and given as

$$E = 71.9z^{-1.49}, \qquad (4)$$

where z is the depth of the water table (m). Table 3 depicts the values for this parameter for the hydrological year 2003–2004 and the Kharif (wet) and Rabi (dry) seasons.

Return flow from irrigation

Most of the groundwater in the watershed is pumped for irrigation purposes. However, the crops use only a fraction of this pumped water and the remaining volume either returns to the aquifer by direct infiltration from the irrigated fields or evaporates to the atmosphere. Return flow is expressed as a product of the total pumping flows multiplied by the return flow coefficient (RFC). The return flow coefficient, depending on the crop type, varies from 0 to 1. Hence, the total return flow depends on the

Fig. 3 Study area with location of pumped wells and abandoned wells used as piezometers

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Table 5 Piezometric levels (Piz) and priority indices of the piezometers (where X and Y are the eastings and northings of the wells in meters. ALT is the altitude of the wells in meters above mean sea level; Piz-June 2003, Piz-Dec 2003 and Piz-June 2004 are the piezometric levels for June 2003, December 2003 and June 2004 respectively. Residual is the difference between the observed piezometric value and the estimated piezometric value calculated using the cross-validation test respectively

X(m)	Y(m)	ALT (m)	Piz-June 2003 (m)	Piz-Dec 2003 (m)	Piz-June 2004	Residual-June 2003	Residual-Dec 2003	Residual-June 2004	Average	Absolute value	Priority
228815.2	1897267.4	635	615.66	628.69	622.36	−8.860535762	−9.1680709	−9.7827142	−9.2704403	9.2704403	1
229741	1897049	624	602.66	618.29	605.35	8.775605548	4.7820165	12.79542	8.7843473	8.7843473	2
223723	1897884	633	601.09	611.45	606.35	10.74003253	7.1208818	8.1773611	8.6794251	8.6794251	3
229479	1895628	634	608.54	625.58	618.27	12.39296787	5.7594422	7.3655909	8.5060003	8.5060003	4
223436	1898002	635	612.5	617.02	615.12	−11.10952244	−5.5640535	−8.303227	−8.325601	8.325601	5
226659.24	1898717.7	619	599.21	610.91	613.92	−5.001978232	−5.7372707	−13.397905	−8.0457179	8.0457179	6
223624	1895477	651	628.37	634.17	633.23	−8.815416264	−6.3187132	−8.5306638	−7.8882644	7.8882644	7
230240	1900419	601	580.78	587.43	584.36	7.225664984	8.5085862	6.690584	7.4749451	7.4749451	8
226655.49	1898525.1	612	591.24	601.57	597.4	4.038974826	7.4758877	10.753354	7.4227388	7.4227388	9
225638.51	1898175.4	629	610.76	623.64	615.01	−5.82838961	−7.7821925	−8.4825176	−7.3643666	7.3643666	10
230363.57	1897293.7	633	615.09	623.91	619.1	−8.099003862	−6.0599178	−7.7460299	−7.3016505	7.3016505	11
228670.65	1893628.6	655	638.79	640.95	639.62	−9.688191838	−3.8630394	−8.2912096	−7.2808136	7.2808136	12
227009	1901611	615	603.9	613.65	609.32	−5.12702954	−6.4010171	−10.001258	−7.1764349	7.1764349	13
231799	1895701	640	616.9	622.22	620.8	7.045657025	8.6789051	5.2040943	6.9762188	6.9762188	14
229410	1893850	651	625.72	631.7	627.67	7.672259514	5.0448266	8.1863387	6.9678083	6.9678083	15
225140.02	1897757.8	627	601.41	613	603.16	7.033463334	4.5934582	8.5789703	6.7352973	6.7352973	16
231259.05	1895224.2	653	629.13	636.65	633.2	−6.064639447	−6.9979249	−7.0210246	−6.6945297	6.6945297	17
228924.94	1896705.7	631	608.07	622.45	615.48	8.812350065	6.0312723	4.5443082	6.4626435	6.4626435	18
230463.42	1900782.8	610	589.13	593.21	590.81	−7.86899879	−5.7558265	−5.6774963	−6.4341072	6.4341072	19
229542	1902449	589	565.29	579.06	569.16	8.362195036	2.3660237	7.8497321	6.1926503	6.1926503	20
231862	1899287	634	611.91	614.6	612.91	−7.247635211	−3.8292586	−7.2824386	−6.1197775	6.1197775	21
226907.74	1893915	656	635.45	643.26	637.22	4.629205846	6.2781722	6.0815731	5.6629837	5.6629837	22
227062	1893064	667	646.72	653.45	650.48	−5.839952699	−2.2280879	−8.4407721	−5.5029376	5.5029376	23
226655	1893971	656	640.29	651.4	643.93	−3.390205488	−7.4307955	−5.4531589	−5.42472	5.42472	24
230925.07	1898634	619	597.96	606.83	599.2	5.865196855	3.1973011	6.8199815	5.2941598	5.2941598	25
224935.29	1897494.8	634	609.69	616.93	613.06	−6.104327082	−2.2991071	−6.841748	−5.0817274	5.0817274	26
227143	1893035	661	641.1	651.73	642.21	5.272305477	1.2499049	7.8597065	4.7939723	4.7939723	27
227864.65	1897624	625.11	610.01	620.41	615.01	−6.4916005	−3.8425094	−3.8048588	−4.7129896	4.7129896	28
226078.11	1898087.6	623	599.58	609.5	600.44	2.753096754	4.112821	7.1797835	4.6819004	4.6819004	29
226498.28	1893243.7	661.63	637.74	646.51	641.22	5.233467873	4.317804	4.4663513	4.672541	4.672541	30
230403.12	1896653.1	628	609.78	623.45	616.37	5.70066422	3.4732344	4.6246622	4.5995203	4.5995203	31
228058.97	1894724.9	651	630.91	637.11	633.56	−4.789243257	−4.0336446	−4.1052057	−4.3093645	4.3093645	32
229956.07	1900244.6	606	585.84	596.53	590.57	−2.531369524	−7.0171587	−3.2504004	−4.2663095	4.2663095	33
224735.4	1897796.7	633.99	603.84	615.24	607.78	3.875515961	5.1589649	3.5649079	4.1997962	4.1997962	34
231278.64	1899146.3	625	606.8	613.49	607.77	−3.851388246	−4.3065172	−4.3807796	−4.1795617	4.1795617	35
229306	1901152	602	582.23	585.75	583.78	1.779479365	6.3947005	4.2830016	4.1523938	4.1523938	36
226774.72	1896614.8	639	611.75	618.05	615.52	−4.526600544	−3.3160799	−4.4638625	−4.102181	4.102181	37
224621.35	1897905.4	639	608.47	622.8	612.83	−2.749344448	−5.721927	−3.2130182	−3.8947632	3.8947632	38
223969.51	1896428.7	639.17	614.46	618.39	616.66	1.277800788	6.6703882	3.4812358	3.8098083	3.8098083	39
230664.81	1894837	649	627.07	633.87	629.44	1.920439817	4.1460369	5.0556808	3.7073858	3.7073858	40
229221.19	1895844.8	640	621.3	629.92	624.05	−5.665005182	−2.2890415	−3.1059291	−3.6866586	3.6866586	41
227944.83	1899975.3	618	600.43	607.35	604.17	−2.697988076	−3.0167366	−4.7210468	−3.4785905	3.4785905	42
229922.99	1895188.8	642	623.83	635.98	629.99	−2.896587239	−3.9130387	−3.2539226	−3.3545162	3.3545162	43
229839.71	1896557.5	629	612.85	625.55	619.3	−3.381898843	−1.3298344	−5.2211926	−3.3109753	3.3109753	44
227632.68	1896243.2	635	612.45	624.07	616.08	3.592606049	−0.9935721	6.8013762	3.1334701	3.1334701	45
227946.2	1894255.7	657	630.31	638.23	633.68	4.183476625	1.9248709	3.061007	3.0564515	3.0564515	46
226864.44	1896920.7	630.89	604.43	613.34	609.53	3.753823293	2.074557	2.892029	2.9068031	2.9068031	47

