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Impact of urbanization on the groundwater regime in a fast growing city in central India

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Abstract This paper describes the impact of urbanization on the groundwater regime in a fast growing city, Solapur, in central India, giving special emphasis on the management of the present and ultimate demand of water in 2,020 AD. The objective is to apprise the city planners and administrators of the effects of urbanization on the groundwater regime in a fast growing medium-sized city in a developing country where the infrastructure developments are not in conformity with the rapid growth in population. Solapur city with an area of 178.57 km^2 receives a recharge of about 24 million m^3 of groundwater from various sources annually. Reduction in recharge, as conventionally assumed due to the impact of urbanization, could not, however, be well established. Instead, there was a rise in recharge as water use in the city grew from time to time and more and more water was supplied to satisfy the human needs. Compared to mid-1970s, groundwater levels have increased within the main city area due to increased recharge and decreased groundwater abstraction. However, outside the main city area, there is a general decline in groundwater levels due to increased groundwater utilization for irrigation purposes. Groundwater quality deterioration has been highly localized. Water quality has deteriorated during the last 10 years, especially in dugwells, mainly due to misuse and disuse of these structures and poor circulation of groundwater. However, in case of borewells, comparison of the present water quality with that in mid-1970s and early 1980s does not show any perceptible change. Deeper groundwater tapped by borewells can still be used for drinking purposes with caution.

Keywords India · Urbanization · Population · Groundwater · Hydrogeology · Recharge · Quality · Sewage · Sewerage · Wastewater · Pollution · Water supply · Water demand

Introduction

India, with a population of 1,103,371,000 (July 2005), is the most populous country in the world after China. All its developmental sectors are in growing state; villages which once did not have the basic amenities for water and electricity even after several years of independence are being provided with these facilities in recent years through several government-sponsored programs. Despite these efforts to improve rural facilities, there is a rapid migration of rural population to urban areas possibly for better work opportunities and living conditions.

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The urban areas are fast getting densely populated and are expanding rapidly to adjoining areas putting unwanted stress on the natural resources. Agricultural lands around the urban areas are rapidly vanishing giving place to pukka houses and tall buildings. While value of these lands is on the rise, the environmental health around these areas is on the decline. Civic administrators and city planners are making all attempts to provide basic amenities to the growing urban population and plan the newly added areas in a systemic manner. But, with the availability of the limited natural resources and fund constraints, their efforts are implemented in a very slow pace and are not in conformity with the rapid growth in population. The demand on water is ever increasing and although attempts are being made to supply adequate quantity of water, the sewerage systems installed years back are inadequate to contain the quantum of water converted to sewage. With the improvement in infrastructural facilities and increase in trained manpower, several small to large-sized industries are being rapidly established with no proper disposal facilities for their effluents. There is thus an environmental mess, especially in the rapidly expanding towns and cities across the country. Groundwater quality is soon getting deteriorated due to seepages from unlined sewerage lines and effluent channels.

The impact of urbanization on the groundwater regime within a specific urban area depends both on its geographical location and the economic status of the city or even the country (Vazquez-Sune et al. 2005). Chilton et al. (1999) give the environmental status of selected cities across the world. Zaporozec and Eaton (1996), Niemczynowicz (1999), Howard and Israfilov (2002), Aronica and Lanza (2005a) describe the current hydrological problems of in urban areas. Table 1 gives a list of studies carried out in cities in different parts of the world historically on various aspects of urban groundwater. The present investigation is an attempt to study the impact of urbanization on the groundwater regime in Solapur city, a rapidly growing medium-sized city in central India in the State of Maharashtra (Fig. 1). Special emphasis has been given on the management of the present and ultimate demand of water in 2,020 AD. Pollution threat to the groundwater regime has also been studied. The purpose is to apprise the world readers of the hydrogeological changes that occur due to urbanization in a growing medium-sized city in a developing country so that proper planning could be done beforehand to counter the ill effects, if any.

Solapur, with a population of 907,400 (2003), is the 37th most populous city in the country and eighth in the State of Maharashtra. From a population of 75,288 in 1901, its population increased to 873,009 in 2001, a rise of 1,160% in 100 years (Fig. 2). Until about early 1990s, it covered an area of 33.03 km^2, but major expansion of the city took place in 1992 with the inclusion of 13 adjoining villages within the city limits. The city now has an area of 178.57 km^2 – a five-fold increase in its previous area. With such a sudden expansion, Solapur was soon identified as one of the fast growing cities in India in terms of geographical area in the decade 1990–2000. Solapur Municipal Corporation (SMC) looks after the civic administration of the city.

Climate

Solapur experiences a sub-tropical monsoon type of climate. The southwest monsoon lasts from June to October and brings about 87% of the annual rainfall (long-term normal 677.7 mm). The winter season lasts from November to February and the summer extends from March to May. December is the coldest month with the diurnal temperature varying between 15 and 30°C. May is the hottest month with the diurnal temperature ranging between 26 and 40°C. The air is humid during monsoon months; relative humidity ranges between 45 and 89% in the morning (930 h) and 17–70% in the evening (1,730 h). The wind speed varies between 5.3 kmph in December and 17.3 kmph in June averaging 10.3 kmph annually.

Land use

Solapur is highly urbanized in an area of about 35 km^2. In its periphery semi-urban to rural scenarios still prevail. Only 20% of the city is fully developed with basic infrastructural facilities and about 70% of land is still under agricultural uses. After the expansion of Solapur municipal area in 1992, the city is divided into 16 administrative sectors. Sectors 1–9 consist of the main city area with an area of about 30 km^2 and sectors 10–16 consist of the newly expanded areas (141 km^2) of which about 80% of land is under agricultural uses. An area of 7.50 km^2, most of which is fully developed, comes under the

Table 1 List of selected studies carried out worldwide in major cities on urban groundwater

Worker	Year	City	Purpose of study
Fleetwood	1969	Stockholm, Sweden	Nitrate pollution
Piskin	1973	Nebraska, United States of America (USA)	Nitrate pollution
Long and Saleem	1974	Chicago, USA	Sulfate and chloride pollution
Tryon	1976	Phelps County, Missouri, USA	Groundwater quality
Olania and Saxena	1977	Jaipur, India	Chloride and iron pollution
Cross	1980	Halifax, Canada	Chloride in deicing salts
Cruickshank et al.	1980	Merida, Mexico	Bacterial pollution
Eisen and Anderson	1980	Milwaukee, USA	Sulfate, chloride and bacterial pollution
Katz et al.	1980	Nassau County, New York, USA	Nitrate pollution
Ku	1980	Long Island, New York, USA	Metal pollution
Martini et al.	1980	Orvietto, Italy	Bacteria and nitrogen species
Kakar and Bhatnagar	1981	Ludhiana, India	Metal pollution
Nelson et al.	1981	Several cities, California, USA	Chlorinated hydrocarbon solvents (CHS)
Nemeth and Uduluft	1982	Munich, Germany	Major ions pollution
Handa et al.	1983	Faridabad, India	Chromium pollution
Marsh and Davies	1983	London, United Kingdom (UK)	Groundwater levels
Mcfarlane	1984	Perth, Western Australia	Quantity and quality
Flipse et al.	1984	Long Island, New York, USA	Nitrate pollution
Kimmel	1984	Long Island, USA	Metals and nitrate pollution
Ritter and Chirnside	1984	Southern Delaware, USA	Landuse impact
Cavallero et al.	1985	Milan, Italy	Organic pollution
Fusillo et al.	1985	New Jersey, USA	CHS, organic pollution.
Krill and Sonzogni	1968	Wisconsin, USA	Organic pollution
Thomson and Foster	1986	Bermuda, Bermuda	Bacterial, chloride and nitrate pollution
Appleyard and Bawden	1987	Perth, Western Australia	Impact on nutrient loads
Brassington and Rushton	1987	Liverpool, UK	Rising water table
Dummer and Straaten	1988	Bielefeld, W. Germany	Organic, EC, manganese and chloride pollution.
Foster	1988	Several cities, S. America	Nitrate, bacterial and metal pollution
Lloyd et al.	1988	Birmingham, UK.	Major ions, metals and organic pollution
Marton and Mohler	1988	Bratislava, Czechoslovakia	Oil pollution
Merkel et al.	1988	Munich, West Germany	Majors ions and metals pollution
Razack et al.	1988	Narbonne, France	Sulfate and nitrate pollution
Shahin	1988	Cairo, Egypt	Nitrate, major ions and metal pollution
Sharma	1988	Bhopal, India	Major ions and metal pollution.
Vossen and Huijsmans	1988	Tilburg, Netherlands	Cynide and organic pollution
Zipfel and Horalek	1988	Upper Rhime, W. Germany	Organic pollution
Atwood and Barber	1989	Perth, Western Australia	Groundwater quality
Barker et al.	1989	Ontario, Canada	Organic chemicals
Lerner	1989	Several cities	Groundwater recharge
Sahgal et al.	1989	Luknow, India	Nitrate pollution
Simpson et al.	1989	London, V	Rising water table
Sukhija et al.	1989	Tirupati, India	Nitrate and bacterial pollution
Ford	1990	Birmingham, UK.	Major ions, metals, boron, phosphorous, silicon and cyanide pollution
Gerriste et al.	1990	Swan Coastal Plain, Western Australia	Groundwater quality
Gosk et al.	1990	Coventry, UK.	CHS pollution
Rivett et al.	1990a	Birmingham, United Kingdom	Organic contamination
Rivett et al.	1990b	UK cities, UK	Organic contamination
Barber et al.	1991	Several cities	Groundwater pollution
Lerner and Tellam	1992	Several cities	Groundwater pollution

