Landscape entropy approach to demarcate pathways for oozing of water in a desert area in India

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Oozing of groundwater in Jodhpur city in the desert area of Rajasthan, India has caused weakening of foundations and cellars of buildings and shops. It has become more significant since 1996 when Kaylana lake was connected with Rajiv Gandhi Lift Canal (RGLC) water supply and filling of the lake had started. This has resulted in fear among dwellers about any future calamity. The hydrogeological, hydrochemical and isotopic studies clearly indicated that the lake water is responsible for the oozing phenomenon in the area. This article highlights a landscape entropy approach to assess pathways causing rise in the level of groundwater integrating the measured lake water level and groundwater table in a few selected wells in the city. With the fractional information of lake water and groundwater, marginal entropies of lake water and depths to groundwater in the selected wells sites are calculated. Mutual information, on common uncertainty associated in the measurements of lake water and groundwater, is also provided. Subsequently, ratios of mutual information to marginal entropy of the lake water are used as a measure for demarcating the pathways of weak zones, which correlate well with the lineaments delineated from satellite imagery. The results of this study represent a base for additional insight on future work, which will help in tracing the connectivity of weak zones causing oozing of water in Jodhpur city, and evolving a plan for remedial measures.

Keywords: Desert area, landscape entropy, marginal entropy, oozing of water.

WATER shortage has been a serious problem in the entire desert state of Rajasthan, India. At the same time Jodhpur city in the desert area is facing a contradictory scenario of oozing of groundwater, causing building collapse[1]. Government and local people are being forced to pump out large amounts of water to save their shops and basements of houses. It has been observed that groundwater level has risen to barely a few centimetres below ground surface and has covered 40% of the land area of the city. To lower the groundwater level in the city, the government agencies have now started pumping out water from wells and other resources.

The groundwater occurrence, distribution and movement is a subsurface phenomenon, depending on terrain features like physiography, drainage, lithology, geological structures and hydrogeology[2,3]. The water which occurs below the ground surface of the earth usually held in cracks, fractures, porous and permeable rock formations is called groundwater, whereas surface water occurs above the surface of the earth. If both surface and subsurface waters get connected to each other, then the groundwater get recharged with the surface water resulting in rise in the water table[2]. The rise and fall of the water table depends on many factors. Heavy rains or melting of snow causes rise in the water table[4,5]. But successive dry periods and extensive groundwater exploitation cause fall in the water table[6]. While a large part of the world, including India is presently facing the problem of decline in groundwater table, the phenomenon of rise in groundwater table in some parts of Jodhpur city is considered to be associated with Kaylana lake[1], which was connected with the Rajiv Gandhi Lift Canal (RGLC) supply in 1996.

The previous of hydrogeological, hydrochemical and isotopic studies clearly indicated that the source of groundwater level rise in the city is mainly from the Kaylana reservoir. In this context, the hydrochemcial analysis of inundated water[7,8] indicated that major cations and anions in oozing water are mostly less than that of nearby hand pumps or dug wells. Similarly, the absence of faecal coliform (*Escherichia coli*) in the basement samples rules out the possibility of seepage from sewer lines/sewer water[7,9]. The δ^2H, δ^{18}O and environmental tritium contents of water samples collected from different sources (i.e. lake, filter houses, ponds, basement, hand pump and dug wells) were also measured[10]. The cross plot of δ^2H and δ^{18}O indicates that the basement samples fall between lake water and groundwater. This implies that the lake water contributes to the groundwater and a mixed water is inundating the basement complexes due to rise in groundwater table. Tritium results also suggest that the basement samples are mixtures of lake water and groundwater. The causative analysis of the water table rise points out the presence of lineaments/joint sets in the rocks apart from (i) reduced groundwater extraction from existing bore

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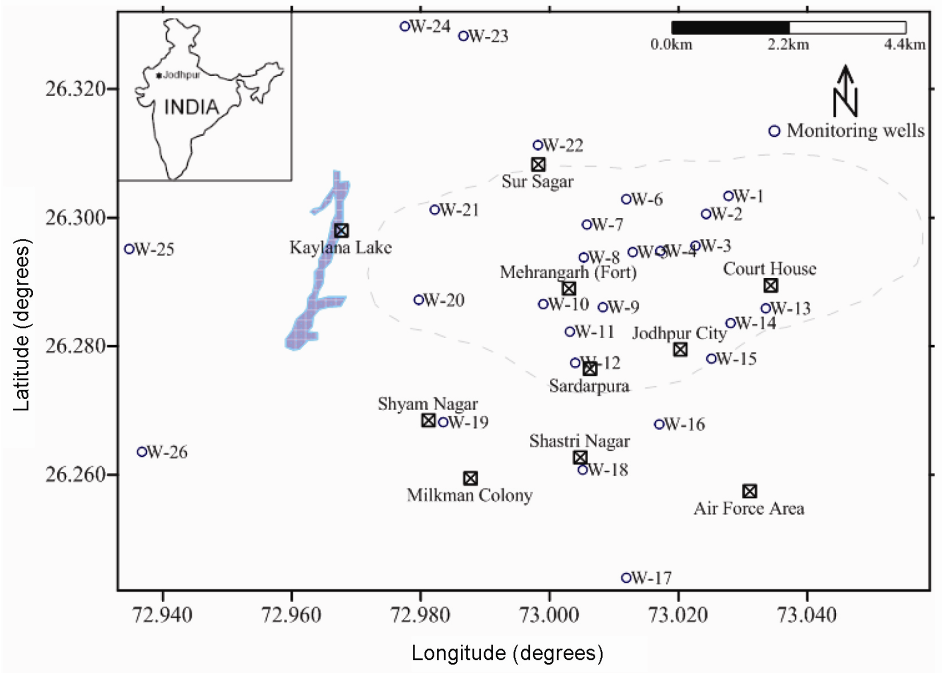