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224972.9	1895519.8	637	614.78	627.58	620.72	5.208921489	−0.8395424	4.3440472	2.9044754	2.9044754	48
226182.85	1898760.6	627	596.4	610.86	600.81	3.604570951	1.6161094	3.4662368	2.895639	2.895639	49
230245.93	1895893.2	640	620.92	634.1	627.1	−2.508235698	−3.2399093	−2.7711249	−2.8397567	2.8397567	50
226462.07	1893550	662	641.91	649.49	643.52	−4.376356082	−2.0954264	−1.8987746	−2.7901857	2.7901857	51
230314.62	1897656	628	606.87	615.91	611.63	3.112537955	3.2961115	1.2545058	2.5543851	2.5543851	52
224511.11	1898261.2	646	610.86	621.45	614.06	−4.067619038	−0.5099448	−2.7579951	−2.4451863	2.4451863	53
230910.21	1898394.3	620	604.06	609.8	605.81	−3.346727798	−0.5946729	−3.3529015	−2.4314341	2.4314341	54
227869	1898844	615	594.3	603.97	598.99	2.335323825	2.9172963	1.7762141	2.3429447	2.3429447	55
224167	1893333	640	622.59	636.1	629.49	2.567881409	1.3280687	3.0874103	2.3277868	2.3277868	56
228060.14	1895248.2	643.65	622.29	629.01	625.25	2.830658169	1.7596222	1.7577696	2.1160167	2.1160167	57
225237	1893376	649	623.88	641.27	633.14	5.695922681	−1.3909632	1.6983097	2.0010897	2.0010897	58
227591.56	1899826.1	612	598.08	605.44	600.53	1.166040007	1.8575668	2.7212252	1.914944	1.914944	59
225496.76	1897843.9	636	608.37	617.92	611.56	−1.955653141	−0.6260735	−2.9905263	−1.8574177	1.8574177	60
229635	1902156	592	572.65	580.15	575.44	−3.381371745	0.3383526	−2.3663621	−1.8031271	1.8031271	61
226271.12	1897066.2	626	604.35	609.42	607.63	1.805319572	2.3409007	1.1181785	1.7547996	1.7547996	62
228236.41	1895839.9	644	620.96	625.7	625.48	−2.200095568	0.2716129	−3.2497883	−1.7260903	1.7260903	63
227471	1901251	615	603.88	612.3	605.59	−2.123525833	−2.6885604	−0.3462909	−1.719459	1.719459	64
229833.41	1895749.2	636	618.39	631.24	624.6	−2.744679617	−0.812519	−1.3039282	−1.6203756	1.6203756	65
226726.52	1895351.5	641	620.17	625.62	622.1	0.880107666	1.6602857	1.7649384	1.4351106	1.4351106	66
229708	1894279	652	630.38	636.29	632.82	−1.585980898	−1.3691103	−0.8872344	−1.2807752	1.2807752	67
226359.63	1897558.9	622	603.61	608.3	605.11	−3.931544807	1.1037535	−0.9662694	−1.2646869	1.2646869	68
226191.2	1894406.2	657	629.29	636.55	632.25	0.757187989	1.3430418	1.3195697	1.1399332	1.1399332	69
226788.95	1899991.7	617	600.94	608.35	603.21	−0.204044738	3.5838062	0.0392533	1.1396716	1.1396716	70
226753.52	1898164.9	620	588.33	606.4	600.35	6.661562788	−2.0476948	−1.2154289	1.132813	1.132813	71
228394.08	1895710.7	644	620.17	625.73	624.08	0.7400172	0.8746674	1.5943831	1.0696893	1.0696893	72
226801.52	1894741.4	646	626.55	634.08	630.49	2.221810242	0.6267075	0.311952	1.0534899	1.0534899	73
231464	1896882	641	613.76	621.65	617.68	−0.812216181	−2.303109	0.0435259	−1.0239331	1.0239331	74
225944.19	1898826.9	632	601.78	615.41	604.42	−1.658100452	−1.323358	−0.071525	−1.0176612	1.0176612	75
229789	1894104	657	630.86	635.69	633.4	−0.778969659	0.0596334	−2.2479097	−0.989082	0.989082	76
226528.57	1894392.9	655	633.51	639.78	636.39	−1.780081448	0.3951594	−1.539744	−0.9748887	0.9748887	77
224365	1892933	644	625.16	636.9	632.45	−0.031257393	2.1026931	0.813979	0.9618049	0.9618049	78
228829.26	1898883.7	617.24	601.14	608.11	605.19	−2.14590542	1.3911581	−1.8423148	−0.8656874	0.8656874	79
229022	1895901	642	620.74	629.3	623.31	−1.152623338	−1.0485178	−0.3181873	−0.8397761	0.8397761	80
226017.65	1895212.5	647	619.57	626.86	623.83	1.014352078	1.3383965	−0.0943527	0.7527986	0.7527986	81
228000.82	1898650.2	620	596.53	607.13	601.43	0.382239397	−0.1604183	1.9502487	0.7240233	0.7240233	82
226114.96	1896932.1	626	606.84	612.32	609.7	−0.79580942	−1.1385479	0.2243906	−0.5699889	0.5699889	83
223877	1900513	631	600.48	610.27	607.61	0.064963587	0.5850608	−2.1429589	−0.4976448	0.4976448	84
226176.43	1894565.5	653	627.68	634.89	630.68	−0.602249495	−0.202349	0.1396651	−0.2216445	0.2216445	85
223857	1900568	630	600.22	610.6	605.38	−0.218891783	−0.810668	1.6628172	0.2110858	0.2110858	86
224469.36	1897525.4	646	607.19	618.83	611.59	−0.24075415	0.7808583	−0.9807287	−0.1468748	0.1468748	87
224504.36	1897435.2	646	607.25	619.93	610.55	0.461208656	−1.5929399	1.4707802	0.1130163	0.1130163	88
227172.33	1899277.9	620	595.95	608.22	601.15	0.971394985	−1.8817037	1.1721633	0.0872849	0.0872849	89
226558.58	1898970.1	623	599.87	611.29	606.1	−1.638096497	−0.8548549	2.6278181	0.0449556	0.0449556	90

Average is the mean of the residual values for June 2003, December 2003 and June 2004 respectively; absolute value has been taken for the average of residuals; and priority is the priority indices of the piezometers ranked according to the decreasing order of the absolute values of the residuals.

