Impact of over-exploitation on groundwater quality: A case study from WR-2 Watershed, India

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The WR-2 watershed is located in the Deccan trap basaltic terrain of Maharashtra State, India. The watershed area incorporates a rich orange orchard belt that requires a huge quantity of water for irrigation. This requirement is mostly met through groundwater, extracted from the shallow aquifers of the WR-2 watershed. However, over the years, excess withdrawal of groundwater from these aquifers has resulted in depletion of groundwater level. The declining trends of groundwater level, both long term and short term, have had a negative impact on the groundwater quality of the study area. This effect can be gauged through the rising electrical conductivity (EC) of groundwater in the shallow aquifers (dug wells) of the WR-2 watershed. It is observed that the long term declining trend of groundwater level, during 1977–2010, varied from 0.03 to 0.04 m per year, whereas the corresponding trend of rising EC varied from 1.90 to 2.94 $\mu\text{S}/\text{cm}$ per year. During 2007–2010, about 56% dug wells showed a positive correlation between depleting groundwater level and rising EC values. The groundwater level depletion during this period ranged from 0.03 to 0.67 m per year, whereas the corresponding trend of rising EC ranged from 0.52 to 46.91 $\mu\text{S}/\text{cm}$ per year. Moreover, the water quality studies reveal that groundwater from more than 50% of the dug wells of the WR-2 watershed is not suitable for drinking purpose. The groundwater, though mostly suitable for irrigation purpose, is corrosive and saturated with respect to mineral equilibrium and shows a tendency towards chemical scale formation.

1. Introduction

Groundwater resources play a major role in the social and economic growth of any country. Groundwater overdraft, a form of ‘over-exploitation’, occurs when extraction exceeds both natural and induced aquifer recharge over a long period. Adverse effects of groundwater overdraft include, uneconomic pumping conditions, water quality degradation through induced intrusion of saline or poor quality groundwater, flow reduction in streams, wetlands and springs, land subsidence, interference

with pre-existing water uses and water rights, and gradual depletion of groundwater storage. Consistent lowering of water table can dry up wells, drain springs and wetlands, and turn perennial streams into desert washes (Sophocleous 2003; Zekster *et al.* 2005; Harou and Lund 2008).

The global scenario of groundwater overdraft indicates that over-exploitation of groundwater from the shallow aquifers has deteriorated its quality. For example, in the alluvial Pleistocene wells of Jericho area, Palestine, groundwater overdraft has led to high salinity and high susceptibility to

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contamination of groundwater sources due to anthropogenic influences of agricultural backflow and sewage effluent (Khayat *et al.* 2006). In the aquifers of Zakynthos Island, Ionian Sea, Greece, the total abstraction of groundwater exceeded natural recharge, during the last decade, resulting in saline water intrusion and deterioration of groundwater quality (Diamantopoulou and Voudouris 2008). The hydrographs and water quality trends for key aquifers in Jordan indicate a strong relationship between depleting water levels and deterioration, stemming from groundwater overdraft, point and non-point source contamination from agriculture, industrial and domestic uses also being a major problem (El-Naqa and Al-Shayeb 2009). In the Kerman province of SE Iran, over-exploitation of groundwater from the Sirjan watershed has led to significant drop in groundwater level, at an average rate of 70 cm/year from 1984 to 2005. This has resulted in greater saltwater interface in the freshwater aquifers and caused deterioration of groundwater quality in a major part of the Sirjan watershed (Bagher and Rasoul 2010).

In India, over-development of groundwater resources resulted in water level depletion, shortage in water supply, worsening groundwater quality, and intrusion of saline water in coastal areas (Sivasankar *et al.* 2012). These factors have serious implications on the environment and socio-economic conditions of the populace. About 85% of rural population and ~50% of urban population in India is directly dependent on groundwater for their drinking, domestic, and irrigation needs. Moreover, during the last few decades, the demand of groundwater as a reliable source for fulfilling these requirements has increased manifold (CGWB 2007). Thus, the increased need of water for various purposes has culminated in excessive withdrawal of groundwater from all sources beyond the perennial yield of many watersheds. The impact of over-exploitation of groundwater resources on its quantity and quality can be witnessed in many leading states, including Maharashtra, where the agricultural productivity has been downgraded.

In Maharashtra, about 82% of the rural population is directly dependent on groundwater for irrigation, drinking, and domestic purposes. The total rechargeable fresh groundwater resources in the state are computed as 35.79 billion cubic meters (BCM), whereas the net groundwater availability is to the tune of 33.91 BCM. The present annual gross draft of groundwater in the state, for all purposes, is 17.00 BCM. Out of this about 15.95 BCM of groundwater is used for irrigation purposes and the rest for drinking and domestic uses. This quantum of groundwater for irrigation is extracted through 1.87 million abstraction

structures throughout the state. These structures include 1.68 million dug wells (with mhot and pump sets) extracting 14.44 BCM of groundwater and 0.19 million bore-wells extracting 1.51 BCM of groundwater, annually. There are totally 1531 watersheds in Maharashtra and the groundwater development has reached more than 100% in most of these watersheds, as compared to groundwater recharge. This has resulted in depleting groundwater levels during either post or pre-monsoon seasons or both, such that out of the total, 66 watersheds have been categorised as over-exploited (GEC 1997; CGWB 1998a, b, 1999; CGWB and GSDA 2005, 2009; Duraiswami 2007, 2008). This scenario demands an urgent need for sustainable development of groundwater resources in the state and this requires an understanding of its origin and renewability.

The present study was carried out in one such over-exploited watershed 'WR-2', which is located in the basaltic terrain of the Eastern Deccan Volcanic Province of Vidharbha region in Maharashtra. The areal extent of the watershed incorporates a rich orange orchard belt that requires a huge quantity of water for irrigation. Due to limited availability of surface water in this area, the groundwater is extensively utilised for irrigation, domestic, and industrial purposes. Use of groundwater particularly for irrigation of orange cultivation and other agricultural practices is quite rampant. This is increasing at an alarming proportion due to the recent increase in the orange orchards in this area, resulting in over-exploitation of groundwater and depletion of water level in the shallow aquifers. It has been observed that the groundwater draft is more than the natural recharge; hence these unconfined shallow aquifers are under continual stress of water level decline and over-exploitation. Groundwater development in WR-2 watershed has reached 156%, leading to its categorisation as over-exploited watershed (GEC 1997; CGWB 1998a, b, 1999; CGWB and GSDA 2005, 2009). Moreover, the impact of over-exploitation of groundwater on its overall quality is quite significant, which is reflected by the rising electrical conductivity (EC) of groundwater in the dug wells of the study area. Although, there are many water conservation structures constructed in this area by various Govt. agencies and non-governmental organisations (NGOs) for restoring the water level, the benefits of these structures do not reflect on the overall groundwater scenario of the study area (CGWB 2012). Hence, in order to study, ascertain, and correlate the depleting groundwater levels, due to over-exploitation, and its impact on deteriorating groundwater quality, hydrogeological and hydrochemical investigations were carried out in the study area.

2. Study area

The WR-2 watershed is located in the Warud taluka of Amravati district, Maharashtra State, India. It extends for ~ 30 km from north to south and ~ 28 km from east to west and has an areal extent of about 632 km^2 (figure 1). It is bounded by latitudes $21^\circ 19' 36''$ – $21^\circ 35' 26''$ and longitudes $78^\circ 05' 00''$ – $78^\circ 22' 18''$, and is covered under the Survey of India Topographical Sheet Nos. 55 K/2, 55 K/3, 55 K/6 and 55 K/7. This watershed constitutes a part of Wardha river sub-basin and is located along the surface water divide between Wardha river sub-basin and Purna river sub-basin

(figure 2) (CGWB 1998a). It has a general slope of ~ 10 – 20 m per km, from north to south.

The WR-2 watershed is bounded by the Satpura hill ranges towards the north while Wardha river flows along its southern boundary, from east to west. The watershed is mainly covered by a thick pile of Deccan Trap basaltic lava flows with associated intertrappean sediments of Cretaceous–Lower Eocene age and Wardha river alluvial deposits of Recent to Quaternary age. The alluvium deposits occur along the Wardha river course towards the southern part of the WR-2 watershed. They have a thickness of about 10 to 30 m and consist of detrital material like sand and silt with admixture of clay,

Figure 1. Location map of WR-2 watershed.