Table 1 (continued)

Worker	Year	City	Purpose of study
Longstaff et al.	1992	Luton and Dunstable, UK.	CHS contamination
Burston et al.	1993	Coventry region, UK	CHS pollution
Knipe et al.	1993	Birmingham, UK	Rising water table
O'Shea	1993	Wilkinson, UK	Rising water table
Halliday	1993	Nottingham, UK	Sewer pollution
Khadka	1993	Kathmandu, Nepal	Groundwater quality
Bocanegra et al.	1993	Mar del Plata, Argentina	Groundwater decline, salt water intrusion and contamination
Martinez et al.	1993	Mar del Plata, Argentina	Impact of urban solid wastes
Nazari et al.	1993	Coventry, UK	Groundwater pollution.
Somasundaram et al.	1993	Madras (now renamed as Chennai), India	Groundwater pollution
Cox and Hillier	1994	Brisbane, Queensland, Australia	General effects
Foster et al.	1994	London, UK	Groundwater recharge
Ford and Tellam	1994	Birmingham, UK	Inorganic contamination
Greswell et al.	1994	Birmingham, UK	Rising water table
Mehta et al.	1994	Bhubanehwar, India	High iron hazards
Lerner et al.	1994	Several cities	Impact of sewers
Rismianto and Mak	1994	Jakarta, Indonesia	Groundwater decline and contamination
Rojas et al.	1994	Lima, Peru	Groundwater contamination
Appleyard	1995	Perth, Western Australia	Groundwater recharge and quality
Otto et al.	1995	Perth, Australia	Groundwater quantity and quality
Barber et al.	1996	Gwellup wellfield, Western Australia	Landuse changes and groundwater quality
Benkar et al.	1996	Perth, Western Australia	Trichloroethene (TCE) contamination
Cardoso	1996	Rio de Janeiro, Brazil	Groundwater contamination
Grischek et al.	1996	Dresden, Germany	Groundwater pollution
Hasan	1996	Dhaka, Bangaladesh	Groundwater decline and contamination
Howard et al.	1996a	Southern Ontario, Canada	Urban impacts on national resources
Howard et al.	1996b	Toronto	Impact of landfilling practices
Jacobson	1996a	Canberra, Australia	Groundwater contamination
Jacobson	1996b	Kathmandu, Nepal	Groundwater contamination
Lerner and Barrett	1996	Cities across UK	Several issues
Cox et al.	1996	Brisbane, Australia	Various urban effects
Rao and Thangarajan	1996	Chennai, India	Groundwater decline, saline water intrusion and contamination
Rivers et al.	1996	Nottingham, UK	Nitrogen contamination
Sharma et al.	1996	Perth, Australia	Nutrient discharge
Subrahmanyam	1996	Hyderabad, India	Groundwater decline and contamination
Tirtomihardjo	1996	Jakarta, Indonesia	Groundwater decline, contamination and land subsidence
Armienta et al.	1997	Zimapan, Mexico	Arsenic contamination
Barrett et al.	1997	Nottingham, UK	Groundwater quantity and quality
Bonomi and Cavallin	1997	Milan, Italy	Groundwater management
Butler and Verhagen	1997	Pretoria, South Africa	Environmental isotope tracing
Molenaar et al.	1997	Rotterdam, The Netherlands	Groundwater information system and environmental management
Riemann	1997	Dessau, Germany	Groundwater lowering
Turin et al.	1997	Albuquerque, New Mexico, USA	Groundwater quality
Barrett	1998	Nottingham, UK	Rising groundwater table and pollution
Butwell	1998	Ruwaishid, Irbid, Jordan	Lowering water table and deteriorating water quality
Coutinho	1998	Bridgetown, St. Michael, Barbados	Groundwater contamination

Table 1 (continued)

Worker	Year	City	Purpose of study
Esslinger	1998	Calgary, Alberta, Canada	Groundwater contamination
Fung	1998	Beijing, Hubei, China	Groundwater decline and contamination
Janet	1998	Honolulu, Hawai, USA	Groundwater contamination
Keizer	1998	Fredericton, New Brunswick, Canada	Groundwater contamination
Loehnert	1998	Muenster, North-Rhine–Westfalia, Germany	Groundwater contamination
Morrill	1998	Tokyo, Japan	Groundwater recharge and contamination
Pokrovsky et al.	1998	Tomsk, West Siberia, Russia	Groundwater table decline and contamination
Baechler	1999	Sydney, Nova Scotia, Canada	Groundwater contamination, salt water intrusion, etc.
Barrett et al.	1999	Nottingham, UK	Groundwater recharge
Cheney et al.	1999	Wigan, northwest England, U.K.	Urbanization impacts on groundwater and industrial development
Drouin-Brisebois	1999	Kingston, Jamaica	Groundwater decline and contamination
Dubruovoskaya and Zemstov	1999	Tomsk, West Siberia, Russia	Groundwater table decline and contamination
Dutova et al.	1999	Tomsk, West Siberia, Russia	Groundwater contamination
Farah	1999	Khartoum, Sudan	Groundwater quality
Gossel et al.	1999	Berlin, Germany	Sustainable groundwater management
Herrington	1999	Ta'iz, Central Highlands, Yemen	Groundwater recharge, salt water intrusion and contamination
Houser	1999	Albuquerque, New Mexico, USA	Groundwater quantity and quality
Johansson et al.	1999	Managua, Nicaragua	Groundwater protection
Lam	1999	Tomsk, West Siberia, Russia	Groundwater table decline and contamination
Lok	1999	Lima, Peru	Groundwater contamination
Petrou	1999	San Antonio, Texas, USA	Groundwater extraction and land subsidence
Pokarajac	1999	Bijeljina, Bosnia	Wastewater and groundwater management
Ramkhalawan	1999	Port-of-Spain, Trinidad and Tobago	Groundwater level decline, salt water intrusion and contamination
Stanley	1999	Mineola, New York, USA	Groundwater recharge and pollution
Whitehead et al.	1999	Liverpool, UK	Sewage contamination
Yang et al.	1999	Nottingham, UK	Groundwater recharge
Lawrence et al.	2000	Hat Yai, Thailand	Groundwater evolution
Vazquez-Sune et al.	2000	Barcelona, Spain	Groundwater recharge
Lee	2000	Several cities, Latin America	Urban water management
Czemiel	2000	Kalmar, Sweden	Phosphorous and Nitrogen pollution
Campana and Tucci	2001	Porto Alegre, Brazil	Floods from urban development
Chan	2001	Tianjin, Hubei, China	Declining water table and land subsidence
Chebbo et al.	2001	'Marais' Urban Catchment, Paris, France	Urban wet weather pollution
Gutierrez	2001	Valletta, Malta	Groundwater contamination and seawater intrusion
Larson et al.	2001	Los Banos-Kettleman City, California, USA	Land subsidence
Lee et al.	2001	Seoul, Korea	Groundwater budget
Lóaiciga and Leipnik	2001	Santa Barbara, California, USA	Sustainable groundwater management
Wellman	2001	Port Louis, Mauritius	Groundwater level decline and pollution
Kouraa et al.	2002	Benslimane, Morocco	Reuse of urban wastewater
Gray and Becker	2002	Ellenbrook, Perth, Australia	Contaminant flows
Diaz-Fierros et al.	2002	Santiago, Spain	Contaminant loads and sewer systems
Kolokytha et al.	2002	Thessalomini, Greece	Water demand management
Vaze and Chiew	2002	Melbourne, Australia	Pollutant characteristics on urban road surfaces
Faye et al.	2004	Thiaroye, Senegal	Urban development

Table 1 (continued)

Worker	Year	City	Purpose of study
Thomsen et al.	2004	Several cities, Denmark	Groundwater protection
Zanfang et al.	2004	Hangzhau, China	Detection of nitrate sources in urban groundwater
Zekster and Loaiciga	2004	Selected cities, southwestern USA	Environmental impacts of ground water
Angelakis et al.	2005	Selected cities, ancient Greece	Urban wastewater and stormwater technologies
Aronica and Lanza	2005b	Genoa, Italy	Drainage efficiency
Choi et al.	2005	Seoul, South Korea	Hydrochemistry, land use effect
Cox et al.	2005	Brisbane, Australia	Water Quality conditions
Ozeler and Yetis	2005	Ankara, Turkey	Solid waste management
Vazquez-Sune et al.	2005	Barcelona, Spain	Groundwater quality and quantity
Liu et al.	2005a, b	Beijing, China	Sewage irrigation
Burian and Shepherd	2005	Houston, USA	Diurnal rainfall pattern
Howard et al.	2005	Kampala, Uganda	Piped urban supplies
Athanasiadis et al.	2005	Thessaloniki, Greece	Water management
Subba Rao and Reddy	2006	Visakhapatnam, India	Environmental impact assessment
Pandit and Bhardwaj	2006	Jaipur, India	Hydrogeological regime
Raju and Reddy	2007	Tirupati, India	Environmental impact assessment