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RFC for the individual crops and the area occupied by that crop. RF can be determined as

$$RF = RFC \times PG \tag{5}$$

Because RFC varies from crop to crop, the average RFC of a given region depends on the area occupied by the different crops. Table 4 shows the irrigation return flow in the study area for the Kharif and Rabi seasons (Maréchal et al. 2006).

In the areas characterized by a monsoon climate type, maximum rainfall falls during July and September, thus, dividing the hydrological year into two distinct dry and wet seasons. This result allows one to divide the hydrological year into two distinct seasons, and combining the water-budget Eq. (2) and water-table fluctuation Eq. (3), the new equation becomes

$$R + RF + Q_{\text{in}} = E + PG + Q_{\text{out}} + \text{Sy}\Delta h, \tag{6}$$

where two parameters, natural recharge, R, and specific yield, Sy, are unknown (other flow components are independently estimated and piezometric fluctuations are measured using well hydrographs). Therefore, Eq. (6) is applied twice a year during the dry and wet season to determine both the unknown

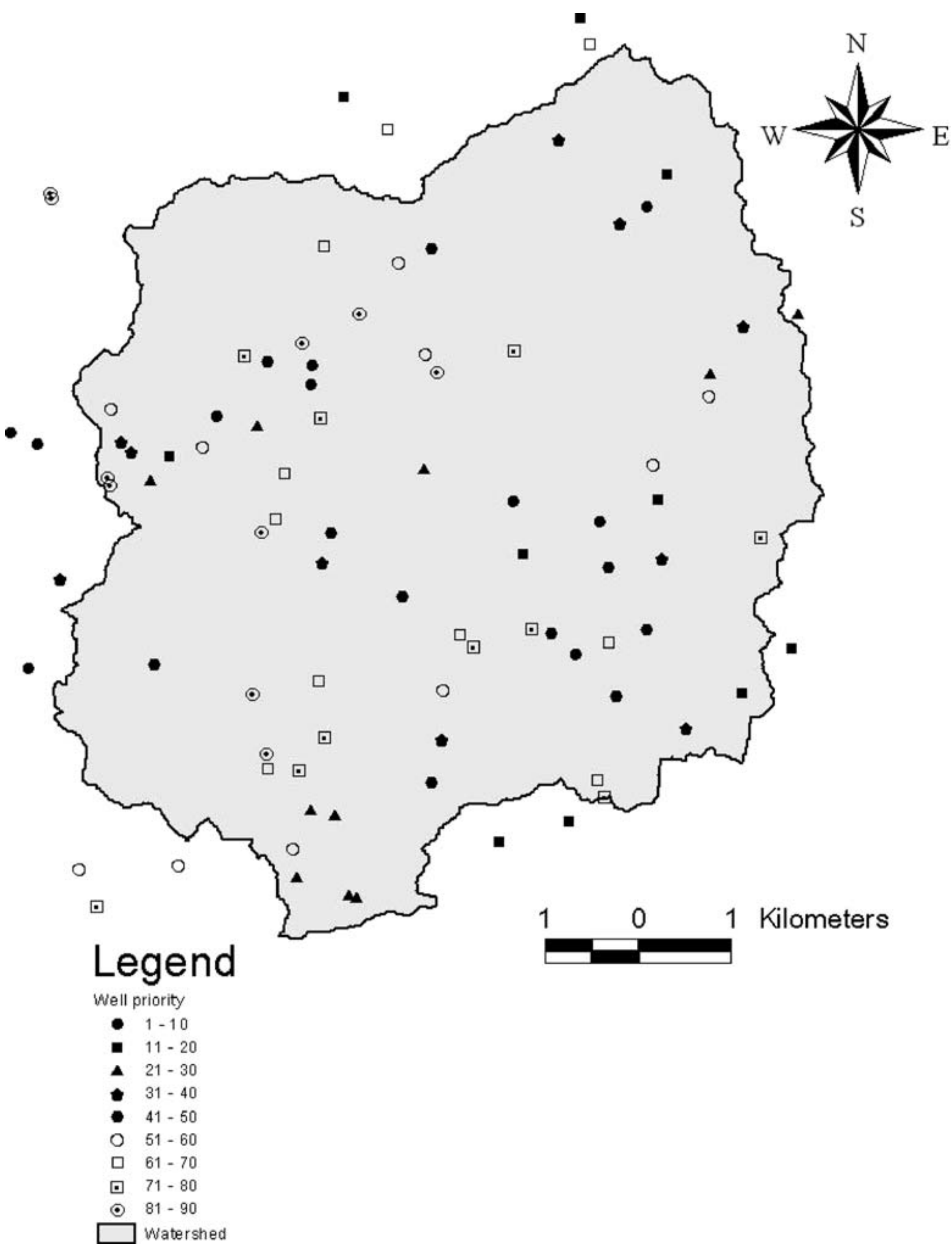

Fig. 4 Map showing locations of the ranked piezometers

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parameters. That is why the method is called the "double water-table fluctuation" (DWTF) technique. Methodology details can be found in Maréchal et al. (2006) and this method overcomes the indeterminacy problem faced by earlier workers, e.g., Raj (2004).

Methodology of piezometric network optimization

Most of the components, and particularly the recharge and specific yield, are based on the difference between piezometric levels, or rather the groundwater levels, between the post-monsoon and pre-monsoon season. Thus, evolving a representative and optimal network of wells for water-level measurement is necessary. There are more than 900 wells in the Maheshwaram watershed of which about 200 are not in use and considered abandoned (Fig. 3). These abandoned wells constitute a potential piezometers network and are monitored for the purposes of piezometric mapping. Because the budget calculation is based on the double water-table fluctuation (Maréchal et al. 2006), piezometric measurements are carried out twice a year in the pre-monsoon (June) and post-monsoon (November) seasons, the minimum and maximum levels, respectively.

The piezometric survey started in June 2001 with the number of piezometers increasing from 40 in June 2001 to 155 in June 2003. The entire methodology is based on a two-step procedure. This methodology is also a top-down approach that, in general, provides better results than the bottom-up approach. In the first step, all the water-level values are used to determine the variability of the water level using variogram analysis. The obvious removal of trends or calculation of the variogram in the perpendicular direction of the mean flow and other factors is considered to obtain a bounded variogram. After ascertaining the best estimation of the experimental variogram by selecting an appropriate lag and tolerance and best fit of the theoretical variogram, the same variogram is subjected to a cross-validation test (CVT). The CVT ensures that the variogram represents the true variability of the parameter and it is able to reproduce the measured values. Both the removal of one datum value from the set and the estimation of the same at its measuring location using the remaining values and the estimated variogram are used in this analysis. Then the estimated and the observed values are compared and conditioned by the corresponding estimation error. On average, if the comparison is satisfactory, that means the variogram is able to reproduce the observed values within the stipulated norms (Ahmed and Gupta 1989), and the final CVT is used to analyze the individual values. Based on the difference between the observed and estimated values, each point (well) is ranked with a priority number. This priority index is the priority of their measurements. Thus, the larger is the difference; the lower is the index, providing high priority for further measurements (Ahmed