Figure 1. Location map of Jodhpur city, Rajasthan showing groundwater monitoring wells and Kaylana lake along with anomalous zone (dotted grey colour) of oozing groundwater.

wells and hand pumps after commissioning of the RGLC water supply; (ii) leakage of used household water from unlined drain system, and (iii) presence of impervious sandstone basement at shallow depth below the porous rhyolite aquifer in the city.

The problem came to light when subsoil water started oozing out from the underground structures in several shops situated in the heart of the city. The groundwater table has been continuously rising approximately 1.0 m/yr in the old walled city and adjoining areas. Thus a landscape entropy approach has been made to analyse the time-series data of depth to groundwater level, rainfall and water level in the Kaylana lake for assessing the possible pathway of weak zones, which are responsible for rising groundwater table in the city.

Description of the study area

Jodhpur city situated in the western part of Rajasthan, falls under arid and semi-arid climatic conditions (Figure 1). The city is characterized by undulating topography partly along the foothills and partly in the plains formed by weathering of rhyolite and sandstone. Major part of this city is located on pediment zone. The sills of rhyolite rise to an elevation of 395 m amsl, where the prominent elevated geomorphological features exit near the Kaylana lake in the western part of the city. The plain low topography of 210 m amsl is observed in the southeastern part[1]. The sewerage is directed to Jojari River through various drains/channels in the southeastern part of the city. The drainage pattern is not fully developed, but the satellite image depicts that the drainage could be parallel to sub-parallel and structurally controlled. The main ephemeral streams in this region are Golasni and Jojari.

A general overview of rainfall pattern, as recorded in the city, indicates that precipitation occurs mainly through the southwest monsoon, but it is mostly irregular. Most of the rainfall occurs by the first week of July and withdraws by the second week of September. The southwest monsoon contributes an average of 90% annual rainfall in the study area. The mean annual rainfall was about 452 mm/yr during 1994–2001. Temperature increases slowly to a maximum of 45°C in summer months up to June and heat wave prevails over the area. In contrast, during December and January, the mean night temperature is 6–10°C. Minimum temperature reaches the freezing associated with cold waves of western disturbances during winter season.

Geological and hydrogeological set-up

Geologically the study area is composed of sedimentary rocks and rhyolites[11]. In Jodhpur city, Malani rhyolite and Jodhpur sandstone are found inter-layered with shale. The lower flow of Malani rhyolite is highly faulted, folded, weathered and fractured forming highly porous strata. Geomorphologically the area is located on a pediment starting from the foothills which encompasses the city along the northern and western boundaries. The city area consists of mainly alluvium and rhyolite, whereas Kaylana lake situated about 10 km to the west of the city, is located over highly fractured and columnar jointed rhyolite[7,10].

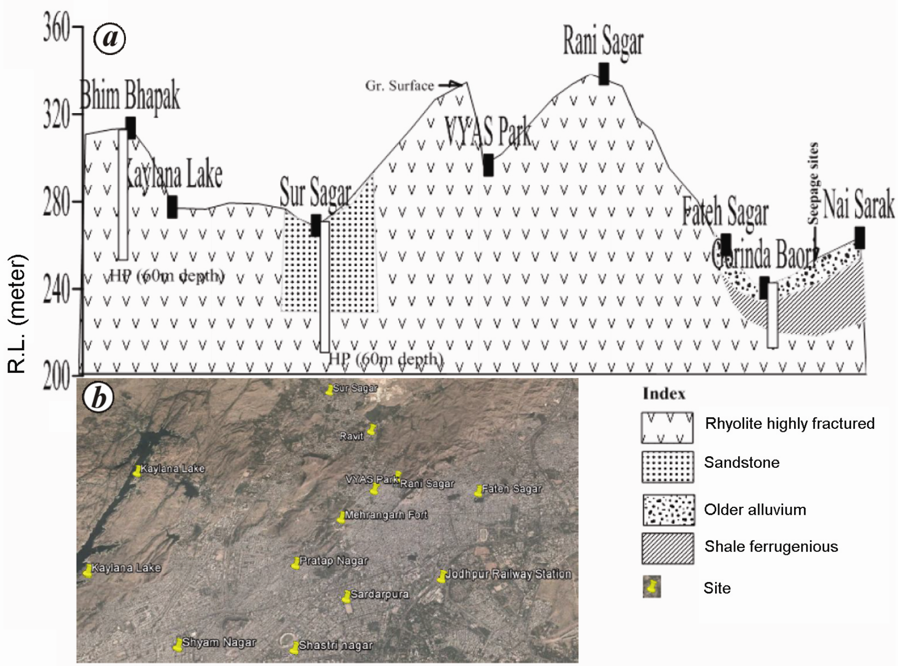

Figure 2. ***a***, Reduced level of seepage locations and Kaylana lake along with geological setting; ***b***, Sites along with Kaylana lake.