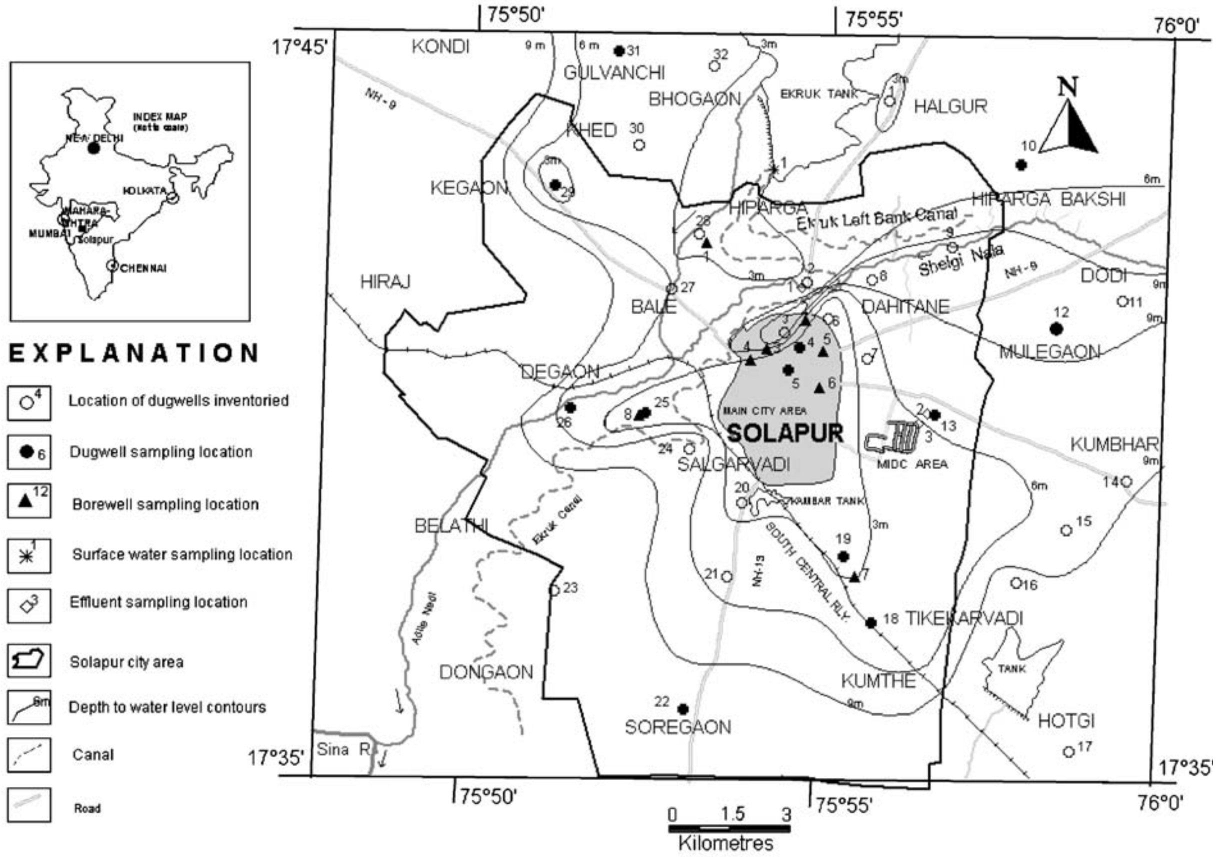

Fig. 1 Location of Solapur city, Maharashtra, India with depth to water levels and sampling sites

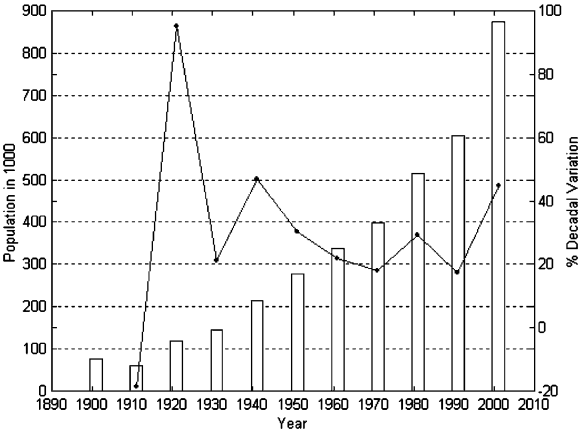

Fig. 2 Population growth pattern of Solapur city, Maharashtra India

administration of Maharashtra Industrial Corporation (MIDC) and Maharashtra Housing and Area Development Authority (MHADA). Table 2 gives the land use details of Solapur city.

Land use of the main city area is available for the year 1980. About 47% of the city was developed in 1980 with the basic infrastructural facilities, and about 25% of the land was under agricultural uses. When the same land use details are compared with those of the year 1994 for the same area (Table 3), it is found that residential areas increased to 35%, mixed uses to 61%, commercial uses to 78% and area under transport and communication to 60% within a span of 15 years. But there was a drastic decrease in the areas allotted to public utilities, agricultural activities and vacant lands, clearly due to urban development. Industrial growth too was very sluggish. Rapid urbanization is now taking place in sectors 10–16 that were added in 1992.

Industries

Solapur is world famous for its textile industries and products, mainly towels, bed sheets and cotton blankets (called “chaddars” in Hindi). There are about 25,000 power looms today employing about 100,000 workers. The textile manufacturing processes involve dyeing and bleaching activities, and are the major sources of industrial pollution in the city. Apart from textile, other industries include that of food processing and doubling, winding/warping, saw mills, cloth, spinning mills, oil mills, paint, rubber etc. In an area developed by Maharashtra Industrial Development Corporation (MIDC) in the eastern part of the city, there are about 300 major industries that include textile, chemical, steel fabrication, mosaic tiles, pharmaceutical, foundry, plastic, cattle feed, detergent powder, dyeing and coloring industries. Effluent disposal facilities of these industries are very poor. However, in the past two decades, the industrial

Table 2 Land use in Solapur city, Maharashtra, India

Sr. no.	Land use	Area (km^2)			Percent with total area			Percent with developed area		
		Sector 1–9	Sector 10–16	Whole city	Sector 1–9	Sector 10–16	Whole city	Sector 1–9	Sector 10–16	Whole city
1	Residential	5.24	6.36	11.60	17.62	4.50	6.78	31.62	37.48	34.59
2	Mixed use	1.21	0	1.21	4.07	0	0.71	7.30	0	3.61
3	Industrial	0.80	2.07	2.87	2.70	1.47	1.68	4.83	12.20	8.56
4	Commercial	1.41	0.27	1.68	4.74	0.19	0.98	8.51	1.59	5.01
5	Transport and communication	4.55	4.41	8.96	15.30	3.12	5.24	27.46	25.99	26.71
6	Public and semi-public	3.30	3.51	6.81	11.1	2.48	3.98	19.92	20.68	20.3
7	Public utilities	0.06	0.35	0.41	0.2	0.25	0.24	0.36	2.06	1.22
	Developed area	16.57	16.97	33.54	55.72	12.01	19.61	100	100	100
8	Burial cremation ground	0.71	0.06	0.77	2.39	0.04	0.45			
9	Water bodies	1.01	2.76	3.77	3.40	1.95	2.20			
10	Agricultural land	7.83	111.43	119.26	26.33	78.87	69.73			
11	Vacant land	3.62	10.07	13.69	12.17	7.13	8			
	Undeveloped area	13.17	124.32	137.49	44.28	87.99	80.39			
	Total area	29.74	141.29	171.03[a]	100	100	100			

[a] Excluding about 7.50 km^2 under MIDC (Maharashtra Industrial Development Corporation) and MHADA (Maharashtra Housing and Development Authority)

Table 3 Land use in Solapur city, Maharashtra, India in 1980 and 1994

Sr. no	Land use	1980			1994			Percent increase or decrease
		Area (km^2)	Percent with respect to total area	Percent with respect to developed area	Area (km^2)	Percent with respect to total area	Percent with respect to developed area	
1	Residential	3.80	14.89	31.85	5.12	20.06	31.30	+34.74
2	Mixed use	0.75	2.94	6.29	1.21	4.74	7.40	+61.33
3	Industrial	0.73	2.86	6.12	0.80	3.13	4.89	+9.59
4	Commercial	0.79	3.10	6.62	1.41	5.53	8.62	+78.48
5	Transport and communication	2.82	11.05	23.64	4.52	17.71	27.63	+60.28
6	Public and semi-public	3	11.76	25.15	3.29	12.89	20.11	9.67
7	Public utilities	0.04	0.16	0.34	0.01	0.04	0.06	−75.00
	Developed area	11.93	46.75	100	16.36	64.11	100	37.13
8	Burial cremation ground	0.71	2.78		0.71	2.78		0
9	Water bodies	0.70	2.74		1.01	3.96		44.29
10	Agricultural land	6.35	24.88		3.83	15.01		−39.69
11	Vacant land	5.83	22.84		3.61	14.15		−38.08
	Undeveloped area	13.59	53.25		9.16	35.89		−32.60
	Total area	25.52[a]	100		25.52[a]	100		

[a] Excluding about 7.55 km^2 under MIDC (Maharashtra Industrial Development Corporation) and MHADA (Maharashtra Housing and Development Authority)

growth in the main city area (35 km^2) has become very sluggish, which possibly is s sign of the late stage of urban development (Vazquez-Sune et al. 2005).