Figure 2. Generalised geological map of WR-2 watershed with village/dugwell locations.

with a few kankers forming badland topography (figure 2). About 2-m thick black cotton soil with occasional calcareous kankers envelop the basaltic terrain of this watershed (CGWB 1998a). The study area of WR-2 watershed falls under assured rainfall zone with nearly 55 rainy days and an average annual rainfall of 691 mm. This area experiences subtropical to tropical temperate monsoon climate (CGWB 1998a, 2010).

3. Methodology

In the WR-2 watershed area, the water requirement of the local populace for irrigation and domestic usage is met through dug wells located on the phreatic shallow aquifers. These dug wells are hosted in jointed, fractured, vesicular, and weathered Deccan Trap basalts and Wardha river alluvium deposits. Hence, during the present study,

Table 1. Well inventory and hydrogeological data of the key dug wells of WR-2 watershed.

Sl. no.	Dugwell no.	Village/location	Latitude	Longitude	Altitude (a msl)	Aquifer lithology	Depth (m bgl)	Diameter (m)	Depth of weathering (m bgl)	Use	Lifting device
1	DW1	Rawala	21°34'21.6"	78°16'28.1"	497.13	VB	13.65	2.60	5.10	I	EP
2	DW2	Satur	21°33'25.5"	78°17'47.9"	464.52	JFMB	4.85	1.80	1.30	D	EP
3	DW3	Malkapur	21°31'31.5"	78°17'45.6"	437.70	FMB	15.50	3.00	3.70	D	EP
4	DW4	Tiwsaghat	21°31'40.9"	78°16'21.2"	432.21	Bouldary	14.70	1.90	1.40	I	EP
5	DW5	Jhatamziri	21°32'21.2"	78°14'5.5"	484.03	WB	17.85	4.00	2.00	I	EP
6	DW6	Shekdari	21°31'26"	78°11'38.2"	502.62	WB	15.80	3.20	5.50	I	EP
7	DW7	Gahwankund	21°30'21.7"	78°12'24.3"	462.39	WB	13.40	2.75	3.20	I	EP
8	DW8	Tembukherda	21°29'35.5"	78°14'29.2"	456.60	MB	10.90	3.00	3.00	I	EP
9	DW9	Pusla	21°29'11.8"	78°20'0.5"	420.94	WVB and JFMB	20.00	2.10	2.20	I	EP
10	DW10	Dhanodi	21°28'41.2"	78°17'58.7"	385.88	WVB	14.55	1.90	3.05	I	none
11	DW11	Warud	21°28'2.8"	78°15'24.5"	408.75	FMB	14.10	2.45	5.10	D	EP
12	DW12	Bahada	21°28'53.6"	78°12'17.1"	443.79	WVB	15.15	2.50	2.80	I	EP
13	DW13	Manikpur	21°28'20.9"	78°08'47"	453.24	WVB and JMB	12.10	2.20	2.70	D	Manual
14	DW14	Benoda	21°27'21.9"	78°11'18.2"	415.75	VB	11.85	3.10	6.00	D	EP
15	DW15	Jarud	21°27'15.8"	78°12'53"	412.09	WB	26.80	2.10	5.60	I	EP
16	DW16	Surali	21°26'47.4"	78°18'14.6"	400.82	VB	10.72	4.25	3.83	D	Manual
17	DW17	Chandas	21°26'9.3"	78°20'45.3"	388.63	RD (Alluvium)	11.50	1.80	3.45	D	Manual
18	DW18	Udapur	21°24'47.6"	78°19'45.9"	396.55	VB	17.40	2.25	5.25	I	EP
19	DW19	Chinchargavhan	21°24'50.2"	78°17'50"	380.39	WVB	13.70	3.50	9.40	I	EP
20	DW20	Amdapur	21°25'16.6"	78°16'7.1"	401.73	FMB	17.06	2.65	3.40	I	EP
21	DW21	Davargaon	21°25'37.6"	78°14'41.5"	385.88	WB and JMB	27.80	4.80	7.25	I	EP
22	DW22	Pimpalkhuta	21°25'49.6"	78°12'26.4"	400.51	WVB	16.80	4.50	5.70	I	EP
23	DW23	Goregaon	21°25'25.6"	78°09'54.4"	387.71	JWB	9.40	2.80	3.00	I	EP
24	DW24	Karajgaon	21°24'27.1"	78°11'53.9"	381.00	VB	6.95	1.50	1.65	D	Manual
25	DW25	Mangruli	21°24'12"	78°13'45.7"	379.18	VB	21.50	3.60	9.70	I	EP
26	DW26	Wadegaon	21°23'16.8"	78°16'12.2"	388.02	FMB	19.15	3.20	2.90	I	EP
27	DW27	Wadala	21°22'45.3"	78°17'41.3"	367.59	Alluvium	27.00	4.50	14.30	I	EP
28	DW28	Gadegaon	21°21'30.6"	78°15'21"	377.04	WB	24.65	4.30	6.20	I	EP
29	DW29	Nandgaon	21°21'31"	78°13'52.1"	369.42	VB	14.35	2.90	9.80	I	EP
30	DW30	Loni	21°22'34"	78°11'11.3"	362.72	VB and MB	22.00	1.10	3.10	D	Manual
31	DW31	Mamdapur	21°22'40"	78°07'43"	344.12	WB	7.30	4.30	3.00	I	DP
32	DW32	Belona	21°23'11.4"	78°06'1.6"	349.61	WVB	14.70	3.00	6.05	I	EP
33	DW33	Jamalpur	21°21'1.5"	78°08'59.2"	340.47	WB and JMB	6.90	3.30	–	I	EP
34	DW34	Haturna	21°20'10.3"	78°13'47.4"	365.76	Alluvium	25.85	3.40	–	D	EP

DW: Dugwell; VB: Vesicular Basalt; MB: Massive Basalt; WB: Weathered Basalt; JFMB: Jointed and Fractured Massive Basalt; RD: Local River Deposit; I: Irrigation; D: Drinking; EP: Electric Pump; DP: Diesel Pump.

Table 2. DTWL and spot/field EC data from the key dug wells of WR-2 watershed.