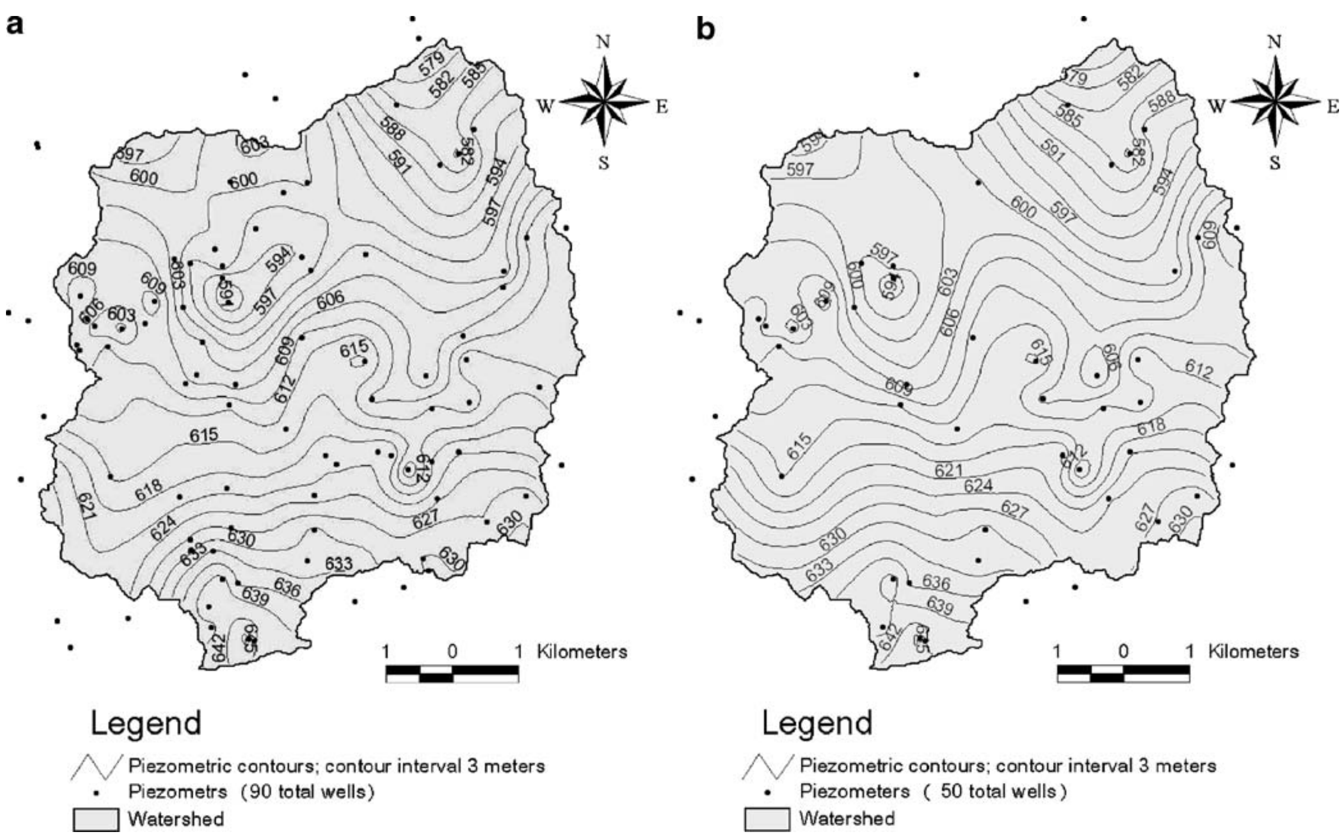

Fig. 5 **a** Piezometric contour map for the watershed based on measurements from 90 wells (June 2003). **b** Piezometric contour map for the watershed based on measurements from 50 wells (June 2003)

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et al. 2003). The well with the smallest difference is given the highest index, simply because the observed value at that location is being accurately estimated from the remaining measurements and, thus, these wells need not be measured. The highest index will provide lower preference for further measurement.

The first step in calculating the index was to select the seasons with the maximum number of piezometers from where measurements were taken: June 2003 (114 wells), November 2003 (155 wells), and June 2004 (134 wells). However, the piezometers used for measurements were not the same each season due to problems in the field. The same 90 wells were measured during the three seasons. Three seasons of data were used for testing the methodology. After the three data sets were treated independently for geostatistical analysis, theoretical variograms were obtained by fitting the spherical model (Pannatier 1996) with a linear drift on the 90 selected wells. A linear drift was selected because the topography affects the values, with water levels closely following the topography.

Satisfactory fitting of the experimental variogram with the theoretical model cross-validation test was performed. This process was carried out for all the three data sets and based on the average residual for the three cases, a priority index was assigned to all wells. Therefore, the well with the highest value of residual was given a priority of 1 and the well with the lowest value of residual was given a priority of 90 (Table 5). Therefore, a well having a priority of 90 will have the minimum difference between the observed piezometric value and the estimated piezometric value using cross-validation and, hence, it can be removed from the monitoring network first, if needed. Similarly, a well having a priority of 1 will always be a part of the monitoring network because estimating its value by kriging shows an unacceptable difference from its observed piezometric value, thereby affecting the mean piezometric level of the watershed. Figure 4 shows the different well locations marked according to their priority. However, one problem was encountered in that the priority of the monitoring network changed from the pre-monsoon to the post-monsoon and again in the next pre-monsoon season because the cross-validation depends on the variogram parameters. These parameters have been selected and the variogram parameters, in turn, depend on the piezometric values. Because the piezometric level is a dynamic parameter, the cross-validation results for the three data sets are not the same. To avoid this difference in cross-validation results, the residual values obtained from these results for the three seasons were added and then divided by 3 to calculate an average residual. Then, a resultant priority was assigned to all the wells so that the monitoring network remained the same for all the further calculations.