Water supply

Solapur relies mainly on surface water supply for drinking, industrial and other domestic purposes. There are three different sources of surface water supply: (1) Ujjani Dam Reservoir about 100 km west of the city, (2) Bhima River at village Takli about 30 km south of city and (3) Ekruk Tank near village Hipparga about 3 km north of the main city. Arrangement has been made for direct supply of 90 million liters per day (MLD) of water to Solapur from the Ujjani Dam, which is basically a hydro-electric-cum-irrigation project. Bhima River scheme at village Takli, designed to supply about 120 MLD of water, collects the released water from the Ujjani Dam. Ekruk Tank, constructed for irrigation purposes in 1871, can supply up to 27 MLD of water. However, in recent years, due to scanty rainfall, these reservoirs do not get filled to their full capacities. As per SMC's Public Health Engineering (PHE) Department, which looks after the water supply and sewerage facilities in Solapur city, 60 MLD of water from Ujjani Reservoir, 50 MLD from Bhima River at Takli and 10 MLD from Ekruk Tank are currently drawn totaling a supply of 120 MLD of water. There are three water treatment plants (water works) for these three different surface water sources.

Groundwater is not used for public water supply through pipelines. There are about 2,600 borewells constructed in the city. These borewells suffice the additional demand of surface water supply in most parts of Solapur city.

Sewerage/effluent discharge facilities

Solapur city has an underground drainage system, which is in operation since 1968. It covers most parts of the main city area (33.03 km^2) and does not include the newly extended area of 1992. There is a sewage treatment plant at Degaon in the west, but it is not in operation for the past few years. Data provided by the Drainage Department of SMC indicate that out of 12 MLD of water supplied to the main city, 80%, i.e., 9.6 MLD, is converted to sewage out of which 5.4 MLD is drained through underground drainage system. But, since more than 100 MLD of water is actually being supplied to the city on daily basis, much of the wastewater remains untapped by the underground drainage system and flows in small open channels to join the adjoining Shelgi Nala in the north. The Shelgi Nala joins the Adila Nadi, a tributary of the Sina River, in the west ('Nala' and 'Nadi' are the terms in Hindi meaning stream and river, respectively). The wastewater from the Shelgi Nala is lifted for irrigation purposes by local farmers. Even lifting of sewerage water from the main sewerage line at the outskirts of the city is allowed by SMC. In the western part of the city, the wastewater from the main sewage line is applied on lands for growing a variety of green grasses for commercial purposes. SMC and State Irrigation Department gain revenue from such lifting of wastewater.

Solid wastes generated in the city amount to about 250–275 million tons per day. For disposal of the solid wastes, there are two solid waste disposal sites at Tuljapur Depot and Bhogaon Depot north of the city. Tuljapur Depot covers an area of 55 ha and Bhogaon Depot an area of 15 ha. The solid wastes are not treated after their disposal. The decomposed wastes are sold at a price to the farmers by the SMC for use in the walnut/grape plantation areas for enhancement of moisture content in soil.

Groundwater conditions

Solapur city is situated on the basaltic lava flows of the Deccan Volcanic Province of the late Cretaceous to lower Eocene age. The basaltic flows are highly inhomogeneous and anisotropic in nature. Each flow consists of two main trap units, i.e., (1) a lower massive unit and (2) an upper vesicular unit. The massive unit constitutes the main trap unit and forms 60 to 85% of the basaltic flows. It is mostly fine-grained, dense, compact and greenish to dark gray in color. The massive unit possesses negligible primary porosity and permeability, and generally acts as an impermeable layer. However, the process of weathering and the occurrence of joints and fractures at places make it moderately permeable. It occasionally exhibits columnar structures, well-developed joints and spheroidal weathering. The vesicular unit forms the upper horizon of each basaltic flow and constitutes 15–40% of the flows. It is generally soft, fine grained and greenish to brownish in color. The vesicles are usually rounded to oval-shaped and are either open and interconnected or filled with secondary minerals, such as zeolites, quartz and calcite. The vesicular unit possesses primary porosity, and is weathered in most parts. The weathering is conspicuous, even at depth. The density of vesicles increases toward the top of each flow. Often, these vesicles are interconnected, thus making it highly permeable. However, when the vesicles are filled with secondary minerals, such as quartz and calcite, permeability decreases. Because of weathering, these secondary minerals are often removed from exposed rock surfaces leaving a pitted appearance. Generally, the consecutive lava flows are separated by a red layer, varying in thickness from 0.15 to 1 m, termed as 'redbole'. Redboles are considered to be in-situ products of weathering (lateritization), during a long time gap after the earlier flow (CGWB 1984), and subsequently backed by the succeeding flow. Redboles possess low permeability.

Large-diameter wells or dugwells (DW) and borewells (BW) are the prevalent groundwater structures in Solapur city. Dugwells are mostly 5–15 m deep, and rarely reach 20 m depth. Diameters range from 2 to 15 m. Many dugwells are rectangular in shape. The borewells, mostly 150 mm in diameter, are generally 30–90 m deep; most of them are 50–70 m deep. The dugwells thus tap shallow aquifers (<30 m), and the borewells the deeper aquifers (>30 m). Groundwater occurs under water table conditions in shallow aquifers. Inventory of 32 dugwells in the month of February 2003 shows that depth to water levels (DTW) is less than 3 m below ground level (mbgl) in most parts of Solapur main city (Fig. 1). Surrounding this zone, a DTW of 3–6 mbgl is generally observed, which becomes 6–9 mbgl in the eastern parts. A narrow patch in the northeastern parts shows a DTW of more than 9 mbgl, so do the areas around southern and western parts. Groundwater levels are deep in the western parts beyond Degaon.

An analysis of 797 borewells drilled by Groundwater Survey and Development Agency (GSDA), Government of Maharashtra, around Solapur Municipal area shows that 88% of the borewells drilled are successful giving a yield of 500–52,100 L/h. Out of the successful wells, 121 (15%) are high-yielding (>5,000 L/h). The depths of the borewells vary between 24 and 90 m and the casing depths between 0.70 and 36.32 m. Static water levels vary between 1.52 and 80 m. The depth, yield and static water level ranges indicate that the groundwater in deeper levels in most of the borewells occurs under semi-confined to confined conditions. No specific trend exists while plotting the yield of borewells with depth, thus indicating (Fig. 3) that the occurrence of groundwater at depth is generally controlled by fractures occurring at various depths. A recently drilled exploratory borewell for a depth of 171 m by Central Ground Water Board (CGWB), Government of India, in Solapur encountered five different basaltic flows below the city area. The exposed flow on the surface ends at about 15–17 m depth. The second flow goes up to 31 m, the third up to 75 m, the fourth flow up to 151 m and the fifth flow continues below 171 m depth. A yield of 53,568 L/h in this borewell is the highest yield of all the borewells on record in Solapur city, suggesting thereby that there is a good potential of groundwater even at a depth of 150–200 m.

Present demand on water

The expert committee of the Central Public Health and Environmental Engineering Organization (CPHEEO) constituted by the Ministry of Urban Development, Government of India has recommended the following maximum water supply levels for the urban population in India for domestic needs (CPHEEO 1999):

1. Metropolitan and mega cities provided with piped water supply where sewerage system is existing/contemplated: 150 liters per capita per day (lpcd).
2. Cities provided with piped water supply where sewerage system is existing/contemplated: 135 lpcd.
3. Towns provided with piped water supply but without sewerage system: 70 lpcd.
4. Urban areas, where water is provided through public stand posts: 40 lpcd.

CPHEEO (1999) remarks that the above figures include requirements of water for commercial, institutional and minor industries. However, the bulk supply to such establishments should be assessed separately with proper justification. The above figures exclude 15% of the total water requirements mostly for transmission losses through leakages from pipelines. These losses are termed as “UFW” (unaccounted for water).

Solapur is neither a metropolitan nor a mega city; it is a medium-sized fast growing city. Therefore, for the people having tap water supply and adequate sewerage facilities, the water requirements are taken as 135 lpcd. Out of the 900,000 population, about 50%, i.e., about 450,000 people, living mostly in the main city

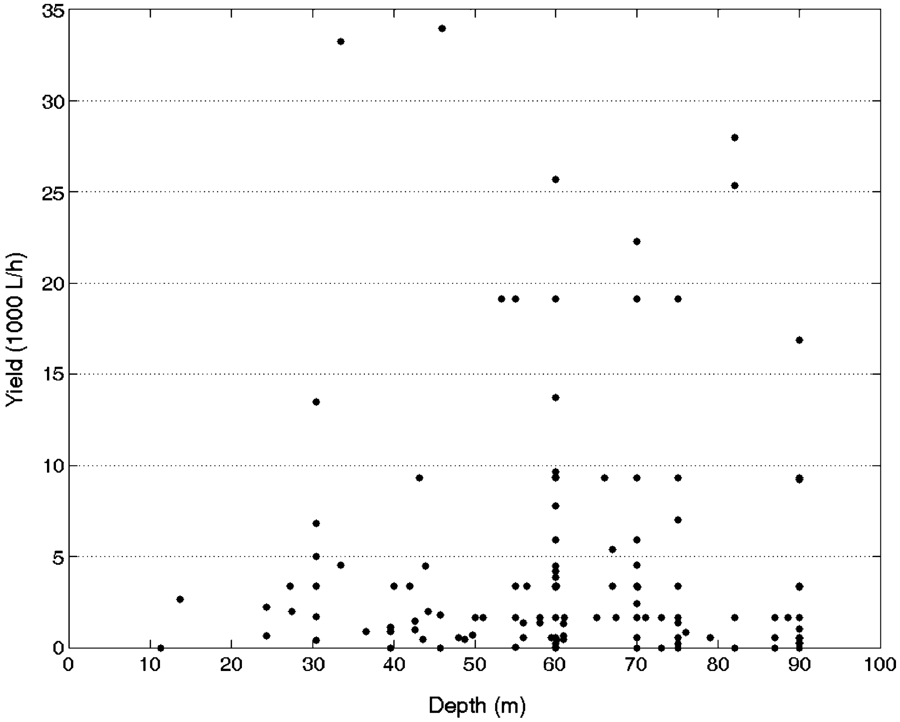

Fig. 3 Relationship of yield of borewells with depth in Solapur city, Maharashtra India

limit, come under this category. SMC has a very ambitious plan to improve the underground drainage system in the old city limits and also to extend it to the adjoining areas, which do not have these facilities at present (MJP 1999; SMC 2003). But this plan is yet to be fully implemented and about 20% of population, especially in the extended areas, is not likely to avail this facility in the next few years. The water requirements for this 20% of population numbering about 180,000 are about 70 lpcd. About 30% of population in Solapur city are slum-dwellers and do not have their own tap water supply connections. These people depend on water supply stand posts provided by the SMC. Total number of people under this category is estimated at 270,000 presently and the water requirements for this population are 40 lpcd. Also, there are a number of water consuming industries operating in Solapur city, and water requirements for these industries are estimated at 41 MLD by the SMC. Accordingly, the current water requirement for the city as a whole works out to be 145 MLD as follows:

(1) 50% of population connected with tap water supply and sewerage facilities at 135 lpcd	61 MLD
(2) 20% of population connected with tap water supply but without sewerage facilities at 70 lpcd	13 MLD
(3) 30% of population depending on water supply stand posts at 40 lpcd	11 MLD
(4) Industrial uses	41 MLD
(5) UFW (transmission losses) (15% of the total supply)	19 MLD
Total	145 MLD

These water requirements are currently met by the existing sources, i.e., (1) Ekruk Tank (10 MLD), (2) Bhima Scheme (50 MLD) and (3) Ujjani Project (60 MLD) totaling 120 MLD on daily basis. Thus, there is a shortfall of about 25 MLD of water (145–120 MLD) for the city as a whole for the existing population and industries. As per the PHE Department of SMC, there is no steady supply of 120 MLD of surface water every year. In some scarcity years, the supply goes down to 65–95 MLD. In such cases, much of the shortfall is met by the groundwater sources through about 2,600 borewells constructed across the city. In some high demand periods, depending on storage and scarcity, the authority supplies surface water once in every 2 days. The water crunch is not so much felt now because the extended areas (13 villages) have not yet been connected with the main water supply pipelines. Much of the water needs of these villages are currently met by groundwater; a few villages have their own water supply schemes from nearby surface water sources.

Estimation of groundwater recharge

Several studies have been done on the groundwater recharge in urban areas (Table 1). Lerner (1986) discussed about the groundwater recharge through leaking pipes. Foster and Chilton (2004) recognized urban wastewater as a major source of groundwater recharge. In Solapur city, there have been mainly four prominent sources of groundwater recharge: (1) rainfall infiltration, (2) transmission losses due to leakages in water supply pipelines, (3) irrigation from wastewater and (4) percolation from surface water tanks. Recharges from these sources have been estimated for the years 2003 (present), 1980, 1994 and 2020.

Conventionally, direct infiltration is greatly reduced in cities because a large portion of the city surface area is relatively impervious, but studies carried out by Lerner (1990); Grischek et al. (1996) and Vazquez-Sune et al. (2005) reveal that this effect is counterbalanced by increased indirect recharge via pluvial soakaways from roofs and paved surfaces and radical reductions in evapotranspiration. An attempt has been made, however, to examine the impact of impervious surfaces on rainfall infiltration without considering the indirect recharges through pluvial soakaways or reduction in evapotranspiration. Hence, the groundwater recharge through rainfall infiltration has been estimated in two different cases: (1) with impervious surfaces and (2) without impervious surfaces.

Groundwater recharge in 2003 (present)

Recharge due to rainfall infiltration

Census data of Solapur show that the city has 161,349 houses, but the actual area of these houses is not known. Sharma et al. (2000) have estimated the average roof size of a house to be 50 m^2 in Solapur city. Taking this average size, the total roof area for the city as a whole is estimated at 8.07 km^2, which is about 25% of the total developed area (33.54 km^2) of the city (Table 2). Again, an area of about 8.96 km^2 is covered by transport and communication facilities, such as pathways and roads, which may/may not be metalled. Assuming that about 50% of these roads may be acting as hard pans preventing rainwater infiltration, the total hard pans due to roads is estimated at 4.48 km^2. The total land surfaces preventing direct infiltration of rainfall in Solapur city is thus estimated at 12.55 km^2, i.e., 8.07+4.48 km^2.

The city receives a rainfall of 677.7 mm annually. Assuming a rainfall infiltration factor of 7% for weathered basalts (CGWB 1998), the total annual recharge through rainfall for an area of 178.57 km^2 is estimated at 7.93 million m^3 (MCM) as follows:

$$\begin{aligned}&\text{Rainfall} \times (\text{total city area} - \text{impervious surfaces})\\&\quad \times \text{rainfall infiltration factor}\\&\quad = 677.7\,\text{mm} \times (178.57 - 12.55)\text{km}^2 \times 7\%\\&\quad = 0.6777\,\text{m} \times \left(166.02 \times 10^6\text{km}^2\right) \times 0.07\\&\quad = 7.88\,\text{MCM}.\end{aligned}$$

If the impact of the impervious surfaces is considered negligible, the estimated recharge would be 8.47 MCM because the 12.55 km^2 of impervious surfaces will not be deducted from the total area of the city. These estimates show that, in the absence of indirect recharges, rainfall infiltration is reduced by 7% due to impervious surfaces. However, indirect recharges due to pluvial soakaways from roofs and paved surfaces and reduction in evapotranspiration due to hard surfaces are inevitable. Therefore, the 2003 (present) groundwater recharge due to rainfall infiltration is taken as 8.47 MCM, not 7.88 MCM.

Recharge due to transmission losses

Transmission losses generally exceed 15% of the total water supply (CPHEEO 1999). Personal discussions with the water supply officials at SMC indicated that these losses mostly occur during transmission of surface water through pipelines inside the city limits. Thus, from a daily supply of 120 MLD of surface water, the daily recharge to groundwater is estimated at 18 MLD (15% of 120 MLD), i.e., 6.57 MCM annually.

Recharge due to wastewater irrigation

City dwellers and industries receive a supply of 126 MLD of water (145–19 MLD of transmission losses), both through surface water and groundwater sources, for actual use. SMC has estimated that about 80% of the water supplied to the city gets converted to wastewater in the form of sewage. Thus, the daily generation of wastewater in the city is estimated at 100.8 MLD (80% of 126 MLD), i.e., 36.79 MCM annually. All these wastewaters are used by farmers for irrigation purposes. Irrigation through wastewater is generally practiced throughout the year except during the rainy season. However, there are dry spells even during the rainy season and irrigation is often required during these dry spells. In about 90 days in a year, irrigation is not generally practiced. Out of the 365 days in a year, irrigation is thus applied in about 275 days, i.e. three fourths of a year. Assuming that about 30% of this applied irrigation water infiltrates into the groundwater reservoir (CGWB 1998), a recharge of 8.28 MCM (i.e., three fourths of the 30% of 36.79 MCM) occurs annually due to application of wastewater for irrigation purposes. The wastewaters generated in the newly added villages have not been included in the above estimation. These villages until now have their own water supply systems (either through groundwater or surface water sources or both), but do not have sewerage facilities through pipelines.

Percolation from surface water tanks

There are two major surface water tanks, namely Siddheswar Tank in city and Kambar Tank on the south of the main city. Siddheswar Tank is several hundred years old and covers a water spread area of 0.19 km^2. Kambar Tank too is very old with a water spread area of about 0.13 km^2. Siddheswar Tank contains about 1.04 MCM and Kambar Tank about 0.53 MCM of surface water (personal discussion with A.B. Narayanpethkar, Head, Department of Geology, Solapur University, 25th August 2006). The total volume of water in both these tanks is about 1.57 MCM. CGWB (1998) recommends that about 60% of the total volume of surface water tanks seeps into the ground under natural conditions in basalts. But, the above two tanks are very old, and much of them have been silted up. Therefore, the average recharge factor from these tanks is taken as 30%. Thus, about 0.47 MCM (i.e., 30% of 1.57 MCM) is actually annually recharged to the groundwater reservoir through surface water tanks in Solapur city.

Total recharge

The total quantum of recharge to groundwater thus available to Solapur city as a whole on annual basis from various sources is listed below.

(1) Recharge through rainfall infiltration	8.47 MCM
(2) Recharge through transmission losses of surface water	6.57 MCM
(3) Recharge through application of waste water for irrigation	8.28 MCM
(4) Recharge through percolation from surface water tanks	0.47 MCM
Total annual recharge to ground water	23.79 MCM

If the 7% inhibition of rainfall infiltration by impervious surfaces is considered, the total recharge would be 23.20 MCM instead of 23.79 MCM. No estimation could be made, however, for the ground water available at deeper levels beyond 30 m depth. State Government, local authorities and the general public so far have been tapping groundwater up to a depth of 90 m, but there is a vast potential of ground water at a depth beyond 150 m as evidenced by the drilling results of CGWB in Solapur city.