Dugwell no.	Parameters	May 2007	Nov 2007	Jan 2008	May 2008	Aug 2008	Nov 2008	Jan 2009	May 2009	Aug 2009	Nov 2009	Jan 2010	May 2010
DW1	DTWL	12.5	7.65	10.80	12.05	11.10	11.70	10.30	Dry	9.50	6.20	10.60	11.25
	EC	500	900	500	600	600	600	600	Dry	700	800	700	700
DW2	DTWL	3.85	2.90	3.30	3.90	2.95	3.40	4.50	7.80	3.05	2.85	5.10	5.35
	EC	300	500	300	400	500	500	900	600	700	850	700	500
DW3	DTWL	15.15	6.10	10.20	7.95	4.50	6.50	8.60	12.70	4.80	5.00	8.80	9.10
	EC	400	600	400	600	600	500	600	700	700	800	750	640
DW4	DTWL	Dry	Dry	7.40	12.35	10.35	10.65	11.50	14.6	9.40	6.20	12.35	13.85
	EC	NA	NA	NA	1300	1300	600	1200	1100	1300	1470	1200	640
DW5	DTWL	17.30	3.90	6.20	10.90	Dry	11.00	Dry	Dry	10.35	8.80	Dry	Dry
	EC	300	600	300	500	NA	500	NA	NA	600	620	NA	NA
DW6	DTWL	8.48	6.50	8.40	8.10	7.60	6.80	9.80	15.10	5.50	6.40	11.25	13.3
	EC	300	400	300	500	400	400	900	400	600	540	600	490
DW7	DTWL	9.55	5.30	4.50	7.54	8.80	7.90	9.50	11.8	11.25	10.20	9.65	10.20
	EC	400	600	400	1100	600	500	600	600	600	550	600	570
DW8	DTWL	10.78	3.00	4.60	6.80	4.50	5.55	8.35	8.20	5.85	5.80	8.10	10.4
	EC	1200	1600	1200	1500	1300	1400	1200	1100	1200	1400	1300	1190
DW9	DTWL	Dry	Dry	10.10	13.40	4.40	11.25	Dry	13.90	4.85	5.00	11.35	18.90
	EC	NA	NA	NA	600	400	700	NA	600	500	800	700	460
DW10	DTWL	Dry	Dry	11.2	11.8	10.3	12.9	13.45	14.6	10.95	10.45	11.7	12.25
	EC	NA	NA	NA	700	1000	900	900	800	1100	1200	1000	910
DW11	DTWL	13.10	8.80	9.80	11.55	10.20	10.50	11.20	13.90	12.30	10.60	11.77	14.00
	EC	1300	400	1300	1100	600	1000	1200	1200	800	700	1100	1350
DW12	DTWL	12.65	3.80	6.55	9.50	7.90	8.60	11.20	Dry	11.80	7.80	12.35	14.10
	EC	700	900	700	900	900	800	800	NA	900	960	900	830
DW13	DTWL	Dry	Dry	2.95	9.65	4.15	4.70	7.45	12.10	4.90	4.70	8.50	11.85
	EC	NA	NA	NA	700	800	700	700	700	900	790	800	740
DW14	DTWL	9.80	5.35	7.95	9.05	7.55	7.75	8.35	11.35	7.10	6.15	8.35	10.40
	EC	1100	800	1100	700	700	500	600	600	700	640	600	650
DW15	DTWL	16.45	8.90	11.5	12.55	11.50	13.90	15.20	18.90	11.50	16.40	17.20	19.50
	EC	1200	700	1200	600	700	700	800	700	800	830	700	670
DW16	DTWL	10.18	4.00	5.94	7.89	4.69	5.39	5.59	7.29	5.39	4.59	6.10	Dry
	EC	800	1400	800	1600	1400	1200	1200	1500	1700	1120	1100	1072
DW17	DTWL	10.62	6.45	8.00	9.90	8.70	8.75	10.20	11.30	9.35	7.20	9.35	10.20
	EC	700	1100	700	1200	1300	1200	1200	800	1300	1360	NA	NA
DW18	DTWL	13.30	9.00	12.00	11.60	9.75	11.20	16.90	14.85	12.85	10.42	10.85	12.90
	EC	500	800	500	800	800	800	800	700	700	850	800	830
DW19	DTWL	Dry	Dry	10.75	11.60	10.90	12.45	12.30	13.10	12.75	12.80	12.90	13.10
	EC	NA	NA	NA	1200	1100	1600	1000	1000	800	1030	1000	1100
DW20	DTWL	17.06	9.75	13.00	16.20	12.20	16.20	Dry	17.50	15.15	11.40	12.65	17.85
	EC	600	1000	600	900	900	900	NA	1100	1000	910	950	1030
DW21	DTWL	Dry	Dry	21.37	21.55	19.30	20.40	21.70	23.00	24.85	25.10	25.25	26.00
	EC	NA	NA	NA	800	800	800	900	800	900	NA	800	830
DW22	DTWL	Dry	Dry	12.40	11.50	10.80	15.50	16.20	15.70	13.05	11.50	12.70	15.80
	EC	NA	NA	NA	700	700	600	600	600	700	700	700	740
DW23	DTWL	Dry	Dry	4.00	Dry	Dry	6.70	Dry	Dry	Dry	Dry	Dry	Dry
	EC	NA	NA	NA	NA	NA	600	NA	NA	NA	NA	NA	NA
DW24	DTWL	3.75	3.02	4.50	4.30	3.10	3.60	4.15	5.05	4.25	3.95	4.15	4.40
	EC	1600	1900	1600	1000	1600	1200	700	1100	1400	1500	1400	1350
DW25	DTWL	17.20	9.50	14.30	16.75	15.40	18.30	20.00	18.65	18.85	16.60	17.15	18.50
	EC	1600	800	1600	1400	1000	1400	1700	1600	1300	1200	1300	1730
DW26	DTWL	9.90	9.40	9.75	9.90	9.45	9.60	10.00	11.40	10.25	9.50	10.15	10.85
	EC	700	1100	700	1200	800	700	1000	800	900	680	700	850
DW27	DTWL	Dry	NA	22.45	22.40	21.10	23.75	23.80	24.50	23.50	23.00	23.15	23.90
	EC	NA	NA	NA	1000	900	1000	1000	1000	1100	1200	900	1060

Table 2. (Continued.)

Dugwell no.	Parameters	May 2007	Nov 2007	Jan 2008	May 2008	Aug 2008	Nov 2008	Jan 2009	May 2009	Aug 2009	Nov 2009	Jan 2010	May 2010
DW28	DTWL	17.54	15.45	17.20	16.70	16.10	19.50	20.20	20.00	19.75	18.45	20.15	21.35
	EC	600	1100	600	1100	1100	1100	1100	1100	1200	1150	1100	1080
DW29	DTWL	12.65	9.90	11.10	13.00	8.10	10.80	Dry	12.60	10.50	8.90	DRY	12.45
	EC	1000	800	1000	700	800	700	NA	700	800	800	800	810
DW30	DTWL	19.85	13.20	14.30	17.25	13.80	14.50	16.40	20.50	17.80	16.80	19.20	21.80
	EC	1100	1600	1100	1200	700	800	1400	1200	1000	1560	1100	1130
DW31	DTWL	4.70	2.55	3.05	4.05	2.95	3.50	3.70	5.55	4.80	3.40	4.10	5.40
	EC	1500	600	1500	600	800	600	600	600	1000	870	700	690
DW32	DTWL	Dry	Dry	11.60	Dry	11.80	Dry	Dry	Dry	14.85	12.00	12.85	Dry
	EC	NA	NA	NA	NA	1600	NA	NA	NA	1600	1740	NA	NA
DW33	DTWL	Dry	Dry	1.90	2.25	0.70	2.50	3.00	3.75	2.00	1.80	2.60	3.70
	EC	NA	NA	NA	500	NA	500	900	500	NA	550	500	470
DW34	DTWL	Dry	Dry	15.70	16.80	16.65	16.70	17.85	19.80	18.20	17.45	18.70	20.30
	EC	NA	NA	NA	1200	1200	1200	1200	1000	1200	1300	1200	1230

totally 34 key dug wells, representing shallow aquifers and covering all the hydrogeological units of WR-2 watershed were selected to study the groundwater regime and its quality, over the area of 632 km² (figure 2). The selected dug wells include two 'Groundwater Monitoring Wells' DW11 and DW30 of the Central Ground Water Board (CGWB) that are located at Warud and Loni villages, respectively. The representative dug wells were monitored for DTWL and spot/field EC from January 2007 to May 2010 on quarterly basis, i.e., for the months of January, May (pre-monsoon), August (monsoon) and November (post-monsoon). This was carried out to verify the trends of DTWL and EC variation and its impact on groundwater quality. Out of 34 dug wells, 32 were selected for analysis due to continuity and availability of data.

The DTWL and spot/field EC data of CGWB recorded at Warud (DW11) and Loni (DW30) villages, during 1977–2010 (CGWB 2010) was utilised to study the impact of long term over-exploitation of groundwater on its quality along with the data collected from key dug wells, during present study. The well inventory data and hydrogeological details of these dug wells collected during present field investigations are shown in table 1, whereas the DTWL and EC data are presented in table 2.

Moreover, groundwater sampling from the key dug wells was carried out during pre-monsoon season of 2008 (May 2008) for detailed hydrochemical investigations. Totally 32 groundwater samples were collected from representative dug wells, as two dug wells (DW23 and DW32) were found dry during the sampling period. Physical parameters of water samples like pH and spot EC were measured in the field, immediately after the sampling, using portable EC meter. All standard precautions, necessary for reliable estimation were

observed during field measurement. The accuracy of measurement was ± 0.1 units. The groundwater samples after collection were subjected to determination of hydrochemical parameters such as total dissolved solids (TDS) and total hardness (TH) along with calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), carbonate (CO₃), bicarbonate (HCO₃), chloride (Cl), sulphate (SO₄), nitrate (NO₃) and fluoride (F) ions. The sampling, preservation, and analytical techniques used are as per the reputed laboratories for analysis of groundwater samples and American Public Health Association (APHA) manual of 'Standard Methods for Examination of Water and Wastewater' (Handa 1981; NEERI 1986; APHA 1998). The accuracy of chemical data for major ions is estimated from the electro neutrality condition (Rossum 1975; Friedman and Erdmann 1982; Appelo and Postma 1993). The specific analysis for identification of pesticides and fertilizers was not carried out; hence, the risks associated with it to human being are not included.