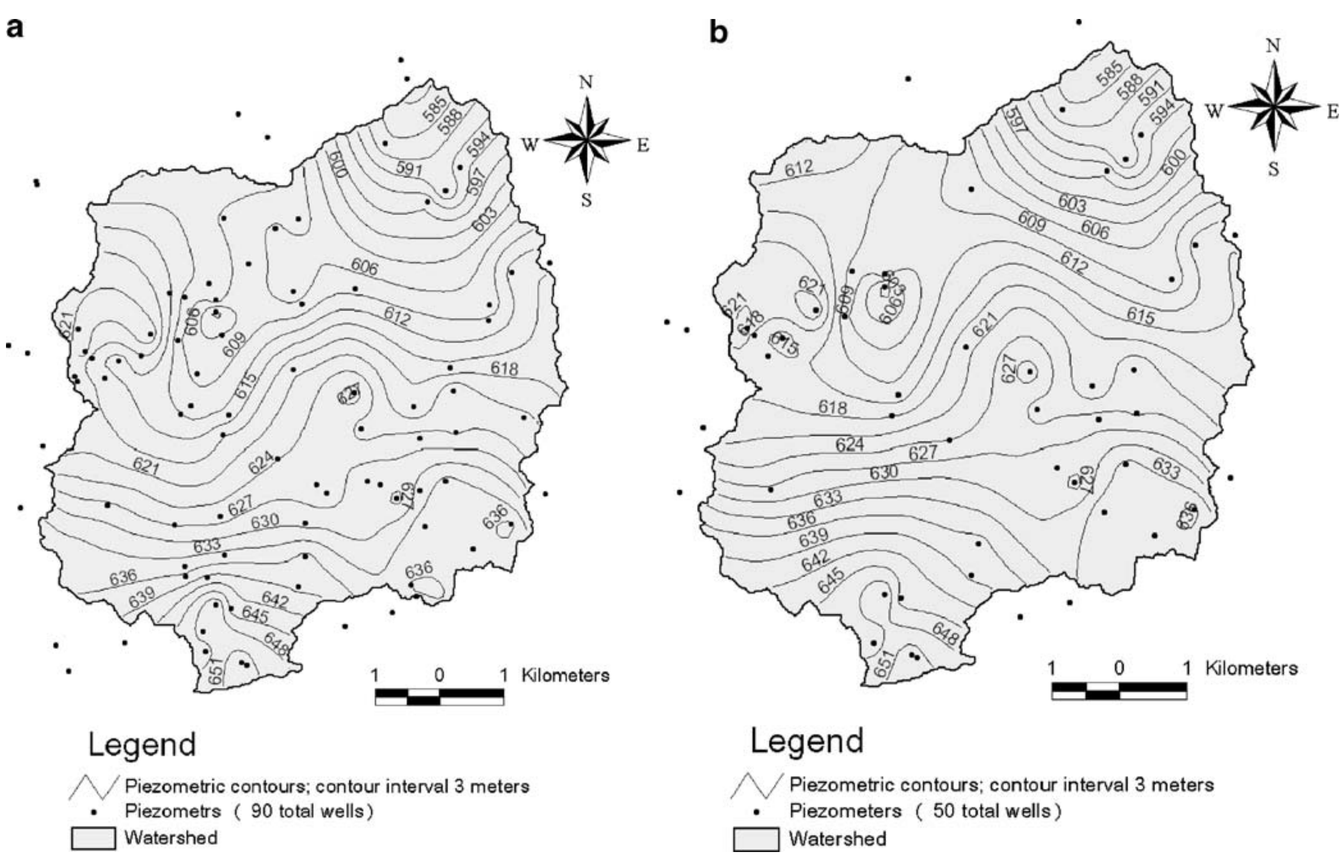

Fig. 6 **a** Piezometric contour map for the watershed based on measurements from 90 wells (December 2003). **b** Piezometric contour map for the watershed based on measurements from 50 wells (December 2003)

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Having assigned a priority to the piezometers, the next step was the calculation of the mean piezometric level for June 2003, December 2003, and June 2004. Eighteen sets of measurements from the network were collected for each three seasons starting from 90 piezometers to 5 piezometers, each time removing the wells of lower priority, 5 at a time. Figures 5a,b; 6a,b; and 7a,b show the piezometric contour maps for the periods of June 2003, December 2003, and June 2004 using 90 and 50 measurements, respectively, for illustration. These values were incorporated for the calculation of the water budget and optimization of the monitoring network according to the sensitivity of the recharge, specific yield, and annual water-balance values.

Discussion

Piezometric contour maps for June 2003, December 2003, and June 2004 seasons were made using measurements from the network of 90 monitoring wells and then with 85, 80, 75, and so forth from the priority-assigned monitoring wells. The evolution of mean piezometric levels when removing different numbers of piezometers for one hydrological year are shown in Table 6. A monsoon type of climate that is characterized by a distinct rainy season lasting from mid June to mid October, is present over the study area. This feature helps in dividing the hydrological year into two seasons: the post-monsoon season (from June to December) and the pre-monsoon season (from January to May). Because of the rainfall events in the post-monsoon season, water levels rise.

Table 6 Evolution of mean piezometric level when removing differing numbers of piezometers for one hydrological year

No. of wells	June 2003	December 2003	June 2004
90	609.50	618.48	613.48
85	609.48	618.44	613.55
80	609.45	618.39	613.47
75	609.45	618.45	613.38
70	609.48	618.38	613.39
65	609.45	618.82	613.59
60	609.39	618.91	613.55
55	609.75	619.17	613.85
50	609.99	619.67	614.18
45	610.76	620.01	615.05
40	610.28	619.86	614.95
35	610.49	620.42	615.29
30	610.23	619.74	614.90
25	610.35	619.74	614.90
20	609.25	618.65	614.41
15	609.89	619.13	615.34
10	604.95	616.91	611.19
5	608.52	620.99	612.68

All piezometric levels are given in meters above mean sea level.