Groundwater recharge in 1980

Recharge due to rainfall infiltration

Solapur had a geographical area of 33.03 km^2 in 1980 with 87,313 houses. Taking 50 m^2 as the average roof size of a house, the total area covered by roofs in the city is estimated at 4.37 km^2, which is about 37% of the total developed area (11.93 km^2) of the city in 1980. Transport and communication facilities in the form of roads and pathways covered an area of 2.82 km^2 (Table 3), and assuming that 50% of this area (1.41 km^2) too prevented direct infiltration of rainfall apart from the roof area, the total area that acted as hardpan for rainfall infiltration is estimated at 5.78 km^2 (i.e., 4.37+1.41 km^2). With an annual rainfall of 677.7 mm (i.e., 0.6777 m), the recharge through 7% of rainfall infiltration (CGWB 1998) in an area of 27.25 km^2 (33.03−5.78 km^2) is thus estimated at 1.29 MCM annually, i.e., 3.54 MLD. If the area covered by the impervious surfaces is neglected, the total rainfall infiltration would be 1.57 MCM, i.e., 4.29 MLD. In this case, reduction of recharge due to impervious surfaces, if considered, would be about 18% in a given year.

Recharge due to transmission losses

The Bhima River at Takli surface water supply scheme became operational in late 1970s. Although its initial designed capacity was 54 MLD, there was never the full utilization of its storage capacity. In 1980, about 40 MLD water was drawn daily from this reservoir along with about 20 MLD from the Ekruk Tank. Thus, there was a steady supply of 60 MLD of water to Solapur city. Taking 15% of this volume to be the transmission losses, there was a recharge of about 9 MLD (i.e., 3.29 MCM) annually to groundwater through pipeline leakages.

Recharge due to wastewater irrigation

Solapur had a population of 514,860 in the year 1980. To estimate the volume of wastewater generated during 1980, it is necessary to know the actual volume of water consumed in the city. The water requirements for Solapur during 1980 are given below:

(1) 50% of population connected with tap water supply and sewerage facilities at 135 lpcd	35 MLD
(2) 20% of population connected with tap water supply, but without sewerage facilities at 70 lpcd	7 MLD
(3) 30% of population depending on water supply stand posts at 40 lpcd	6 MLD
(4) Industrial uses	30 MLD
Total	78 MLD

End users in Solapur city received an actual surface water supply of about 51 MLD of water, i.e., 60 MLD of supply−9 MLD of transmission losses. The rest 27 MLD, i.e., 78−51 MLD, was managed by ground water through several dugwells, now abandoned, in the city. Borewell technology was introduced in Solapur in early 1980s. With the above estimate, the wastewater generated in the city is estimated at 62.4 MLD (80% of 78 MLD). Irrigation practices through city's wastewater started in the 1980s. But that time, not full, but at least half of the total volume of wastewater generated was used for irrigation of lands for growing green grasses. As in the case previously, barring 90 days of rainy season, irrigation was practiced in about 275 days, i.e. three fourths of a year. Assuming that 30% of this lifted volume recharged the groundwater reservoir (CGWB 1998), the total recharge is estimated at 7.02 MLD, i.e., three fourths of the 30% of 50% of 62.4 MLD, or 2.56 MCM annually.

The irrigated areas through wastewater, however, were found outside the city limits in 1980. Inside the city, irrigation through wastewater was limited or almost negligible.

Recharge through percolation from surface water tanks

The area of surface water tanks was nearly the same in 1980 as in 2003. Thus, as in the case of 2003, the recharge due to percolation of surface water through tanks is estimated at 0.47 MCM annually.

Total recharge

The ground water recharge in 1980 is thus estimated as follows for Solapur city:

(1) Recharge through rainfall infiltration	1.57 MCM
(2) Recharge through transmission of surface water	3.29 MCM
(3) Recharge through application of wastewater for irrigation	0 MCM
(4) Recharge through percolation from surface water tanks	0.47 MCM
Total annual recharge to ground water	5.33 MCM

If the impervious surfaces are considered inhibiting the rainwater infiltration, the groundwater recharge would be 5.05 MCM, i.e., 1.29+3.29+0.47 MCM. Again, if the irrigation of wastewater outside the city area in 1980 (now inside the city area) is considered, the recharge would be 7.89 MCM, i.e., 1.57+3.29+2.56+0.47 MCM, without considering the impervious surfaces and 7.61 MCM if the impervious surfaces are considered.

Groundwater recharge in 1994

Recharge due to rainfall infiltration

Since land use details are available for the year 1994, an estimate of ground water recharge has been made for this year as well only for the pre-expansion area, i.e., 33.03 km^2. The roof area is estimated at 5.35 km^2 for the 107,000 number of houses in the city as per 1991 census at the rate of 50 m^2 per house. Assuming that this roof area, which is about 33% of the total developed area (16.36 km^2) of the city, and 50% of the area under transport and communication, i.e., 2.26 km^2 (50% of 4.52 km^2 as given in Table 3), acted as hardpans, the total area that prevented rainfall infiltration is estimated at 7.61 km^2. Thus, the annual groundwater recharge due to rainfall infiltration for an area of 25.42 km^2 (i.e., 33.03−7.61 km^2) is estimated at 1.21 MCM, i.e., 3.30 MLD (0.6777 m of rainfall × 25.42×10^4 m^2 of the city area × 0.07 of rainfall infiltration). If the area under hard pans is neglected, the total annual rainfall infiltration would be 1.57 MCM, i.e., 4.29 MLD, as in the case of 1980. Reduction in recharge due to impervious surfaces, if the indirect recharges are not considered due to these surfaces, is thus estimated at about 23%. The main city in an area of 33.03 km^2 is considered to have reached its matured stage in 1994 on the basis of the water level rise and sluggish industrial growth (Vazquez-Sune et al. 2005).

Recharge due to transmission losses

As population increased, the water supply from the Bhima River at Takli was enhanced from 40 to 50 MLD, but the supply from the Ekruk Tank was reduced from 20 MLD to about 15 MLD due to silting problem in the tank. Thus, there was a steady supply of 65 MLD of surface water in the year 1994. Transmission losses are thus estimated at 9.75 MLD (15% of 65 MLD), i.e., 3.56 MCM annually.

Recharge due to wastewater irrigation

To estimate the volume of wastewater generated in the city, it is necessary to know the quantum of water actually used by the city dwellers and the industries. The population of Solapur in 1991 was 603,870, and in 1994 it is estimated at 605,683 at the rate of 1%/year (the decade between 1980 and 1990 was a low growth period). The water requirements for this population are thus estimated as follows:

(1) 50% of population connected with tap water supply and sewerage facilities at 135 lpcd	1 MLD
(2) 20% of population connected with tap water supply but without sewerage facilities at 70 lpcd	8 MLD
(3) 30% of population depending on water supply stand posts at 40 lpcd	7 MLD
(4) Industrial uses	35 MLD
Total	91 MLD

Against a water demand of 91 MLD in Solapur city in 1994, the actual supply of surface water was 65 MLD. The rest 26 MLD was thus managed by groundwater. Assuming that 80% of the water used was converted to wastewater, the total wastewater generated in 1994 was 73 MLD. In 1994, all wastewaters generated from the city were actually applied on the land surface for irrigation purposes barring 90 days in the rainy season, and so the groundwater recharge effected by such an application, although outside the main area of 33.03 km^2, was 16.43 MLD (i.e., 73 MLD×0.30×3/4) or 6 MCM annually.

Recharge through percolation from surface water tanks

The area of surface water tanks was nearly the same in 1994 as in 1980. Thus, the recharge due to percolation of surface water through tanks is estimated at 0.47 MCM.

Total recharge

The total groundwater recharge in Solapur main city for an area of 33.03 km^2 is thus estimated as follows:

(1) Recharge through rainfall infiltration	1.57 MCM
(2) Recharge through transmission of surface water	3.56 MCM
(3) Recharge through application of wastewater for irrigation	0 MCM
(4) Recharge through percolation from surface water tanks	0.47 MCM
Total annual recharge to ground water	5.61 MCM

However, if the impervious surfaces are considered impacting the rainfall infiltration without any indirect recharge, the recharge would be 5.24 MCM, i.e., 1.21+3.56+0.47 MCM. If the irrigation of wastewater outside the main city area (beyond 33.03 km^2) is considered, the recharge would be 11.6 MCM, i.e., 1.57+3.56+6+0.47 MCM, without considering the impervious surfaces and 11.24 MCM if the impervious surfaces are considered.

Groundwater recharge in 2020

Recharge due to rainfall infiltration

The geographical area of Solapur city (i.e., 178 km^2) is not likely to change for several years from now including 2020. However, the developed area will change. Between 1980 and 1994, the developed area increased 37% from 11.93 to 16.37 km^2. Because of the rapid expansion of the city and upcoming projects for augmentation of the water supply and the sewerage facilities, the growth in the developed area is expected to be 50% from now, viz., in 2020 the developed area is likely to be 50.31 km^2. Assuming that the roof area will be about 33% of the developed area, as in 1994, the roof area in 2020 is estimated at 16.60 km^2. Transport and communication sector had a growth of 60% between 1980 and 1994. The trend is likely to remain the same, and is expected to grow 100% between now and 2020. The area under transport and communication is thus likely to be about 17.92 km^2. Assuming that 50% of this 17.92 km^2, i.e., 8.96 km^2, and the roof top area of 16.60 km^2, totaling an area of 25.56 km^2, will act as hard pans for rainfall infiltration, the total annual recharge due to rainfall for an area of 153.01 km^2 (i.e., 178.57−25.56 km^2) is expected to be 7.26 MCM, i.e., 19.89 MLD, for a rainfall of 0.6777 m and infiltration factor of 7%. If the impervious surfaces are not considered, the total recharge due to rainfall infiltration will remain same as that of 2003, i.e., 8.47 MCM. Inhibition of rainfall infiltration to an extent of about 14% is likely to occur due to urbanization in 2020 if the indirect recharges induced by the impervious surfaces are not taken into account.