Spot/field EC is selected for assessment of groundwater quality as it represents total ionic content in water. It indicates the extent of mineralisation in groundwater and generally increases with contamination, flow, and residence time of water in the aquifers. It is one of the important parameters that reflect even minor changes in the quality of groundwater from shallow aquifers (Deutsch 1997; Madnure *et al.* 2007).

4. Hydrogeology

About 91.27% (577 km²) area of the WR-2 watershed is covered by Deccan trap basaltic lava flows and the rest of the area, about 8.72% (55 km²), by Wardha river alluvium. The basaltic lava flows

have two hydrogeological units, viz., a vesicular unit confined to the upper part and a massive unit restricted to the lower part of the flow. The vesicular units possess interconnected vesicles that provide pore spaces for storage and movement of groundwater and acts as a good aquifer, particularly at shallow depth. Whereas, the lower massive unit is hard, compact, and has less primary porosity and permeability. Groundwater occurs under phreatic conditions in the exposed vesicular lava flows and in semi-confined state in the jointed and fractured portions of massive subsurface flows. The alluvial deposits are unevenly distributed and

restricted to the banks of Wardha river. The coarser detrital material occurring as lenses forms good water bearing strata in alluvium. Whereas, finer clayey and silty material has poor permeability and does not permit movement of groundwater. The groundwater occurs under phreatic conditions in sandy layers.

The availability of groundwater is extremely uneven, both spatially and temporally. The uneven distribution of groundwater can be attributed to heterogeneous lithology of the aquifers and uneven distribution of rainfall (CGWB and GSDA 2005). The shallow groundwater, tapped by large diameter

Figure 3. (a). DTWL vs. time plot of groundwater monitoring dug well of Warud (DW11) during 1977–2009. (b) Long term EC vs. time plot of groundwater monitoring dug well of Warud (DW11) during 1981–2008.

shallow dug wells, is the most important source of water, especially in the large rural tracts of the study area. The groundwater movement in the study area is mainly controlled by topography, drainage pattern, and structural controls over the area. The groundwater flow direction is towards the south which ultimately converges into the Wardha river.

In the WR-2 watershed, the depth of dug wells varies from 4.85 to 27.80 m bgl (meters below ground level), whereas their diameter varies from 1.10 to 4.80 m (table 1). However, at places around Jarud, Davergaon, Mangruli, Wadala, Gadegaon, Loni and Haterna villages, the dug well depth

varies from 20 m bgl to maximum 30 m bgl, piercing the entire unconfined phreatic aquifer. This may be due to deeper DTWL and prevailing local hydrogeological conditions. The depth of weathering in WR-2 watershed was estimated from the depth of curbing in the existing dug wells, well sections of open wells, and borehole logs. The depth of weathering ranges from 1.30 to 14.30 m bgl (table 1) and in general, increases from north to south, i.e., in the direction of general ground slope. In the central part of WR-2 watershed around Jarud–Warud villages, the depth of weathering is relatively high as compared to the surrounding areas. Dug well density and agricultural activity

Figure 4. (a). DTWL vs. time plot of groundwater monitoring dug well of Loni (DW30) during 1989–2010. (b) Long term EC vs. time plot of groundwater monitoring dug well of Loni (DW30) during 1989–2009.

are also relatively more in and around Jarud–Warud areas. However, along the northern bank of Wardha river the thickness of weathered and porous zone in dug well sections is high as these wells are mostly hosted in alluvium (figure 2). The depth of weathering in Deccan Trap basalt and alluvium area is controlled by the nature of lithology, intensity of fracturing, and joints, etc.

4.1 Trends of water level and water quality

The long term depth to water level (DTWL) trend recorded at the ‘Groundwater Monitoring Wells’ of CGWB at Warud (DW11) during 1977–2009, and Loni (DW30) during 1989–2010 shows a decline of 0.03 and 0.04 m per year, respectively. The corresponding trend of EC shows rise of 1.90 and 2.94 $\mu\text{S}/\text{cm}$ per year, respectively in these dug wells, over the same period (CGWB 2010) (figures 3a, 3b, 4a and 4b).

The short term (2007–2010) DTWL and EC trends, recorded in the dug wells of the study area, reveal that during pre-monsoon seasons of 2007–2010, DTWL varied from 2.25 to 26 m bgl and corresponding spot/field EC ranged from 300 to 1730 $\mu\text{S}/\text{cm}$, respectively. Whereas, during post-monsoon seasons of 2007–2009, the DTWL varied from 1.8 to 25.1 m bgl and spot/field EC varied from 400 to 1900 $\mu\text{S}/\text{cm}$, respectively (table 2).

During monsoon season (August) of 2008–2009, the DTWL varied from 0.7 to 24.85 m bgl and corresponding spot/field EC ranged from 400 to 1700 $\mu\text{S}/\text{cm}$, respectively. Whereas, during January months of 2008–2010, the DTWL varied from 1.9 to 25.25 m bgl and corresponding EC ranged from 300 to 1700 $\mu\text{S}/\text{cm}$, respectively, in the dug wells of the study area (table 2).

The data thus collected indicate that irrespective of the sampling seasons DTWL show declining trend and EC show rising trend in the dug wells of the study area and about 18 dug wells out of the total (i.e., 56% dug wells) show positive correlation between decline of DTWL and rise in EC values (tables 2 and 3). The declining trend of DTWL ranged from 0.03 to 0.67 m per year, whereas the corresponding rising spot/field EC trend ranged from 0.52 to 46.91 $\mu\text{S}/\text{cm}$ per year, respectively, during 2007 to 2010 (table 3). The graphical presentation of correlation between DTWL, EC and time for the representative dug wells of DW2, DW6, DW11, DW12, DW13, DW20, DW21, DW22, DW25, DW27, DW28, DW30 and DW34 are shown in figure 5(a and b). The DTWL and EC variation trend maps for the period of 2007–2010 are presented in figures 6 and 7. The variation in long term and short term water level trends may be due to variation in natural

Table 3. Correlation between declining DTWL and rising spot/field EC trends during 2007–2010 in the dug wells of WR-2 watershed.

Dugwell no.	Trend of water level (m/year)*	Trend of spot EC ($\mu\text{S}/\text{cm}/\text{year}$)*	Correlation
DW1	−0.1276	11.25	−0.81
DW2	0.1558	35.14	0.11
DW3	−0.2367	26.89	−0.45
DW4	0.2221	−18.33	−0.49
DW5	−0.1083	26.39	−0.41
DW6	0.3296	22.97	0.05
DW7	0.4033	1.82	0.01
DW8	0.2072	−12.97	−0.58
DW9	0.3174	7.56	−0.07
DW10	0.0291	27.33	−0.65
DW11	0.202	11.01	0.64
DW12	0.4306	10.97	−0.17
DW13	0.4852	9.00	−0.49
DW14	0.0813	−35.56	0.00
DW15	0.5622	−25.59	−0.06
DW16	−0.1817	11.65	−0.27
DW17	0.0783	46.91	−0.34
DW18	0.0994	18.46	−0.24
DW19	0.2512	−34.00	−0.23
DW20	0.1138	26.45	0.04
DW21	0.6741	3.20	0.26
DW22	0.21	7.67	−0.59
DW24	0.0686	−27.80	−0.53
DW25	0.4238	16.54	0.71
DW26	0.082	−11.50	−0.03
DW27	0.1682	12.33	0.32
DW28	0.4217	33.67	0.29
DW29	−0.0271	−11.14	0.01
DW30	0.4115	0.52	0.03
DW31	0.1253	−38.53	−0.02
DW33	0.1418	−10.92	0.00
DW34	0.3948	5.33	−0.40

*Positive values indicate declining DTWL and rising EC trends.

recharge, rainfall, and excessive withdrawal of groundwater.