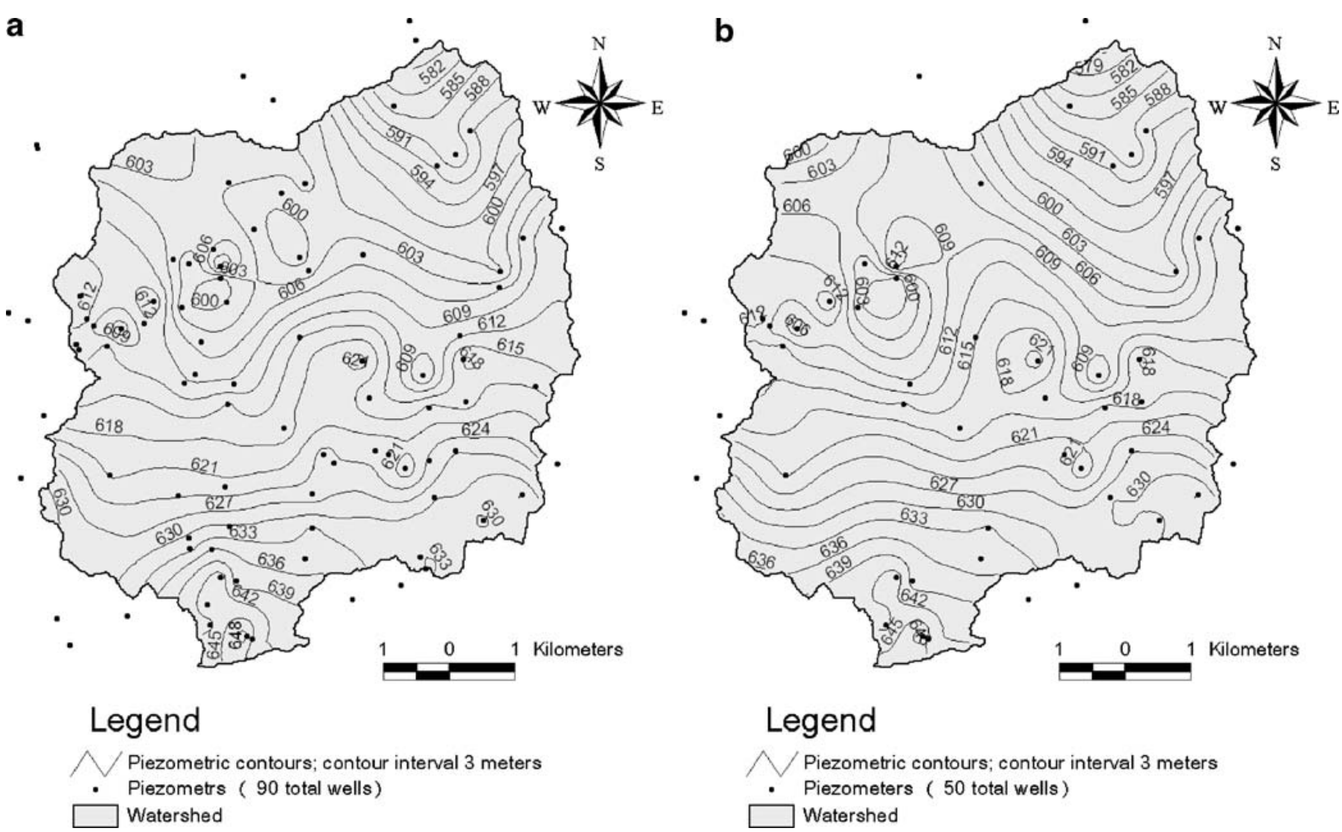

Fig. 7 **a** Piezometric contour map for the watershed based on measurements from 90 wells (June 2004). **b** Piezometric contour map for the watershed based on measurements from 50 wells (June 2004)

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Table 7 Specific yield, recharge, and annual balance calculated using differing numbers of piezometers

No. of wells	Specific yield (dimensionless)	Recharge per year (mm)	Annual balance (mm)
90	1.41E-02	166.53	55.93
85	1.42E-02	166.33	55.73
80	1.37E-02	162.82	52.22
75	1.38E-02	164.79	54.19
70	1.36E-02	165.25	54.65
65	1.33E-02	164.88	54.28
60	1.29E-02	161.98	51.38
55	1.37E-02	164.96	54.36
50	1.37E-02	166.99	56.39
45	1.38E-02	167.80	57.20
40	1.38E-02	167.76	57.16
35	1.36E-02	166.34	55.74
30	1.34E-02	166.09	55.49
25	1.42E-02	172.42	61.82
20	1.44E-02	167.06	56.46
15	1.47E-02	163.73	53.13
10	1.48E-02	169.72	59.12
5	1.24E-02	179.71	69.11

During the pre-monsoon season with little or no precipitation, water levels decline.

Considering there is no precipitation from December to June, the recharge component in Eq. (6) can be ignored and the value of specific yield is obtained precisely. Once the specific yield is known, the value can be used in Eq. (6) to calculate the recharge component in the wet season. The results of the calculations are given in Table 7. These results correspond to only one hydrological year from June 2003 to June 2004. High rainfall in the 2003 monsoon has resulted in a positive annual balance. Eliminating the wells of least priority, as determined by the cross validation, the accuracy of the water-budget calculation is maintained. Also, the density of the monitoring network can be decreased considerably, thus, saving time and cost for the piezometric surveys.

Figures 8 and 9 show a comparison of the specific yield, recharge, and the annual balance calculated using different piezometric networks. Figure 8 shows the value of specific yield and recharge versus the number of wells. The values remain relatively constant even when the piezometric network is reduced to 25 wells. Figure 9 shows the annual balance calculated with differing numbers of piezometers. From Fig. 9, it can be concluded that reducing the piezometric network from 90 to 50 wells can give almost the same results. Therefore, the number of piezometers to be monitored every season can be reduced from 90 to 50 without significantly affecting the results. Figure 10a,b shows the locations of the 90 and 50 wells, respectively. Some of these piezometers fall outside the watershed limits. Taking piezometric levels outside the watershed boundaries is especially important while calculating the horizontal inflows and outflows across the watershed limits.

The idea of optimizing a piezometric network and assigning the priority index with the help of a geostatistical cross-validation test is simply that if the water-level measurement at a particular well could be reproduced using estimation theory with a higher accuracy or minimum variance of the estimation error, then that well need not be measured and can be omitted from the piezometric network. However, on the contrary, a water level at a particular well is estimated with a large error in the form of the variance of the estimation error, so the water level should be measured at that well and the well be given a higher priority in the piezometric network. The top-down approach (reducing the number of wells) is feasible because in the over-exploited areas, a large number of wells are already available. The optimal network has been tested for validity using various parameters simultaneously, with respect to mean water level, specific yield, recharge estimation, and the groundwater balance.

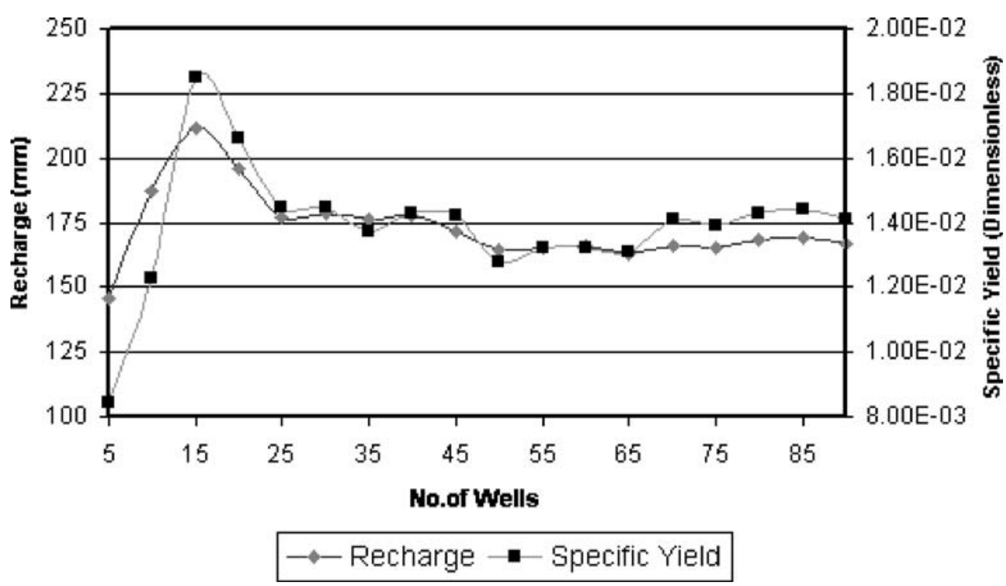

Fig. 8 Recharge (in mm) and specific yield (dimensionless) versus the number of wells

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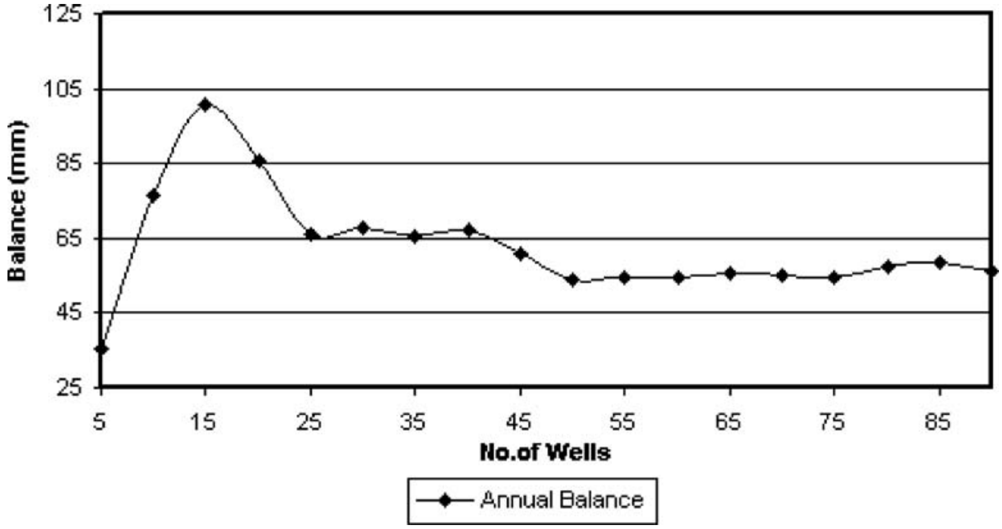