A massive rhyolite runs from northeast to southwest between Kaylana lake and the city. The northern and eastern periphery of the city consists of alluvium and sandstone. A typical geological cross-section (Figure 2) shows reduced levels of seepage in different parts of the city. The reduced level of Kaylana lake between Bhim Bhapak and Sur Sagar is approximately 280 m amsl, whereas reduced level of seepage locations between Fateh Sagar and Nai Sarak is about 250 m amsl. The affected inundated area is sloping from north to east and southeast. Shale and sandstone formations are deformed due to tectonic activity and cover maximum area of the old walled city in Jodhpur. It is also observed that some major lineaments (E–W direction) are developed cutting across the reservoir and extended up to several kilometres towards the city. Apart from E–W traversing lineaments, other lineament sets in the NW–SE, WNW–ESE and NNW–SSE directions are also clearly visible from the satellite imagery. Together these lineaments form a dense fracture network and provide an easy conduit for movement of the lake waters towards the city. Due to dense urbanization, these lineament sets are not clearly visible.

Hydrogeologically the formations of Jodhpur sandstone, Malani rhyolite and Quaternary alluvium are important. The groundwater occurs under water table condition. The water table variation is mainly controlled by aquifer characteristics[12]. The different sets of joints, faults and fractures as well as clay material and ash beds play an important role in the circulation, distribution and movement of groundwater. Hydrogeologically the Jodhpur sandstone forming the main aquifer is grouped into two types, i.e. (i) fine to medium-grained shaly sandstone and (ii) medium to coarse-grained pebbly sandstone. It has been observed that the head difference of about 20–50 m from the lake water to different parts of the city may be adequate for the reservoir-induced water percolation towards the city.

Materials and methods

Data collection and analysis

An important component of hydrogeological survey is monitoring of groundwater level, which directly reflects the change in groundwater storage over a time domain. For this study, 26 wells (Figure 1) in and around Jodhpur city were monitored for groundwater level during pre- and post-monsoon periods for the years 1994 to 2001 (ref. 13). This measurement is required for preparation of well hydrographs, which provide information about recharge and discharge phases of any hydrogeological system[2]. To evaluate the impact of reservoir on groundwater system beneath Jodhpur city, continuous data from 26 wells for 8 years between July 1994 and September 2001 were analysed using entropy theory. Some data gaps for these wells were calculated using a moving average method[14]. The spatial variation in depth to water table, well hydrographs and water table contour maps were prepared using kriging method. In order to collate all the information pertaining to hydrogeological aspects, data such as rainfall and water level of Kaylana lake were also collected for the same period. These data were used to trace the probable pathways of oozing groundwater in Jodhpur city using landscape entropy.

Entropy theory

'Entropy' is Greek word meaning transformation; it is a function of a state. The theory was first developed by Shannon[15]. He defined a quantitative measure of the information content or uncertainty associated with a probability distribution of a random variable in terms of entropy. By application of entropy, uncertainty/information can be quantified taking into account all available information. Thus, entropy is a measure of the amount of uncertainty represented by the probability distribution and is also a measure of the amount of chaos or of the lack of information about a system. If the complete information is available, entropy is zero; otherwise, it is greater than zero[16]. The entropy concept has found widespread application in various problems, e.g. mining industry[17], financial time-series analysis[18], ecology[19], biology[20], economics[21], hydrology[22,23] and groundwater resources[3,24,25].

In this article the information associated with data related to groundwater and lake water levels, and rainfall were subjected to analysis using marginal entropy, conditional entropy, joint entropy, transinformation and information transfer index (ITI). Readers could refer to Mondal *et al.*[3] for more details about these entropies. For a random variable X, with the probability distribution $p(x)$, marginal entropy $H(X)$ is defined as a measure of uncertainty content. The conditional entropy $H(X|Y)$ is not certainly contained in Y, but is a measure of information content of X for two random variables X and Y. The total information is called the joint entropy $H(X, Y)$, which contains in both X and Y variables. Then the information common between X and Y is called mutual information or transinformation $T(X, Y)$. It is interpreted as reduction in uncertainty of X due to knowledge of the random variable Y. Although it is an indicator of the capability of information transmission, it is not a good index for dependence of two variables, because its upper bound varies from site to site. It varies from zero to marginal entropy H. Therefore, it is standardization of information transferred from one site to another by normalizing transformation and known as ITI. The discrete approach proposed by Singh[26] has been adapted for the entropy measures. The unit of information measures bits, depending on the logarithmic base 2 was also considered for this analysis.

Results and discussion

Groundwater level

Pre- and post-monsoons water levels of July 1994–September 2001 for wells with satisfactory spatial coverage of the study area were selected (Figure 1). Statistical

Table 1. Depth to groundwater level (m bgl) in 26 wells in and around Jodhpur city, Rajasthan, India