Moreover, the long term (1977–2010) and short term (2007–2010) record of the DTWL and spot/field EC in the dug wells of the study area indicate that the decline in DTWL is directly proportional to the rising EC values. The declining DTWL trend indicates progressive scarcity of groundwater, whereas rising EC values indicate deterioration of the groundwater quality in the dug wells of phreatic shallow aquifers of WR-2 watershed. This is reflected in terms of higher concentration of Ca, Mg, TDS, and TH in the groundwater of the study area. Moreover, the DTWL data show that the areas in the central and southern parts of WR-2 watershed have deeper DTWL and are more susceptible to groundwater exploitation.

Figure 5. (a). DTWL *vs.* time plot of selected dug wells of WR-2 watershed during 2007–2010. (b) EC *vs.* time plot of selected dug wells of WR-2 watershed during 2007–2010.

These regions have more groundwater overdraft than the natural recharge and show excessive groundwater exploitation as compared to the rest of the areas.

5. Hydrochemistry

Hydrochemical studies were carried out during pre-monsoon season of 2008, in order to verify the DTWL and EC trends related to declining water level and deteriorating groundwater quality. The

parameter-wise results of detailed hydrochemical investigations of groundwater samples are summarized in table 4. The EC values in this case are determined in laboratory and found almost similar to the spot/field EC values for May 2008, except minor variations at some places.

Analytical results show that groundwater of the study area is mildly alkaline in nature, with average pH of 7.8, and moderately mineralized as indicated by the EC and TDS values that range from 580 to 1920 $\mu\text{S}/\text{cm}$ and from 292 to 992 mg/l , respectively. The degree of mineralization was found low

Figure 6. DTWL trend map of the dug wells of WR-2 watershed during 2007–2010.

in the groundwater sample from dug well DW2, while it was highest in groundwater from DW16 (table 4).

Total alkalinity of groundwater ranges from 200 to 575 mg/l as CaCO_3 , with average value more than 336 mg/l (table 4). This may severely affect the use of water for different purposes. The maximum pH of groundwater is 8.0, which indicates bicarbonate as the dominant species in groundwater and mainly contributing towards its alkalinity (Tiwari et al. 2007, 2008).

Total hardness of groundwater ranges from 200 to 690 mg/l, with average value of 386 mg/l. This indicates that groundwater of the study area is hard in nature and hardness is mainly due to the bicarbonate salts of Ca and Mg. The concentrations

of Cl and SO_4 in groundwater are less as compared to HCO_3 ions, indicating that the water has more temporary hardness than permanent and can be removed by boiling the water. The average concentration of fluoride, which exists as minor ion in the groundwater of the study area, is less than 0.5 mg/l (table 4) (Seaber 1962; Tiwari et al. 2007, 2008).

5.1 Schoeller's classification

Schoeller (1955, 1967) has given the classification scheme for water types based on Cl, SO_4 , and $\text{HCO}_3 + \text{CO}_3$ concentrations. As per this classification, chloride concentration below 15 meq/l is termed as normal chloride water. Similarly, water with sulphate content of < 6 meq/l is termed

Figure 7. EC trend map of the dug wells of WR-2 watershed during 2007–2010.

as normal sulphate water (Schoeller 1955, 1967; Freeze and Cherry 1979; Hem 1985).

During pre-monsoon season of 2008, chloride concentration in groundwater samples of the study area is < 15 meq/l, indicating normal chloride water. Differentiation of SO_4 concentration indicates the groundwater as normal sulphate water, as $\text{SO}_4 < 6$ meq/l and differentiation of $\text{HCO}_3 + \text{CO}_3$ concentration indicates it as sulphate carbonate waters, as $\text{HCO}_3 + \text{CO}_3 > 7$ meq/l (Schoeller 1955, 1967). The concentrations of major ions expressed in meq/l are graphically presented using Schoeller's diagram (figure 8). This shows that concentration of Ca exceeds that of Mg followed by Na amongst the cations, while HCO_3 ion has higher concentration

than Cl followed by NO_3 and SO_4 in the groundwater samples of the study area.

5.2 Piper's diagram

The trilinear diagram of Piper (1944) is very useful in bringing out chemical relationships among groundwaters in more definite terms (Walton 1970). The geochemical classification of groundwater of the study area was carried out by subjecting the samples to graphical treatment and plotting them on Piper's trilinear diagram (Piper 1944, 1953) (figure 9). Piper's diagram indicates that groundwater of the study area is predominately of Ca- HCO_3 type and represents characteristics of

Table 4. Chemical analysis of groundwater samples from dug wells of WR-2 watershed for pre-monsoon season of 2008.

Dugwell no.	pH	EC ($\mu\text{S}/\text{cm}$)	TDS	TH	TA	Ca	Mg	Na	K	HCO ₃	Cl	SO ₄	NO ₃	F
(mg/l)														
DW1	7.9	800	402	360	315	70	45	16.3	0.2	384	21	30	27	0.62
DW2	7.9	580	292	245	260	64	21	19.3	0.3	317	11	14	2.8	0.79
DW3	7.9	680	374	295	230	86	19	17.2	0.8	281	32	8	70	0.35
DW4	7.4	1390	850	625	230	156	57	29	0.9	281	113	108	246	0.35
DW5	7.9	690	341	300	320	72	29	19.7	1	390	14	5.8	3.9	0.51
DW6	7.6	590	303	250	245	56	27	19.7	0.6	299	11	16	23	0.58
DW7	7.5	630	332	265	235	64	26	21	1.4	287	32	21	23	0.52
DW8	7.6	1610	928	625	330	124	77	78	0.6	403	184	42	220	0.56
DW9	7.6	640	356	235	200	64	18	37	0.4	244	39	32	43	0.70
DW10	7.7	840	460	370	260	90	35	22	0.9	317	64	12	78	0.26
DW11	7.9	1350	740	535	395	114	61	61	1	482	106	42	113	0.39
DW12	7.5	950	524	420	255	90	47	24	0.2	311	74	39	93	0.31
DW13	7.9	920	490	390	325	78	47	28	4.5	397	43	31	59	0.34
DW14	7.5	680	362	305	220	80	26	14.7	0.4	268	57	20	30	0.12
DW15	7.6	770	412	325	265	72	35	26	0.3	323	32	29	56	0.26
DW16	8.0	1920	992	690	575	160	70	112	9.1	702	262	5.2	22	0.37
DW17	7.6	1530	823	375	570	92	35	161	9.6	696	121	18	38	0.43
DW18	7.8	970	490	330	420	40	56	69	1.2	512	21	14	32	0.18
DW19	7.8	1210	652	450	430	54	77	67	0.7	525	46	10	135	0.29
DW20	7.7	1120	602	390	410	56	61	69	0.6	500	53	13	98	0.41
DW21	7.9	1010	515	395	410	54	63	46	0.3	500	35	11	55	0.31
DW22	7.8	800	418	265	340	46	36	56	1.1	415	21	4	45	0.50
DW23								Dry						
DW24	8.0	1180	627	410	405	80	51	80	0.7	494	85	15	68	0.34
DW25	7.6	1470	800	540	340	76	85	88	0.3	415	199	21	122	0.28
DW26	7.8	1440	774	605	240	168	45	47	4.4	293	291	58	14	0.45
DW27	7.8	1120	602	240	430	46	30	142	1.2	525	57	8	56	0.23
DW28	7.7	1190	630	395	400	54	63	84	0.9	488	89	12	82	0.09
DW29	7.7	700	378	290	245	60	34	23	0.9	299	32	9	70	0.57
DW30	7.9	1400	778	545	350	88	79	67	2.1	427	128	44	156	0.48
DW31	7.8	650	352	285	235	60	33	18.5	0.2	287	25	8	64	0.72
DW32								Dry						
DW33	7.8	670	337	200	315	36	27	54	6.6	384	14	5.2	1.2	0.90
DW34	7.9	1390	720	410	550	46	72	126	0.3	671	64	18	58	0.25
Minimum	7.4	580	292	200	200	36	18	14.7	0.2	244	11	4	1.2	0.09
Maximum	8.0	1920	992	690	575	168	85	161	9.6	702	291	108	246	0.90
Average	7.8	1028	552	386	336	78	46	54	1.7	410	74	23	69	0.50

groundwater from basaltic aquifers. Few samples fall in the category of mixed type of water. The alkaline earths (Ca+Mg) exceed alkalis (Na+K) and weak acids (CO₃+HCO₃) exceed strong acids (Cl+SO₄+NO₃) in a majority of groundwater samples. However, alkalis (Na+K) exceed alkaline earths (Ca+Mg) in the water sample from dug well DW17, while strong acid (Cl+SO₄+NO₃) exceeds weak acid (CO₃+HCO₃) in the groundwater samples from dug wells DW4, DW8, DW25, DW26 and DW30.