Fig. 9 Annual balance (in millimeters) versus the number of wells

Conclusions

The over-exploitation of groundwater reserves has been common in most parts of the world including India because of some of the reasons given below including:

- Abundance of agriculture-dominated areas (the agricultural sector consumes the most water)
- Absence of perennial surface-water resources
- Extreme climatic conditions where the rainy days are limited to around 50 in a year and the rest of the days are dry
- Arid and semiarid climate
- Cultivation of water-consuming crops

The stress on the aquifers not only poses a quantity problem in the form of water-level declines but also affects the quality of water. Thus, it is clear that

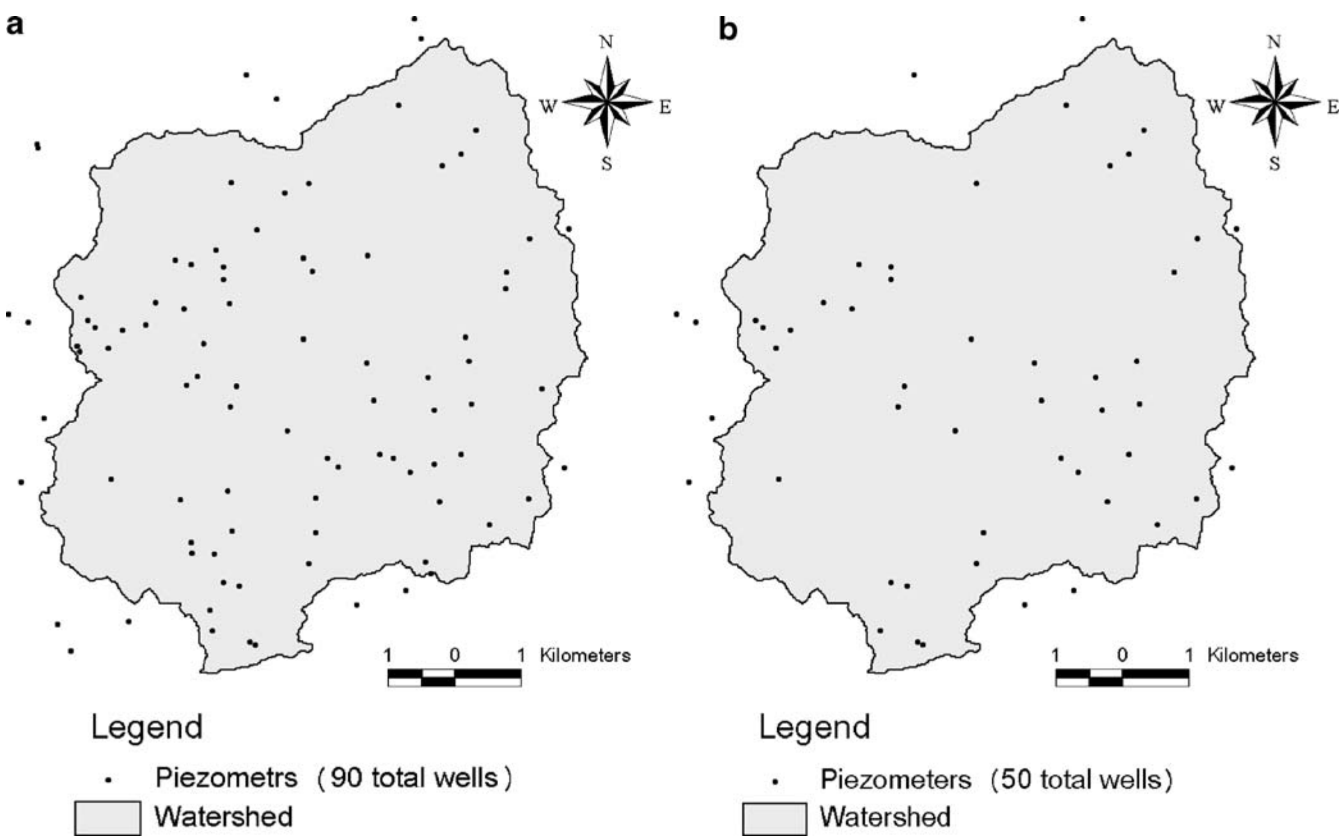

Fig. 10 **a** Location of the piezometers in the analysis with a total number of 90 wells. **b** Location of the optimized piezometers in the analysis with a total number of 50 wells

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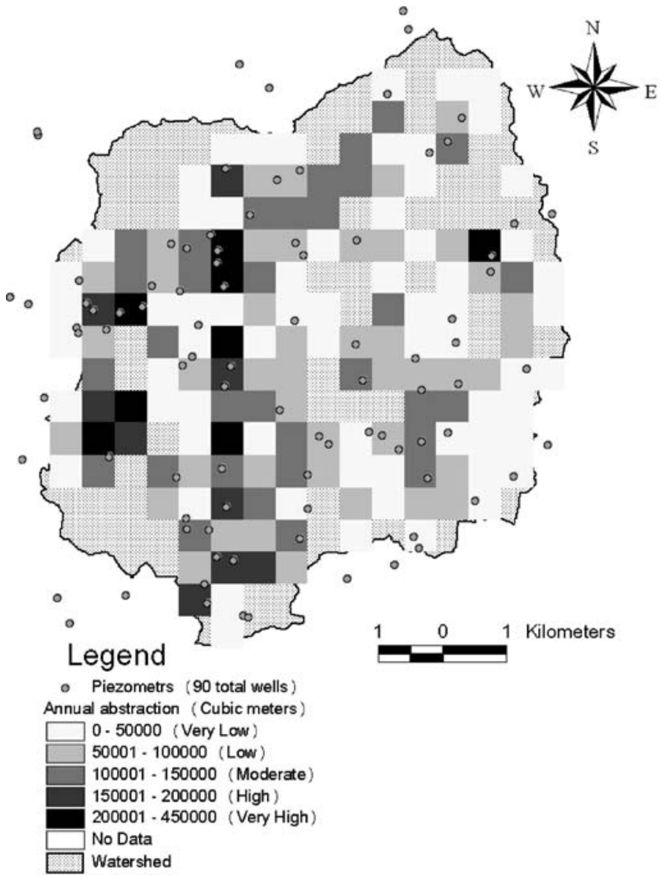

Fig. 11 Map showing the distribution of the pumping categories in the watershed and the location of the piezometers

management of groundwater (to strike a balance between water availability and demand) is essential. For this management, a precise estimate of each component of the groundwater cycle is imperative. In the present study, the various components have been elaborated and calculated for one hydrological year. This results in providing the adequate methodology for computing these components and the aspect of these calculations in the density of data and the frequency of calculations. It is obvious that the higher the density of measurement, the more precise will be the calculations. At the same time, to have these calculations at frequent intervals, a huge amount of data is required. These data requirements threaten the cost-effectiveness of a project, as well as requiring appreciable time. Thus, the application of geostatistics in analyzing each parameter and every measurement point to suit parameter variability and then assigning a priority index for measuring or omitting the variability has been useful. This methodology has been applied to three time periods, thus, making it suitable for further application in later time periods. Also, the methodology has been based on and also tested on different output with respect to mean water level, specific yield, and the resulting water balance. Of course, there always is a chance of improving the piezometric network. The network appears to be optimal and can be used for further piezometric surveys in calculating the water balance that is necessary for predictive modeling, as well as for decision support tools.