Recharge due to transmission losses

The population of the city is forecasted at 1,259,629 in the year 2020, and the total supply is estimated at 269 MLD, out of which 234 MLD will be the actual supply and 35 MLD will be the transmission losses (discussed later). The groundwater recharge through transmission losses is thus estimated at 12.78 MCM annually.

Recharge due to wastewater irrigation

A volume of 69 MLD will be supplied through groundwater in 2020 (discussed later). With an actual surface water supply of 234 MLD, the total water supply will thus be about 303 MLD. Wastewater generated will be about 242 MLD (i.e., 80% of 303 MLD). Irrigation of crops through wastewater is not likely to stop in the future. In fact, there is a countrywide drive now in India as to how to make use of the wastewaters generated in huge quantities in cities, and irrigation of lands is a viable option (Hoek et al. 2002). Because there shall be no irrigation water requirements of crops for about 90 days during the rainy season, the total volume of water applied for irrigation purposes in Solapur city in three fourths of the year (275 days) will be 181.5 MLD. Assuming that 30% of the applied irrigation water shall recharge the groundwater regime (CGWB 1998), the total quantum of recharge is estimated at 54.45 MLD, i.e., 19.87 MCM annually.

Recharge through percolation from surface water tanks

The area of surface water tanks is not likely to change in 2020. Thus, as in the case of 2003, the recharge due to percolation of surface water through tanks is estimated at 0.47 MCM annually.

Total recharge

The ground water recharge is thus expected to be about 39.32 MCM for the year 2020 as follows:

(1) Recharge through rainfall infiltration	08.47 MCM
(2) Recharge through transmission of surface water	12.78 MCM
(3) Recharge through application of wastewater for irrigation	19.87 MCM
(4) Recharge through percolation from surface water tanks	0.47 MCM
Total annual recharge to ground water	41.59 MCM

If the impervious surfaces are considered impacting the rainfall infiltration, without indirect recharge, which is not likely the case, the total recharge would be about 40.38 MCM (i.e., 7.26+12.78+19.87+0.47 MCM).

Chemical quality of groundwater

Twenty-four water samples were collected from various sources between 3 and 10 February 2003 for analysis of major chemical parameters and 16 samples for analysis of heavy metals/trace elements. The 24 water samples include 12 from dugwells, 7 from borewells, 2 from surface water sources and 3 from effluents. The 16 water samples collected for analysis of heavy metals include six from dugwells, six from borewells, two from surface water sources and two from effluents. Dugwell samples were collected with the help of a rope and bucket. The bucket was dipped to a depth of about a meter in water while collection of the water samples. Borewell samples were collected after pumping the borewell water for few minutes. The sampling sites are shown in Fig. 1.

Chemical analyses of water samples were carried out as per the procedures recommended by APHA (1998). The analyses include the determination of the major ions and heavy metals expressed in milligram per liter (mg/L). Apart from the determination of hydrogen ion concentrations (pH), electrical conductivity (EC), total hardness (TH) as calcium carbonate ($CaCO_3$) and total dissolved solids (TDS), the major inorganic constituents analyzed include cations, such as calcium (Ca^{++}), magnesium (Mg^{++}), sodium (Na^+) and potassium (K^+), besides anions, such as carbonate (CO_3^{--}), bicarbonate HCO_3^-, chloride (Cl^-), Sulfate (SO_4^{--}), nitrate (NO_3^{--}) and fluoride (F^-). The heavy metals analyzed include copper (Cu^{++}), iron (Fe^{++}), cadmium (Cd^{++}), manganese (Mn^{++}) and zinc (Zn^{++}). Major cations, namely Na^+ and K^+, were determined by using flame photometer-128 while Ca^{++} was analyzed by EDTA (Ethylene Diamine Tetra Acetate) titration. Mg^{++} concentrations were determined from the equation $Mg^{++}=TH-Ca^{++}$ (concentrations were expressed in milliequivalent/liter). CO_3^{--}, HCO_3^- and Cl^- were analyzed by titremetric methods while SO_4^{--} and nitrate (NO_3^{--}) were determined by UV–Visible Spectrophotometric method. F^- was analyzed spectrophotometrically by SPADNS method. The heavy metals were determined by Atomic Absorption Spectrophotometer (GBC-Avanta PM).

Analytical results of the major chemical constituents and heavy metals are given in Table 4. The ionic balance (B_i) of these water samples can be written as:

$$B_\mathrm{i} = \sum(\text{cations}) - \sum(\text{anions}) \times 100 \Big/ \sum(\text{cations} + \text{anions})$$

where cations means concentrations of each cation and anions means concentrations of each anion, both in milliequivalents per liter. The value of B_i for each analysis is less than 10%, thus conforming to the accepted range (Hem 1985). The relationship between

Table 4 Analytical results of the water samples collected from different areas in and around Solapur city between 3 and 10 February 2006

Sl. no.	Well no.	Village	pH	EC	TDS	TH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	Cu	Fe	Cd	Mn	Zn
Source – Dugwell																					
1	DW 4	Bhawanipeth	8.63	2800	1485	1000	32	224	140	3	24	421	557	218	28	1	NA	NA	NA	NA	NA
2	DW 5	North Kasbapeth	8.14	1300	735	405	68	57	87	46	NIL	348	138	157	9	0.51	0.130	3.047	BDL	0.477	0.137
3	DW 10	Hipparga Bakshi	7.92	6000	3985	1675	44	381	270	600	NIL	470	769	1205	480	1.59	0.029	0.242	0.049	0.068	0.231
4	DW 12	Mulegaon	8	780	410	380	48	63	5	3	NIL	329	28	41	55	0.71	NA	NA	NA	NA	NA
5	DW 13	Shankarnagar	7.48	14000	7915	4475	1030	463	1150	10	NIL	214	3925	1098	142	0.8	0.058	0.613	0.108	3.125	0.206
6	DW 18	Tikekarvadi	7.7	2000	1165	735	68	137	133	13	NIL	293	316	329	22	0.95	0.013	0.30	BDL	0.197	0.025
7	DW 19	Majrevadi	7.83	2700	1515	925	74	180	204	2	NIL	305	436	436	32	0.6	NA	NA	NA	NA	NA
8	DW 22	Soregaon	7.72	2200	1240	970	28	219	71	3	NIL	244	355	370	73	1	0.028	BDL	BDL	0.043	0.107
9	DW 25	Koynanagar	8.15	4600	2790	950	34	210	600	5	NIL	537	603	1065	4	1.4	BDL	0.136	0.040	0.077	0.068
10	DW 26	Degaon	8.33	4800	3235	420	46	74	990	20	30	592	738	1025	16	1.2	NA	NA	NA	NA	NA
11	DW 29	Kegaon	7.93	1460	860	490	32	100	47	108	NIL	305	170	203	45	0.6	NA	NA	NA	NA	NA
12	DW 31	Gulvanchi	7.84	2600	1535	780	30	171	206	44	NIL	519	316	312	196	1	NA	NA	NA	NA	NA
Source – Borewell																					
1	BW 1	Juna Karamba Rd	7.72	3900	2290	1515	20	356	244	2	NIL	506	326	1042	50	1.2	0.02	0.325	BDL	0.038	0.093
2	BW 2	Maddivasti	7.83	2500	1370	1190	50	260	15	10	NIL	244	408	248	4.2	0.5	NA	NA	NA	NA	NA
3	BW 3	N. Kasba Road	8.03	1190	705	220	78	6	172	3	NIL	232	152	170	27	0.71	BDL	0.112	BDL	BDL	0.108
4	BW 4	Gold Finchpeth	8.4	1300	725	450	32	90	87	13	27	293	149	146	35	0.95	BDL	BDL	0.065	BDL	0.857
5	BW 5	Dayanand College	7.54	1730	1025	800	208	68	41	3	NIL	256	234	317	26	1.07	0.011	BDL	BDL	BDL	0.058
6	BW 6	Pachhapeth	8.14	1450	880	370	94	33	166	2	NIL	262	195	228	32	1.12	0.037	1.325	BDL	0.02	1.316
7	BW 7	Majrevadi	7.56	2500	1455	1060	238	113	88	BDL	NIL	427	372	361	69	1.12	NA	NA	NA	NA	NA
8	BW8	Koynanagar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	BDL	0.128	0.020	0.026	0.259
Sl. No.	Well No.	Village	PH	EC	TDS	TH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	F	Cu	Fe	Cd	Mn	Zn
Source – Surface water tank																					
1	S1	Ekruk Tank	8.1	380	205	135	36	11	27	1	NIL	159	28	11	10	0.59	0.012	2.147	BDL	0.108	0.011
Source – Treated water tank																					
1	S2	Bhawanipeth Water Works	8.15	530	290	225	36	33	17	4	NIL	146	74	49	4	1.2	BDL	0.492	BDL	0.215	0.152
Source-Effluent																					
1	E 1	Shelgi Nala	7.48	1780	1120	435	148	16	170	50	NIL	250	266	114	223	1.6	0.011	1.886	BDL	0.941	0.065
2	E 2	Shankarnagar	7.7	11000	6490	710	62	135	2092	174	NIL	1196	2979	442	10	0.8	NA	NA	NA	NA	NA
3	E 3	MIDC, Solapur	8.12	8300	4830	1355	347	119	1198	164	NIL	598	2269	426	10	0.9	0.052	2.530	0.058	0.467	0.228

All concentrations are in mg/L, except that of pH and EC (μS/cm)

NA not analyzed; *BDL* below desirable limit as per Indian drinking water standards (BIS 2003) the concentrations of cations and anions is shown in Fig. 4.