This change in type of groundwater of the study area may be attributed to the influence of surface activities. Percolation of waste/wastewater from the surface rich in alkalis and strong acids might have caused such changes in groundwater. Ions

such as Cl and NO₃ usually do not take active part in the processes occurring during circulation and get directly added to groundwater. Possibilities of cation exchange increases when resident time of water is more, leading to strong water-rock interaction. However, in shallow aquifers of the study area, groundwater is under constant circulation and regularly gets recharged. Hence, possibilities of ion exchange during the circulation are negligible (Back 1966; Deutsch 1997; Saini *et al.* 2006; Pophare and Dewalkar 2007).

5.3 Index of base exchange

Control on the dissolution of undesirable constituents in water is impossible during subsurface

Figure 8. Schoeller's classification of the groundwater samples of the study area (after Schoeller [1955](#), [1967](#)).

Figure 9. Chemical classification of groundwater samples from dug wells of the study area, average data of pre-monsoon season of 2008 (after Piper [1944](#), [1953](#)).

Table 5. Chloro-alkaline indices in the ground water samples of the study area.

Dugwell no.	CAI-I	CAI-II
DW1	-0.62	0.49
DW2	-2.42	0.16
DW3	0.05	0.77
DW4	2.78	3.06
DW5	-1.84	0.26
DW6	-2.50	0.15
DW7	-0.15	0.73
DW8	4.53	4.87
DW9	-0.38	0.80
DW10	1.26	1.66
DW11	2.09	2.73
DW12	1.58	1.94
DW13	0.11	1.05
DW14	1.20	1.48
DW15	-0.36	0.73
DW16	6.69	6.95
DW17	1.28	2.82
DW18	-4.53	0.26
DW19	-0.97	1.03
DW20	-0.53	1.19
DW21	-1.05	0.77
DW22	-3.57	0.27
DW24	0.93	2.03
DW25	4.92	5.19
DW26	7.93	7.85
DW27	-2.26	0.96
DW28	1.04	2.12
DW29	-0.23	0.74
DW30	2.78	3.32
DW31	-0.45	0.57
DW33	-5.99	0.00
DW34	-1.24	1.36

run off. However, it is essential to understand various changes that groundwater undergoes during its circulation (Pojasek 1977; Johnson 1979). The mechanism of ion exchange between groundwater and its host environment during residence or circulation can be understood by the study of chloro-alkaline indices CAI-I: $\text{Cl}-(\text{Na}+\text{K})/\text{Cl}$ and CAI-II: $\text{Cl}-(\text{Na}+\text{K})/\text{SO}_4+\text{HCO}_3+\text{CO}_3+\text{NO}_3$ (Schoeller 1955, 1967).

The chloro-alkaline indices can be either positive or negative depending on whether exchange of Na and K is from water with Mg and Ca in rock or *vice-versa*. Positive values of the ratios indicate a base-exchange reaction (chloro-alkaline equilibrium) and negative values indicate chloro-alkaline disequilibrium and the reaction as a cation-anion exchange reaction (Sreedevi 2004). The chloro-alkaline indices of groundwater samples from the study area indicate that 47% (15 samples) show positive CAI-I ratio, whereas, 53%

(17 samples) show negative CAI-I ratio. However, all the groundwater samples of the study area show positive CAI-II ratio indicating that chloro-alkaline equilibrium exists in the groundwater of the study area (table 5).

5.4 Gibbs diagram

Gibbs (1970) proposed a diagram to understand the mechanism controlling groundwater chemistry and the relationship of chemical components of waters from their respective aquifer lithologies. This diagram is based on Gibbs ratio I: $(\text{Cl}/\text{Cl}+\text{HCO}_3)$ for anions and ratio II: $(\text{Na}+\text{K})/(\text{Na}+\text{K}+\text{Ca})$ for cations of water samples and consists of three distinct fields, viz., precipitation dominance, evaporation dominance, and rock dominance. Gibbs ratio-I and II, calculated for the groundwater samples of the study area plot separately against respective values of TDS and show rock dominance over the majority of groundwater samples, indicating interaction between aquifer lithology and groundwater (figure 10).

In WR-2 watershed, basalt is the main water bearing formation. These rocks are usually composed of chain silicates, pyroxene (partly amphibole), and feldspar group of minerals. The dissolution of these minerals mainly yields Ca, Mg and Na ions to groundwater (Plummer and Back 1980; Katz and Choquette 1991; Pawar 1993; Pawar and Nikumbh 2007). The probable chemical reactions during water-rock interaction are as under:

Concentration of HCO_3 ion in groundwater is mainly influenced by the amount of CO_2 dissolved

Figure 10. Mechanisms controlling chemistry of groundwater during pre-monsoon season of 2008. (a) Evaporation dominance and (b) precipitation dominance (after Gibbs 1970).

in water from atmosphere and decay of organic matter. The concentration of K in groundwater of basaltic aquifer is generally very low. It is liberated with great difficulty from K-feldspars as these minerals are very resistant to the attack by water. Potassium has a strong tendency to be reincorporated into the solid weathering product (Tardy 1971; Pedro and Siefferman 1979; Pawar and Nikumbh 2007). In basalts, there is no apparent source of Cl, SO_4 and NO_3 . The groundwater in basaltic terrain of the study area which is rich in these ions is indicative of anthropogenic contamination (Weijden and Pacheco 2006; Tiwari *et al.* 2007, 2008).

6. Quality of groundwater for drinking and irrigation purposes

The groundwater quality assessment for drinking purpose was carried out based on the drinking water standards prescribed by Bureau of Indian Standards (BIS 2003) for various parameters and is summarized in table 6. It is observed that pH and concentrations of parameters such as SO_4 and F in groundwater are within the desirable limits and have less impact on the quality of groundwater. The potability of groundwater is mainly affected by the parameters like TA, Ca, Mg, TH, NO_3 and TDS, as more than 50% of dug well waters have concentrations of these parameters beyond the desirable limits for drinking purpose (table 6). However, the groundwater of four dug wells DW4, DW8, DW16 and DW26 cannot be utilised for drinking purpose as it has crossed the maximum

permissible limit of 600 mg/l for TH, in absence of alternate source. The groundwater in 19 dug wells, classified under the parameter NO_3 is also not suitable for drinking purpose as there is no relaxation under maximum permissible limit in case of alternate source (table 6).

The field observations during the present study have indicated that anthropogenic activities like open unlined sewerages, improper disposal of cow dung for manure in the vicinity of groundwater sampling source, excessive use of fertilizer in agriculture field for orange cultivation, etc., are the main reasons for nitrate contamination in groundwater of the study area. These observations suggest that overall, the groundwater of the study area, in more than 50% dug wells is not suitable for drinking purpose (table 6). This indicates that the water quality deterioration in the study area is due to groundwater overdraft and point to non-point source contamination from agriculture and domestic uses.

Overlay analysis has been carried out using weighted average method in GIS software (Mapinfo 6.5) to identify the risk associated with the groundwater from a particular dug well. This method allows analysis of geospatial data, where the vector parameters overlay by using simple statistical correlation. Logically the weights were assigned as '1' to each parameter, viz., EC, Ca, Mg, NO_3 , TDS, TA and TH of groundwater from each dug well. The cumulative weighted layer was derived at the end and categorized in six zones (table 7, figure 11).

The suitability of groundwater for irrigation purpose is examined using EC, percent sodium (%Na), sodium adsorption ratio (SAR), soluble sodium

Table 6. Classification based on BIS drinking water standards (after BIS 2003).