			Depth to groundwater level (m bgl)			
			Pre-monsoon	Post-monsoon	Pre-monsoon	Post-monsoon
Well no.	Longitude (degrees)	Latitude (degrees)	July 1995	September 1995	July 2001	September 2001
W-1	73.0278	26.3034	5.20	4.85	3.19	2.50
W-2	73.0243	26.3006	7.44	7.36	4.52	4.20
W-3	73.0226	26.2957	2.48	2.25	0.65	0.64
W-4	73.0172	26.2948	8.76	8.77	3.96	2.90
W-5	73.0129	26.2947	7.99	7.71	5.35	4.22
W-6	73.0119	26.3029	3.49	3.38	1.40	1.22
W-7	73.0058	26.2990	7.50	6.95	2.60	2.52
W-8	73.0053	26.2938	5.31	1.98	3.28	1.70
W-9	73.0083	26.2861	34.47	34.30	20.35	18.00
W-10	72.9990	26.2866	11.24	11.10	7.56	7.04
W-11	73.0032	26.2823	34.95	34.80	24.39	23.28
W-12	73.0040	26.2774	30.80	30.60	21.39	20.09
W-13	73.0335	26.2860	14.33	14.17	10.70	7.50
W-14	73.0281	26.2836	10.32	10.27	7.20	4.91
W-15	73.0251	26.2781	20.40	20.20	6.46	5.46
W-16	73.0170	26.2679	24.06	24.08	19.32	18.75
W-17	73.0119	26.2440	36.81	36.82	33.65	32.37
W-18	73.0051	26.2608	33.31	33.33	30.36	27.18
W-19	72.9835	26.2682	22.24	21.97	17.95	16.20
W-20	72.9797	26.2873	21.25	21.29	14.45	12.00
W-21	72.9822	26.3013	17.15	17.36	12.10	9.61
W-22	72.9982	26.3113	20.45	18.80	18.65	10.50
W-23	72.9866	26.3282	10.75	4.50	7.83	1.70
W-24	72.9776	26.3297	18.55	18.37	26.59	20.88
W-25	72.9348	26.2952	13.60	13.50	14.10	11.09
W-26	72.9368	26.2636	17.95	14.10	17.18	16.63

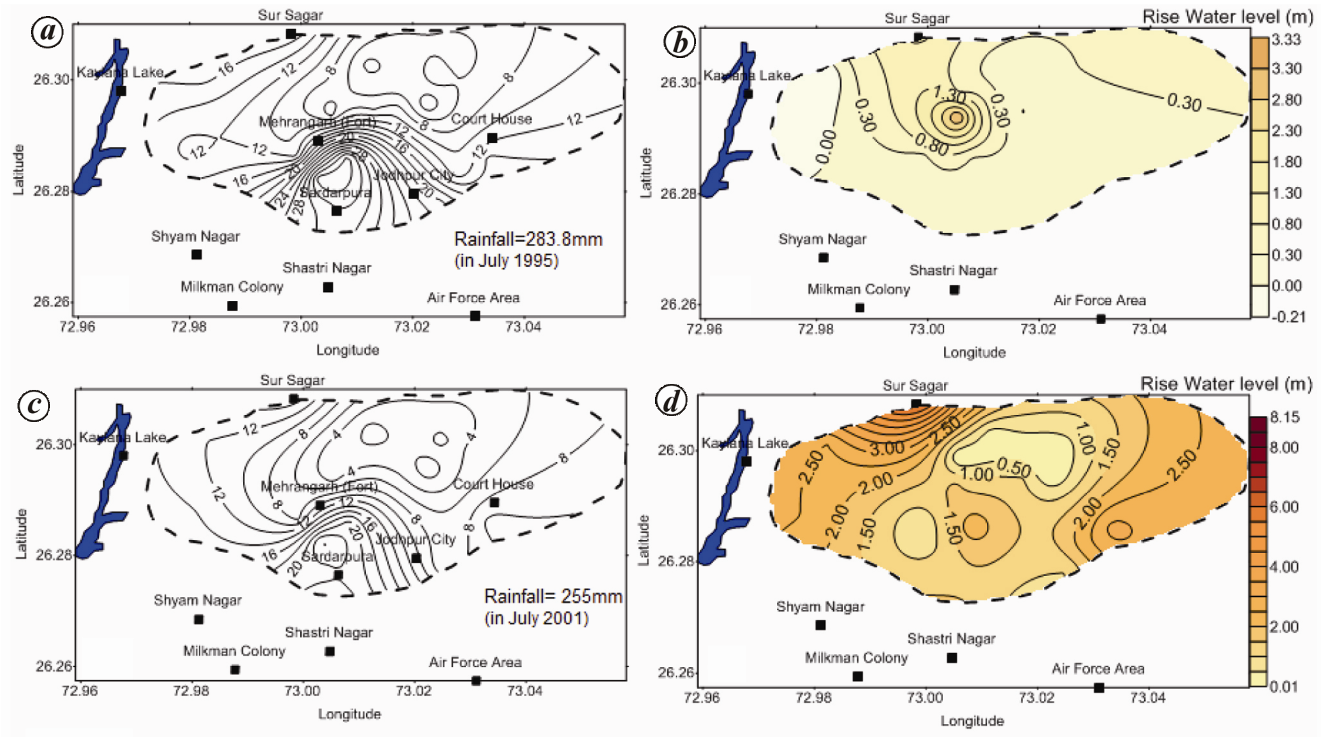

Figure 3. ***a***, Depth to water level contours (m bgl) in July 1995; ***b***, Water level rise (m) during post-monsoon in 1995; ***c***, Depth to water level contours (m bgl) in July 2001; ***d***, Water level rise (m) during post-monsoon in 2001.

analysis of the measured groundwater level for data indicates that groundwater table is highly variable from place to place. It varies from 0.20 to 37.90 m bgl with an average variation of 14.19 m bgl. The recent alluvium is followed by rhyolite in well nos W-9, 11, 12, 16-19, which show average water table fluctuation between 16.20 and 37.90 m bgl. The depth to water table (Table 1) in the area varies from 0.64 to 33.65 m, obtained from pre- and post-monsoon 2001 data at various places. Shallow water table (<5.00 m bgl) was observed in well nos W-1–W-8 in the old walled city, but very shallow groundwater table (<3.00 m bgl) was observed in well nos W-1–W-3 and W-6–W-8 in northeastern part of the city. At some places (i.e. KBK Mandir and Sojati Gate areas) the groundwater reached and over flowed the surface and the basements of buildings were fully saturated with groundwater flow and seepage[1,7].