It is important to know the position of the wells that have been selected by optimization, i.e., their position with respect to the pumping areas or the geology has been analyzed. In general, areas of high pumping should show a much higher variation in the water-level fluctuations as compared to areas with no or minimal pumping. Based on the annual pumped volume of water, grids of 500 by 500 m were made and the volume of water abstracted in each grid was calculated (Fig. 11). There was no value for cells that did not contain any pumping wells, and also no data are available for cells outside the watershed. The entire watershed has been categorized into five classes of pumping: very low, low, moderate, high, and very high pumping.

The number of piezometers in each of the pumping categories was counted starting from 90 piezometers to 45 piezometers, and the corresponding numbers in each of the pumping categories was expressed as a percentage and have been presented in the form of a bar graph (Fig. 12).

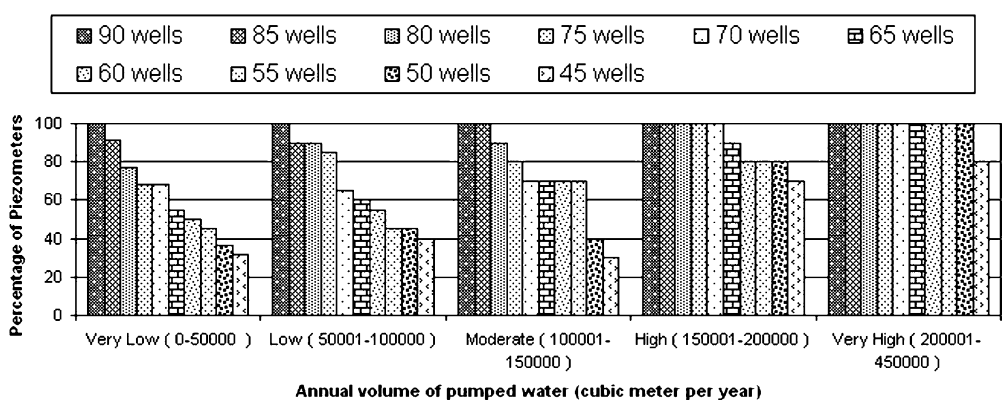

Fig. 12 Percentage of piezometers in the different pumping categories from 90 to 45 wells. Ninety wells have been taken as the standard and their distribution in each of the pumping categories has been represented in the form of percentage. Then the distribution of piezometers in each pumping category has been calculated by removing 5 wells every time according to the well priority established using cross-validation

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This graph gives an overview of the relation between the pumping zones and the position of the piezometers necessary to be monitored in each of the categories.

The findings are in accordance with the optimization as the maximum number of piezometers has been removed from areas of low pumping and there is no change in the number of piezometers to be monitored in the highly pumped areas, even when the piezometers are reduced from 90 to 50 by optimization.

In a situation when the above methodology is to be applied to another watershed, it is advisable to have a detailed investigation of the land-use pattern of the area so as to demarcate the zones of high pumping. The zones of high pumping will closely follow the agricultural land, especially if there is some paddy cultivation in the given area. The density of piezometers in these zones should be higher as compared to the zones of low pumping. Care should be taken that, during the first piezometric set of measurements in a watershed, the piezometers should be evenly distributed throughout the area with high density in the pumped zones. If it is further required, the piezometric data could be geostatistically analyzed to optimize the monitoring network for the subsequent years, in other words selecting the piezometers that have a higher priority and discarding the others, thereby reducing the time and cost involved in the subsequent surveys. In addition to the cost-effectiveness the optimal network also ensures the minimum time required to monitor this time-varying parameter and then it becomes logical to assign the values to a particular time.

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References

Ahmed S, Gupta CP (1989) Stochastic spatial prediction of hydrogeologic parameters: use of cross-validation in Krigings, vol III. In: Gupta et al (eds) Proc of the Internat Groundwater Workshop, Hyderabad, India, Feb–March 1989, pp 77–90

Ahmed S, Bertrand F, Saxena VK, Subrahmanyam K, Touchard F (2003) A geostatistical method of determining priority of measurement wells in a fluoride monitoring network in an aquifer. J Appl Geochem 4(2B):576–585

Beekman HE, Xu Y (2003) Review of groundwater recharge estimation in arid and semiarid Southern Africa. Council for Scientific and Industrial Research (South Africa) and University of the Western Cape Report, CSIR, Pretoria, South Africa

Coudrain-Ribstein A, Pratx B, Talbi A, Jusserand C (1998) Is the evaporation from phreatic aquifers in arid zones independent of the soil characteristics? CR Acad Sci Paris, Sci Terre Planèt 326:159–165

Dewandel B, Maréchal J-C, Lachassagne P, Wyns R, Krishnamurthy NS (2006) A conceptual hydrogeological model of hard rock aquifers structure and hydrodynamic parameters controlled by a multiphase weathering. J Hydrol 330(1–2):260–284

Dewandel B, Gandolfi J-M, de Condappa D, Ahmed S (2007) An efficient methodology for estimating irrigation return flow coefficients of irrigated crops at watershed and seasonal scale, J Hydrol (in press)

Galeazzi (2002) Groundwater balance of a hard-rock aquifer in a semi-arid area, Maheshwaram watershed: a case study. Centre d'hydrogeologie, Université de Neuchatel, Neuchatel, Switzerland

Maréchal JC, Galeazzi L, Dewandel B, Ahmed S (2003) Importance of irrigation return flow on the groundwater budget of a rural basin in India. In: Servat E, Nazem W, Leduc C, Ahmed S (eds) Hydrogeologie des regions mediterranennes et semi-arides [Hydrogeology of semi-arid and Mediterranean regions]. IAHS Publication No. 278, IAHS, Montpellier, France, pp 62–67

Maréchal JC, Dewandel B, Ahmed S, Galeazzi L, Zaidi FK (2006) Combining the groundwater budget and water table fluctuation methods to estimate specific yield and natural recharge. J Hydrol 329:281–293

Pannatier Y (1996) VarioWin-software for spatial data analysis in 2D. Springer, New York, pp 91

Raj P (2004) Classification and interpretation of piezometer well hydrographs in parts of southeastern peninsular India. Environ Geol 46:808–819

Schicht RJ, Walton WC (1961) Hydrologic budgets for three small watersheds in Illinois. Ill State Water Surv Rep Invest 40:40

DOI 10.1007/s10040-007-0167-z