Parameters	Desirable limit	Dug wells in which the groundwater exceeding desirable limit	Total no. of such dug wells
pH	6.5–8.5	Nil	Nil
TDS (mg/l)	500	DW4, DW8, DW11–12, DW16–17, DW19–21, DW24–28, DW30, DW34	16
TA as CaCO ₃ (mg/l)	200	DW1–8, DW10–22, DW24–31, DW33–34	31
TH as CaCO ₃ (mg/l)	300	DW1, DW4, DW8, DW10–21, DW24–26, DW28, DW30, DW34	21
Ca (mg/l)	75	DW3–4, DW8, DW10–14, DW16–17, DW24–26, DW30	14
Mg (mg/l)	30	DW1, DW4, DW8, DW10–13, DW15–22, DW24–26, DW28–31, DW34	23
Cl (mg/l)	250	DW16, DW26	2
SO ₄ (mg/l)	200	Nil	Nil
NO ₃ (mg/l)	45	DW3–4, DW8, DW10–13, DW15, DW19–21, DW24–25, DW27–31, DW34	19
F (mg/l)	1.0	Nil	Nil

Table 7. Categorisation of dug wells based on risk associated to human health in WR-2 watershed.

Category of risk	Resultant assigned weight	Total dug wells	Dugwell numbers
Very high risk dug wells	8	1	DW27
High risk dug wells	7	2	DW24, DW34
Severe risk dug wells	6	6	DW8, DW17, DW20, DW25, DW28, DW30
Moderate high risk dug wells	5	7	DW4, DW11, DW12, DW16, DW19, DW21, DW26
Moderate risk dug wells	4	4	DW10, DW13, DW18, DW22
No risk dug wells	>4	14	DW5, DW7, DW23, DW32, DW2, DW6, DW1, DW3, DW9, DW14, DW15, DW29, DW31, DW33

percentage (SSP), residual sodium carbonate (RSC), Kelly's ratio (KR), magnesium ratio (MR), corrosivity ratio (CR), and permeability index (PI) values of the groundwater samples (tables 8 and 9). The level of salinity hazard based on EC, and sodium hazard based on SAR value is assessed using US Salinity diagram (USSL 1954) (figure 12).

6.1 Per cent sodium (%Na)

Percent sodium parameter in groundwater is computed to evaluate its suitability for irrigation (Wilcox 1948, 1955). Excess Na combining with carbonate will lead to formation of alkaline soils, while Na with Cl forms the saline soils. Either of the soils do not support growth of crops (Sreedevi 2002; Pandian and Sankar 2007). As per the Bureau of Indian Standards, Na up to 60% in groundwater is permissible for irrigation purpose (BIS 2003). %Na is calculated by the following formula using values in meq/l:

$$\%Na = \left[\frac{Na}{Ca + Mg + Na + K} \right] \times 100. \quad (5)$$

In groundwater samples of the study area, %Na in 50% samples is within excellent category, 41% in good category, while only 9% samples are falling in permissible category (table 9).

6.2 Sodium absorption ratio (SAR)

Suitability of groundwater for agricultural purpose is determined by SAR, as it is responsible for sodium hazard (USSL 1954, 1973). Sodium and salinity hazards are the two important parameters, which can indicate suitability of water for irrigation usage (Sreedevi 2002). SAR is calculated by the following formula using values in meq/l:

$$SAR = \frac{Na}{\sqrt{(Ca + Mg)/2}}. \quad (6)$$

In groundwater samples of the study area SAR values indicate that all the samples fall in C2-S1 and C3-S1 category and are suitable for irrigation purposes (table 9, figure 12) (USSL 1954, 1973).

Possibility of sodium hazard to the soil is low (S1) as SAR values of groundwater samples from

Figure 11. Groundwater quality and risk zone map of WR-2 watershed.

all the dug wells are less than 10 (table 8). The low SAR values in the area are due to the low concentration of sodium in groundwater as compared to the alkaline earth, i.e., Ca and Mg ions. However, EC values of most of the samples fall under the category of medium (C2) and high (C3) salinity hazard zone indicating that special crop and water management practices are required for utilizing such water for irrigation purpose (figure 12).

6.3 Soluble sodium percentage (SSP)

Sodium by the process of base-exchange replaces calcium in the soil, which in turn lowers soil

permeability. SSP for water samples was calculated by the following formula using values in meq/l:

$$SSP = \frac{Na \times 100}{Ca + Mg + Na} \quad (7)$$

In groundwater samples of the study area, about 97% samples are suitable for irrigation while only 3% samples fall in unsuitable category (table 9).

6.4 Residual sodium carbonate (RSC)

RSC is the CO_3 and HCO_3 amount in alkaline earths chiefly Ca and Mg, in excess of permissible limits, which affects irrigation adversely

Table 8. %Na, SAR, SSP, RSC, KR, MR, CR and PI in groundwater samples of the study area.

Dugwell no.	%Na	SAR	SSP	RSC	KR	MR	CR	PI
DW1	8.95	0.37	8.96	-0.91	0.10	51.41	0.63	40.67
DW2	14.53	0.53	14.55	0.27	0.17	35.07	0.33	54.07
DW3	11.28	0.44	11.31	-1.26	0.13	26.67	0.91	43.77
DW4	9.15	0.50	9.17	-7.88	0.10	37.56	3.29	24.78
DW5	12.47	0.50	12.52	0.41	0.14	39.87	0.40	49.46
DW6	14.53	0.54	14.57	-0.12	0.17	44.25	0.33	52.23
DW7	14.52	0.56	14.60	-0.63	0.17	40.07	0.92	49.29
DW8	21.27	1.35	21.29	-5.93	0.27	50.55	5.24	37.43
DW9	25.53	1.05	25.57	-0.68	0.34	31.65	1.13	57.37
DW10	11.44	0.50	11.47	-2.18	0.13	39.03	1.82	38.82
DW11	19.79	1.15	19.83	-2.82	0.25	46.83	3.06	40.85
DW12	11.08	0.51	11.09	-3.27	0.12	46.23	2.13	35.08
DW13	13.38	0.62	13.55	-1.26	0.16	49.80	1.25	41.94
DW14	9.41	0.36	9.43	-1.75	0.10	34.85	1.62	40.35
DW15	14.84	0.63	14.85	-1.19	0.17	44.45	0.93	45.09
DW16	25.81	1.86	26.14	-2.25	0.35	41.87	7.39	44.35
DW17	47.53	3.62	48.34	3.93	0.94	38.51	3.45	71.67
DW18	31.12	1.65	31.22	1.78	0.45	69.74	0.62	61.37
DW19	24.34	1.37	24.38	-0.43	0.32	70.12	1.31	48.92
DW20	27.69	1.52	27.72	0.38	0.38	64.20	1.52	54.18
DW21	20.22	1.01	20.23	0.31	0.25	65.76	1.00	49.19
DW22	31.51	1.50	31.63	1.54	0.46	56.30	0.60	65.51
DW24	29.74	1.72	29.79	-0.10	0.42	51.20	2.42	54.16
DW25	26.15	1.65	26.17	-3.99	0.35	64.80	5.64	44.00
DW26	14.33	0.83	14.44	-7.30	0.17	30.60	8.26	29.94
DW27	56.26	4.00	56.42	3.84	1.29	51.77	1.62	83.23
DW28	31.59	1.84	31.66	0.11	0.46	65.76	2.53	56.17
DW29	14.66	0.59	14.71	-0.90	0.17	48.26	0.91	47.28
DW30	21.00	1.25	21.09	-3.90	0.27	59.64	3.67	40.24
DW31	12.33	0.48	12.34	-1.01	0.14	47.52	0.71	45.60
DW33	35.90	1.66	36.86	2.27	0.58	55.25	0.40	76.24
DW34	39.95	2.70	39.98	2.77	0.67	72.04	1.84	64.18
Minimum	8.95	0.36	8.96	-7.88	0.10	26.67	0.33	24.78
Maximum	56.26	4.00	56.42	3.93	1.29	72.04	8.26	83.23
Average	21.95	1.21	22.06	-1.00	0.32	49.11	2.12	49.61

(Eaton 1950; Richards 1954). Continued usage of high residual sodium carbonate waters affects the yield of crops. High concentration of bicarbonate may result in precipitation of Ca and Mg bicarbonates from the soil solution, increasing relative proportion of Na and causing sodium hazard. RSC refers to residual alkalinity and can be calculated by the following formula using values in meq/l:

$$\text{RSC} = (\text{HCO}_3 + \text{CO}_3) - (\text{Ca} + \text{Mg}) \quad (8)$$

RSC values indicate that about 82% groundwater samples of the study area are in the safe category, 9% samples are suitable, while another 9% samples fall in the unsuitable category for irrigation purposes (table 9).