Seepage water accumulated in the basement of buildings resulted in the rising of static water level (SWL) in some parts of the city (i.e. KBK Mandir and Sojati gate areas). Groundwater of all the wells, including seepage water was chemically analysed[7,8]. The analyses indicate that major cations and anions, including electrical conductivity (EC) of seepage water, are mostly less than those of water collected nearby hand pumps or dug wells. Chemical quality of water accumulated in the basement is not completely similar to groundwater in the wells nearby[7,27]. Also, coliform level is found to be above permissible limit in all the samples, irrespective of seepage water and groundwater[9]. But absence of faecal coliform (*E. coli*) in the basement samples signifies the non-contribution of sewer lines/sewer water[7]. Chandrasekharan and Navada[10] measured δ^2H, δ^{18}O and environmental tritium (env. ^{3}H) content of water samples from different sources (three from lake and filter houses, four from ponds, six from basements, and eight from hand pump-fitted bore wells and dug wells). The cross plot of δ^2H and δ^{18}O shows that the water samples from lake and filter houses (supply from lake) are depleted in stable isotopes δ^2H and δ^{18}O compared to other surface water bodies such as ponds. But basement samples fall between lake water and groundwater, which indicates contribution of lake water to the basement seepage water. Tritium results also suggest that the basement water samples are a mixture of lake water and groundwater.

Depth to water level contours were prepared separately for July of 1995 and 2001, and rising water level during the post-monsoon season was plotted using kriging method. Figure 3 show the water level contour maps. Depth contours in and around Jodhpur city varied from 2.48 to 34.95 m bgl during pre-monsoon in 1995 and from 0.65 to 33.65 m bgl in 2001, in spite of precipitation remaining almost same, 283.8 mm in July 1995 and 255 mm in July 2001 (Figure 3 *a* and *c*). Water level during post-monsoon varied from –0.21 to 2.33 m in 1995 (Figure 3 *b*), whereas in 2001, it varied from 0.01 to 8.15 m (Figure 3 *d*). This implies that groundwater in Jodhpur city is influenced by possible subsurface flows.

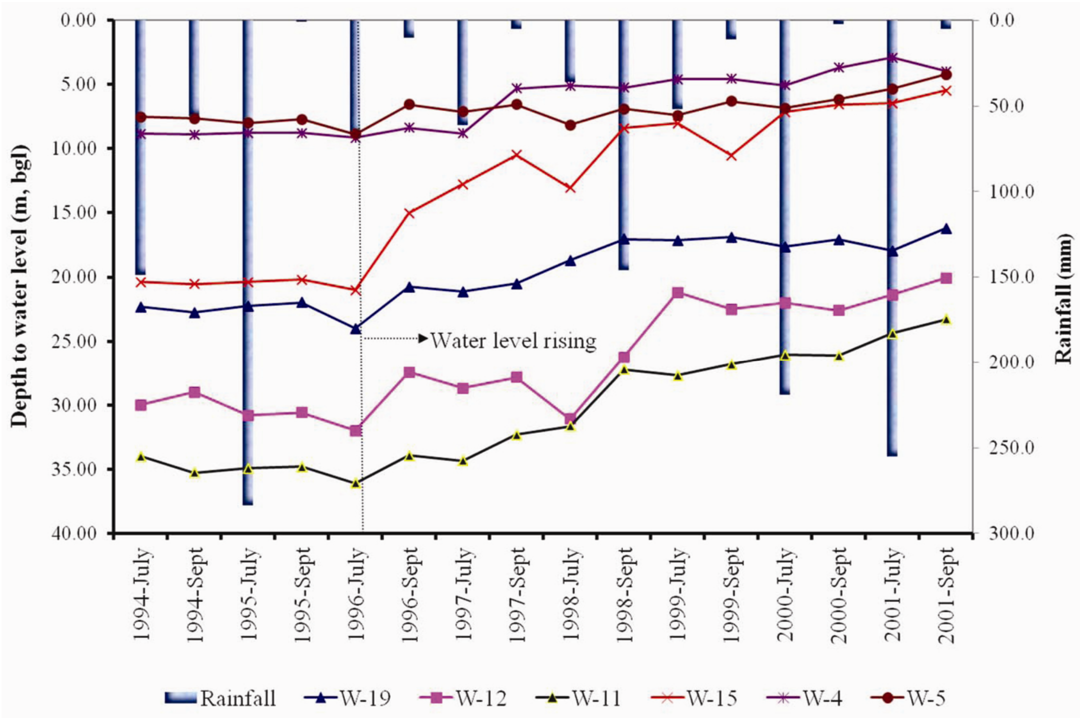

Figure 4. Well hydrographs for the well numbers W-4, 5, 11, 12, 15 and 19 and rainfall (mm) from 1994 to 2001 in Jodhpur city.

Table 2. Correlation matrix for depth to groundwater level in selected wells with rainfall and water level of Kaylana Lake in Jodhpur city

Correlation coefficient between rainfall and water level in the lake is 0.179 and 0.054 during pre- and post-monsoon, respectively	Depth to groundwater level (m bgl) at					
	W-4	W-5	W-11	W-12	W-15	W-19
Pre-monsoon rainfall (mm)	–0.139	–0.484	–0.307	–0.264	–0.049	–0.041
Post-monsoon rainfall (mm)	0.025	0.278	–0.075	0.160	–0.053	–0.134
Pre-monsoon lake water table (m)	–0.780	–0.717	–0.808	–0.738	–0.921	–0.877
Pre-monsoon lake water table (m)	–0.987	–0.717	–0.888	–0.822	–0.967	–0.881

Well hydrographs

Well hydrograph patterns can be grouped into two types. The first type of hydrographs shows rising trend of groundwater table for the wells which are located within the city. Wells located outside the main city in which the water level did not show any significant rising trend fall under the second type of hydrographs. Hydrographs of a few wells for which data on the pre- and post-monsoon periods available continuously were studied to understand the groundwater system behaviour as represented in Figure 4. The hydrographs of well nos W-4, 5, 11, 12, 15 and 19 show a rising trend and have also been collated with rainfall information. The hydrograph signature indicates that the groundwater system is getting recharged additionally through preferred pathways, such as lineaments. They are connected to the surface reservoir existing in the vicinity. Wells which do not show any significant rise in trend, may not be influenced by the reservoir-induced recharge process.

Cross plots among rainfall, groundwater and lake water

Various cross plots among rainfall, groundwater table and water level of Kaylana lake were prepared to study and interpret them in terms of comparative variation. The mean annual rainfall during 1994–2001 was about 452.0 mm. Rainfall showed large variations during these years. But the trend of rainfall pattern was almost similar and showed no significant variation. It was found that the trend of rainfall variation and pattern during the monsoon period was almost similar. This implies that the possibility of contribution of rainfall towards rise of water table is limited or almost negligible. Cross plots of rainfall and lake water level showed correlation coefficient of 0.179 and 0.054 for pre- and post-monsoon period respectively. Correlation coefficient of depth to water table at well no. W-15 with water level of Kaylana lake during pre- and post-monsoon seasons of 1994–2001 is –0.921 and –0.967 respectively (Table 2). The cross-correlation

Table 3. Contingency table for samples of lake water level (m) and depth to groundwater table (m bgl) at well no. W-1 in Jodhpur city during July 1994 to September 2001

		$x(i)$, Lake water table (m amsl)										
		$i = 1$	$i = 2$	$i = 3$	$i = 4$	$i = 5$	$i = 6$	n				
$y(j)$, Depth to water level (m bgl)		262–64	264–66	266–68	268–70	270–72	272–74	Total	P_j	$\log P_j$	$P_j \log P_j$	$H(Y)$
$j = 1$	0–5	2	3	0	2	4	2	13	0.813	–0.300	–0.243	0.696 bits
$j = 2$	05–10	0	0	1	1	0	1	3	0.188	–2.415	–0.453	
$j = 3$	10–15	0	0	0	0	0	0	0	0			
$j = 4$	15–20	0	0	0	0	0	0	0	0			
$j = 5$	20–25	0	0	0	0	0	0	0	0			
$j = 6$	25–30	0	0	0	0	0	0	0	0			
$j = 7$	30–35	0	0	0	0	0	0	0	0			
$j = 8$	35–40	0	0	0	0	0	0	0	0			
	Total	2	3	1	3	4	3	16				
	P_i	0.125	0.188	0.063	0.188	0.250	0.188					
	$\log P_i$	–3.000	–2.415	–4.000	–2.415	–2.000	–2.415					
	$P_{i*} \log P_i$	–0.375	–0.453	–0.250	–0.453	–0.500	–0.453					
	$H(X)$	2.483 bits										
	$P_{i,j}$	0.125	0.188	0.000	0.125	0.250	0.125					
		0.000	0.000	0.063	0.063	0.000	0.063					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
$P_{i,j*} \log P_{i,j}$		–0.375	–0.453	0.000	–0.375	–0.500	–0.375					
		0.000	0.000	–0.250	–0.250	0.000	–0.250					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
		0.000	0.000	0.000	0.000	0.000	0.000					
$H(X, Y)$		2.828 bits										
$T(X, Y)$		0.352 bits										
ITI		0.124										
Lateral influence (%)		14.16										

All entropies were calculated with base 2.

studies clearly indicate that two variables, namely water levels at Kaylana lake and water table in well no. W-15 are much better related when compared to the rainfall and water table.

Entropy-based measures

The value of probability distribution of x, $p(x)$ was estimated for computation of information measures based on frequency analysis of water level of each well. Then using a contingency table for individual wells against the lake water, joint probability $p(x, y)$ was computed. Sixteen events of groundwater level were used for making the contingency table. A typical 2D contingency table (Table 3) is presented as an example of analysis made for water levels of well no. W-1 and Kaylana lake. It illustrates that the depth to water table at W-1 and other wells has a range of values (0–5, 5–10, 10–15, 15–20, 20–25, 25–30, 35–40 m) consisting of eight class intervals, whereas the lake water level was presumed to have six class intervals with a range of 2.00 m bgl. The joint frequency for (i, j) is denoted by f_{ij}, $i = 1, 2, \ldots, 8$; $j = 1, 2, \ldots, 6$, where the first subscript refers to the column (water level of well no. W-1 and other wells) and the second subscript to the row (lake water level). Marginal frequencies are denoted by f_i and f_j for the column and row values of these two sets of water level respectively. Then marginal entropies of individual wells and total entropy, $H(X, Y)$ are estimated. Similarly, transinformation $T(X, Y)$ and ITI were also calculated for water level in each well with the help of marginal and total entropies along with $T(X, Y)$. A typical diagram for entropy measurement