6.5 Kelly's ratio (KR)

The level of Na measured against Ca and Mg is known as Kelley's ratio based on which irrigation

waters can be rated (Kelley 1946; Paliwal 1967). Excess sodium in waters produces undesirable effects of changing soil properties and reducing soil permeability (Kelley 1951; Tijani 1994). Kelley's ratio is taken as an indication of alkali hazard in water (Handa 1981). It is determined from the following formula using values in meq/l:

$$\text{KR} = \frac{\text{Na}}{\text{Ca} + \text{Mg}}. \quad (9)$$

In groundwater samples of the study area, only 3% groundwater samples are unsuitable for irrigation, whereas 97% samples are suitable for irrigation (table 9).

6.6 Magnesium ratio (MR)

Magnesium hazard ratio is the excess amount of Mg over Ca and Mg amount, whereas normally the

Figure 12. SAR vs. conductivity plot of groundwater samples from dug wells of the study area during pre-monsoon season of 2008 (after USSL 1954, 1973).

level of Ca and Mg will be in a state of equilibrium (Lloyd and Heathcote 1985; Sreedevi 2002). Excess Mg affects the quality of soil resulting in poor agricultural returns. MR is calculated by the formula using values in meq/l:

$$MR = \frac{Mg \times 100}{Ca + Mg}. \quad (10)$$

In groundwater samples of the study area about 56% samples are found suitable, while 44% are found unsuitable for irrigation purpose (table 9).

6.7 Corrosivity ratio (CR)

The corrosivity ratio is important to know whether the water can be transported through metallic pipes or not. The groundwater with CR values of <1 is considered to be safe for transport of water in any pipe. If the corrosivity ratio is >1 , only non-corrosive pipes have to be used for transporting water (Ryner 1944; Raman 1985). The intensity of corrosion depends upon certain physical factors like temperature, pressure, and flow velocity of water (Ayer and Westcot 1985). High concentrations of chloride and sulphate also increase the corrosion rate (Ryner 1944; Raman 1985). The corrosivity ratio is calculated by the following formula using values in meq/l:

$$CR = \frac{(Cl/35.5) + 2(SO_4/96)}{2(HCO_3 + CO_3/100)} \quad (11)$$

In groundwater samples of the study area, about 38% samples fall under good category while 62% samples are corrosive and not suitable for transportation through metal pipes (table 9).

Although it is pertinent that the quality of groundwater in shallow aquifers of WR-2 watershed, tapped by dug wells is suitable for irrigation purpose, high concentrations of Ca, Mg, TH, TA and SO_4 in it may affect the quality of soil at places.

6.8 Permeability index (PI)

The soil permeability is affected by long term use of irrigation water and is influenced by Na, Ca, Mg and HCO_3 contents of the soil. The permeability index (PI), as developed by Doneen (1962, 1964) indicates the suitability of groundwater for irrigation. It is calculated as under using values in meq/l:

$$PI = \left[\frac{(Na + \sqrt{HCO_3})}{Ca + Mg + Na} \right] \times 100. \quad (12)$$

According to permeability indices, groundwater can be divided into Class I, Class II and Class III types. Class I and Class II water types are suitable for irrigation with 75% or more of maximum permeability, and Class III types of water with 25% maximum permeability. The PI values of groundwater samples range from 29.94% to 83.23% and thus, on the basis of Doneen's chart all groundwater samples of the study area are suitable for irrigation purpose except at dug well DW4 where PI was 24.78% (tables 8 and 9) (Doneen 1962, 1964).

7. Discussion and conclusions

Groundwater from the shallow aquifers of WR-2 watershed is utilized for irrigation and domestic

Table 9. Classification of groundwater samples based on %Na, SAR, SSP, RSC, KR, MR, CR and PI.

Ratio	Range (meq/l)	No. of samples	Percentage	Category
%Na	< 20	16	50	Excellent
	20–40	13	41	Good
	40–60	3	9	Permissible
	60–80	0	0	Doubtful
	>80	0	0	Unsuitable
SAR	<10	32	100	Excellent
	10–18	0	0	Good
	18–26	0	0	Fair
	>26	0	0	Unsuitable
SSP	<50	31	97	Good
	>50	1	3	Unsuitable
RSC	<1.25	26	82	Safe
	1.25–2.5	3	9	Suitable
	>0.5	3	9	Unsuitable
KR	<1	31	97	Good
	>1	1	3	Unsuitable
MR	<50	18	56	Suitable
	>50	14	44	Unsuitable
CR	<1	12	38	Good
	>1	20	62	Unsuitable
PI	Up to 75%	31	97	Good
	<25%	1	3	Unsuitable

purposes. The long term (1977–2010) and short term (2007–2010) record of both DTWL and spot EC in the dug wells of these aquifers indicate that the decline in DTWL is directly proportional to the rising EC values of the groundwater. The declining DTWL trend indicates progressive scarcity of groundwater, whereas rising EC values indicate deterioration of groundwater quality in the dug wells of phreatic shallow aquifers of WR-2 watershed. Overlay analysis of DTWL shows that the areas in the central and southern parts of WR-2 watershed have deeper DTWL and are more susceptible to contamination as compared to the rest of the areas and have more groundwater overdraft than the natural recharge. The groundwater exploration in the study area has been carried out to a depth of 172 m, where unconfined aquifers comprising of fractured massive and vesicular basalt occur up to the depth from 10 to 41 m with varying thickness. The static water level (SWL) varies from 4.35 to 36 m bgl. A multi-layer fractured aquifer system exists in Deccan Trap basaltic terrain where groundwater occurs only in interconnected fractured zones. Considering this aspect, the up-coning of deeper aquifer due to groundwater exploitation may not be possible, which is often observed in unconsolidated/consolidated alluvium formation.

In the study area, there are several factors inter-related to each other causing over-exploitation of groundwater from the shallow aquifers of WR-2

watershed. This includes the propensity of the local farmers to take cash crop of oranges mostly through traditional irrigation practices, ignoring the depleting groundwater levels in the aquifers, although the traditional technique of flood irrigation causes more groundwater draft than the modern irrigation techniques like drip and sprinkler method. The specific yield of basaltic aquifer in WR-2 watershed is meager and takes about 24 hours to recoup the dug after the pumping is stopped. Besides this, the irregular rainfall pattern over the years causes reduced runoff, which in turn reduces the base flow and ultimately natural recharge to the groundwater resources in the aquifers becomes negligible. These aspects result in depletion of groundwater level in the shallow aquifers of WR-2 watershed. Moreover, excessive use of pesticides and fertilizers has already deteriorated the quality of groundwater, causing leaching of soil and increase in the soil salinity. All these factors lead to a vicious cycle of groundwater over-exploitation and its quality deterioration in the WR-2 watershed (figure 13).

The study of groundwater quality in WR-2 watershed indicates that groundwater from shallow aquifer tapped by more than 50% dug wells is not suitable for drinking and domestic purposes. This is due to higher concentration of parameters like Ca, Mg, NO_3 , TDS, TA and TH, which are beyond the permissible limit. The higher

cost, groundwater, irrigation time, and electrical energy. Another management strategy to improve efficiency of water use is to utilise Pipe Distribution Network (PDN) instead of Canal Distribution Network (CDN). By virtue of PDN the water use efficiency can be improved up to 70–80% from existing efficiency of 40% in the study area of WR-2 watershed.

As part of the participatory groundwater management approach, the stakeholders, people, and administrators should come forward for above-referred interventions by strengthening collaboration and increasing confidence amongst them, before the system deteriorates. Although, the relation between over-exploitation of groundwater and its quality has been observed and established in the study area of WR-2 watershed, it requires detailed investigation. A dense and strong monitoring network for detailed long term water level and quality measurements and rainwater harvesting and other artificial recharge techniques should be implemented effectively to arrest declining water level and improving groundwater quality. The rising trends of EC in such watersheds/areas can be used as an indicator of groundwater over-exploitation. The results can be used for further study of similar over-exploited watersheds, in Amravati district, in particular and Maharashtra State, in general.

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