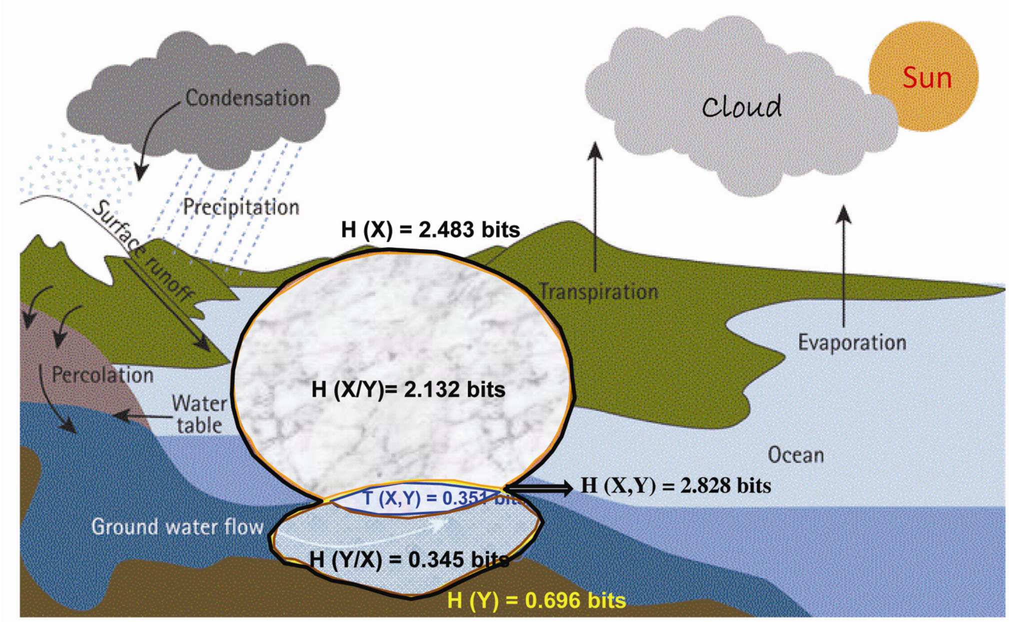

Figure 5. Information $T(X, Y)$ common to lake water (X) and groundwater table (Y) at well no. W-1 in Jodhpur city. $H(X|Y)$ is information only on lake water and not groundwater level; $H(Y|X)$ is information only on groundwater table at W-1 and not lake water table; and $H(X, Y)$ is total information on lake and groundwater table together showing the hydrological cycle.

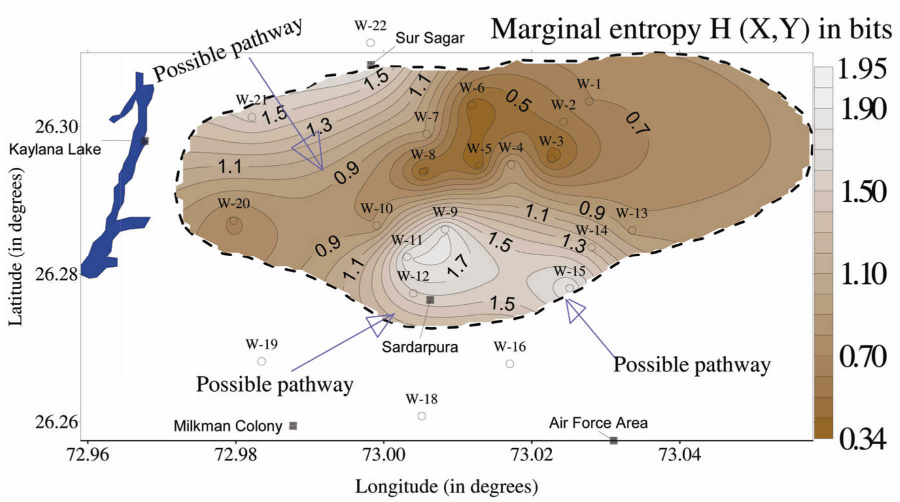

Figure 6. Distribution of marginal entropies $H(X, Y)$ for groundwater level in Jodhpur city.

between depths to water level corresponding to the lake water fluctuation is shown in Figure 5, which represents the bits of information of lake water transferred to groundwater system in Jodhpur city.

Landscape of marginal entropy: The calculated marginal entropy of measured water level ranges from 0.337 to 1.954 bits with an average of 0.995 bits. It was less than the average marginal entropy (~0.995 bits) for 62% monitoring wells in the city and its landscape is shown in Figure 6. It indicates that the information content in the areas of well nos W-9, 11, 12, 14, 15 and 19, in general, increases. This indirectly implies the possible pathways for rising groundwater level in the city. However, similar feature is also observed in the northwestern part of the study area (at well nos W-7, 21 and 22). The presence of impervious sandstone basement at shallow depth below the porous rhyolite aquifer in these areas is another important reason responsible to boost hydrodynamics that induce uncertainty to the measured groundwater level.

Landscape of joint entropy, transinformation and information transfer index: Table 4 shows the calculated

Table 4. Calculated marginal entropy $H(Y)$ at the wells, joint entropy $H(X, Y)$ and information transfer index (ITI) for depth to groundwater level and lake water level in Jodhpur city

Wells no.	Longitude (degrees)	Latitude (degrees)	$H(Y)$	$H(X, Y)$	$T(X, Y)$	ITI = $(T/H(X, Y))$
W-1	73.028	26.303	0.696	2.828	0.351	0.124
W-2	73.024	26.301	0.544	2.858	0.169	0.059
W-3	73.023	26.296	0.337	2.608	0.212	0.081
W-4	73.017	26.295	0.896	3.078	0.301	0.098
W-5	73.013	26.295	0.337	2.656	0.164	0.062
W-6	73.012	26.303	0.337	2.608	0.212	0.081
W-7	73.006	26.299	0.896	2.656	0.723	0.272
W-8	73.005	26.294	0.337	2.483	0.337	0.136
W-9	73.008	26.286	1.802	3.625	0.660	0.182
W-10	72.999	26.287	0.811	2.656	0.638	0.240
W-11	73.003	26.282	1.796	3.500	0.779	0.223
W-12	73.004	26.277	1.579	3.203	0.859	0.268
W-13	73.034	26.286	0.868	2.828	0.523	0.185
W-14	73.028	26.284	1.272	2.828	0.927	0.328
W-15	73.025	26.278	1.805	3.078	1.210	0.393
W-16	73.017	26.268	0.868	3.031	0.320	0.106
W-18	73.005	26.261	0.544	2.656	0.371	0.140
W-19	72.983	26.268	1.000	2.858	0.625	0.219
W-20	72.980	26.287	0.669	2.828	0.324	0.115
W-21	72.982	26.301	1.546	3.075	0.954	0.310
W-22	72.998	26.311	1.954	3.625	0.812	0.224

All entropies are calculated in bits and marginal entropy of lake water measurement, $H(X)$ = 2.483 bits.

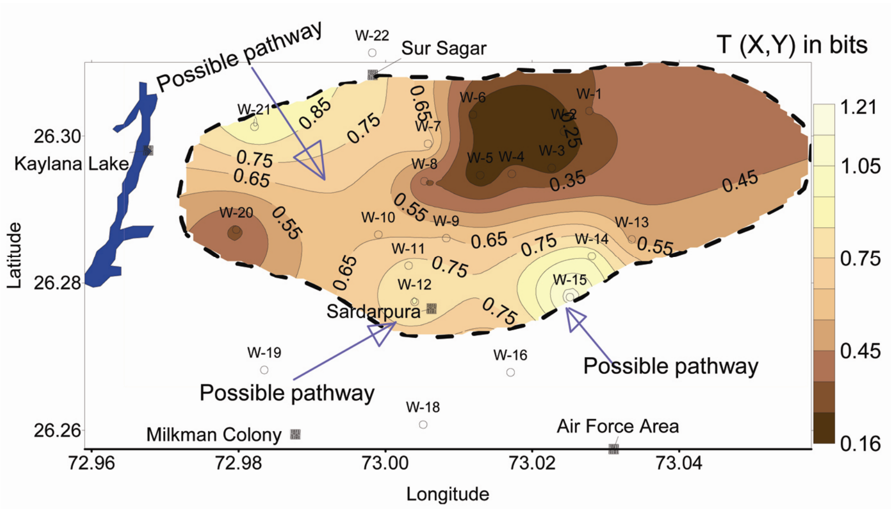

Figure 7. Distribution of estimated transinformation $T(X, Y)$ values in Jodhpur city.

joint entropy, transinformation and ITI. It can be seen from the table that the joint entropy at each well is similar to its marginal entropy. This implies that there is contribution from the lake water. The calculated water level transinformation in each well indicates that the value ranges from 0.164 to 1.21 bits with an average of 0.546 bits (Figure 7). It is found that there is no independent well influenced by the lake water in the city. But the calculated mutual entropy is comparatively low where the marginal entropy is quite less. The ITI values vary from 0.59 to 0.393 with a mean value of 0.183. This indicates that the lake water effectively influences the groundwater levels in the city over the areas covered by well nos W-15, 14, 21, 7, 12, 10, 22, 11 and 19, where the lineaments are well-connected[1].

Conclusion

Previous hydrogeological, hydrochemical and isotopic studies have shown that Kaylana lake water influences the oozing of water in Jodhpur city. We conclude here the probable water pathways through which the lake water influences the oozing of groundwater in the city area using landscape entropy applied to the fluctuations of depth to groundwater level and lake water level. Landscape entropy is applied to determine the areas of wells where marginal entropy is high. The well area having higher marginal entropy gives comparatively higher transinformation from the lake water, which could be considered as a pathway of contribution of lake water to groundwater system in the city. The well area that has lowest marginal entropy gives the lowest transinformation compared to other well areas, and is considered as having lesser influence from the lake.

The *T* values (for transformation/mutual information) show that there are mainly three pathways of lake water influencing the oozing of groundwater in the city. The path is along the areas of well nos W-19, 12 and 11; second path through the areas of well nos W = 15, 14, 13; and the third pathway is along well areas of well nos W-21 and 10. The defined direction of pathways is corroborated by the lineaments demarcated from satellite imagery. The gathered information constitutes a basis for gaining additional insight for future work that will help to trace the connectivity of weak zones influencing oozing of water at micro-scale level and for planning remedial measures.

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