Basalts comprise of plagioclase feldspars (labradorite) and pyroxenes (augite). Since plagioclase feldspar forms a solid solution between anorthite ($CaAl_2Si_2O_8$) and albite ($NaAlSi_3O_8$), the mole ratios of different cations and anions depend on the anorthite content of the plagioclase (Garrels and Christ 1967). For example, in labradorite, anorthite content varies from 50 to 70%. The chemical reaction for plagioclase with 50% anorthite content is given as:

$$\begin{aligned}&4Ca_{0.5}Na_{0.5}Al_2Si_2O_8(s) + 6H_2O + 9CO_2 = 3Al_2Si_2(OH)_4(s) + 2Na + 2Ca + 6HCO_3 + 4SiO_2\\ &\quad (mNa/mCa = 1:1) \qquad\qquad\qquad\qquad (mHCO_3/mSiO_2 = 3:2)\end{aligned} \tag{1}$$

This reaction suggests that as a consequence of the natural water–rock interaction processes, the groundwater would acquire sodium, calcium and bicarbonate in appropriate proportions if not contaminated.

$$\begin{aligned}&CaMgFeAl_2Si_3O_{12}(s) + 5H_2O + 6CO_2 = Al_2Si_2(OH)4(s) + Ca + Mg + Fe + 6HCO_3 + SiO_2\\ &\qquad (mCa/mMg = 1:1) \qquad\qquad\qquad\qquad (mHCO3/mSiO_2 = 6:1)\end{aligned} \tag{2}$$

From this reaction, it can be inferred that the release of calcium, magnesium and bicarbonate ions is governed by the interaction of groundwater with augite.

The above two reactions suggest that plagioclase and augite are the chief sources for supply of major cations (Ca^{++}, Mg^{++} and Na^{+}) and anions (HCO_3^{-}) in groundwater in basalt. Rainwater and anthropogenic activities can be important sources for other constituents, such as SO_4^{--} and Cl^{-} (Pawar et al. 1998) including Ca^{++}, Mg^{++} and Na^{+}.

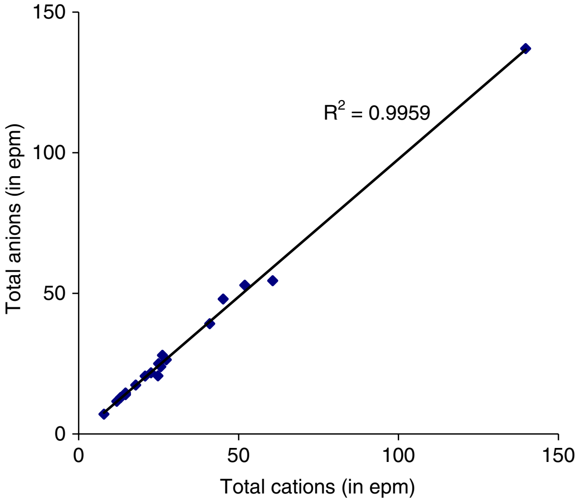

Fig. 4 Relation between concentrations of anions and cations in dugwells and bore wells around Solapur city, Maharashtra, India

The concentrations of the chemical constituents of the dugwell and borewell water samples are plotted on Hill–Piper Diagram (Piper 1944) (Figs. 5 and 6). These figures show that majority of the groundwater samples are dominated by alkaline earths (Ca^{++}+Mg^{++}) (83% from dugwells and 86% from borewells) and strong acids ($SO_4^{--} + Cl^{-}$) (92% from dugwells and 100% from borewells). Romani (1981) modified the Hill–Piper diagram. The nine types of water given by Piper (1944) show essential characters of water rather than grouping them into different types. Further, there are effectively only five classes. The modified diagram (Fig. 7) classifies each cation and anion triangle into seven classes, each with respect to hydrochemical facies (Fetter 1988), and puts them into two broader groups depending on their primary character. Instead of equilateral triangles, Romani (1981) uses right-angled isosceles triangles for plotting cations and anions. Here, the resulting central field showing the primary character is square instead of diamond-shaped. The two right-angled triangles, one for cations and another for anions, are used essentially for classification of waters. The three sides in each triangle, divided in 100 equal parts, represent the percentage reacting values (expressed in epm) of cation and anion groups. The central square field gives the overall character of water.

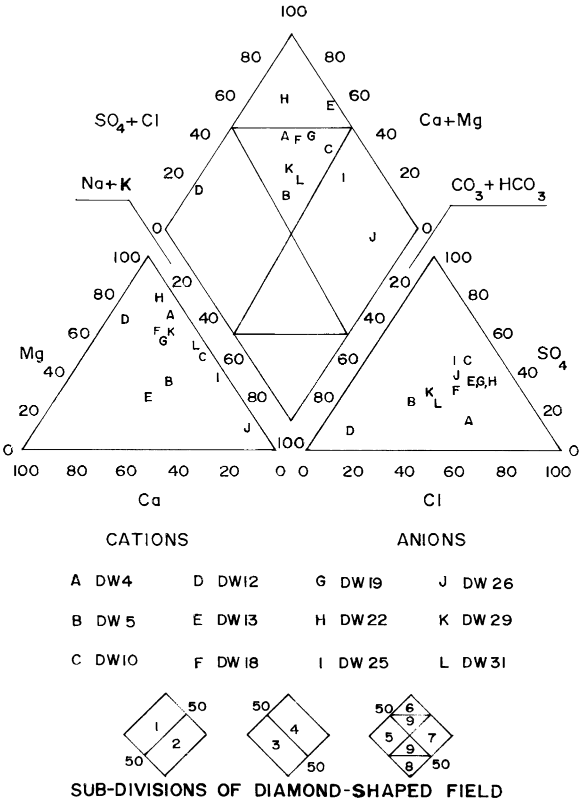

Fig. 5 Plot of chemical constituents of dugwell water samples of Solapur city, Maharashtra India on Hill–Piper diagram (Piper 1944)

Figure 7 shows that in the waters falling in group I, alkaline earths (Ca^{++}+Mg^{++}) are predominant exceeding the bicarbonates. Such waters show permanent hardness and do not have bicarbonate hazard for irrigation. On the other hand, the waters in group II have temporary hardness and residual sodium carbonates. On the basis of Romani's diagram, samples from dugwells in Solapur city are classified as magnesium-chloride-sulfate type (25%), sodium-chloride-sulfate type (18%), magnesium-chloride-bicarbonate type (17%), magnesium-bicarbonate type (8%), magnesium-chloride type (8%), magnesium-bicarbonate-sulfate-chloride type (8%), calcium-magnesium-sodium-chloride type (8%) and calcium-magnesium-sodium-chloride-bicarbonate type (8%). Similarly, the samples from borewells could be classified as sodium-bicarbonate-sulfate-chloride type (29%), calcium-chloride-sulfate type (14%), magnesium-sulfate type (14%), magnesium-chloride type (14%), magnesium-chloride-bicarbonate type (14%), and calcium-magnesium-sodium-sulfate type (14%). In case of dugwells at shallower levels, the several types of water from the same basaltic aquifer show mixed nature of water, thus indicating that the quality of shallow groundwater in the city is possibly affected by several factors. In case of borewells at deeper levels (>30 m) too, mixing of ground waters from several layered basaltic horizons is possible (Naik et al. 2001). Chemical transformation of groundwater due to several factors in urban groundwater is described by Custodio (1997); Gooddy et al. (1997) and Trauth and Xanthopoulus (1997).

Impact of urbanization on groundwater regime

Impact on groundwater recharge

Impervious surfaces, such as rooftops and paved surfaces like roads and pathways, reduce direct infiltration of rainfall. In a given year, such decreases have been in the order of 6% when the city is relatively young, such as in 2003, with an area of

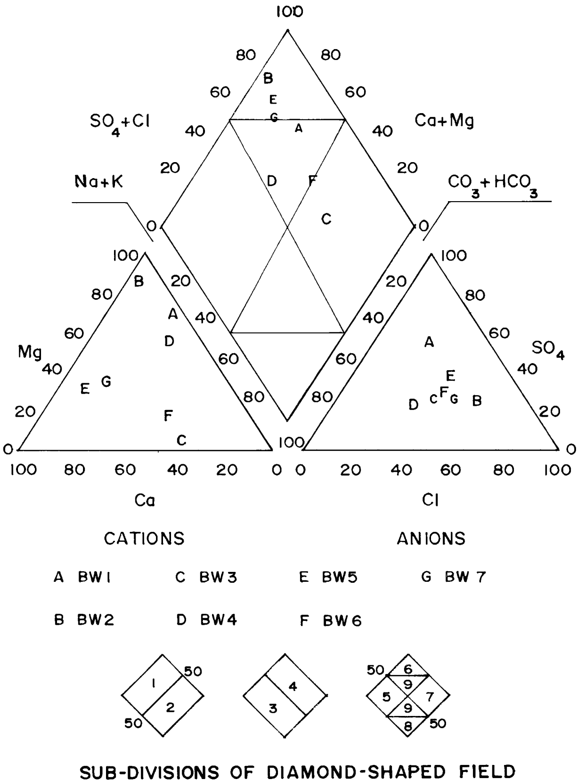

Fig. 6 Plot of chemical constituents of borewell water samples of Solapur city, Maharashtra India on Hill–Piper diagram (Piper 1944)

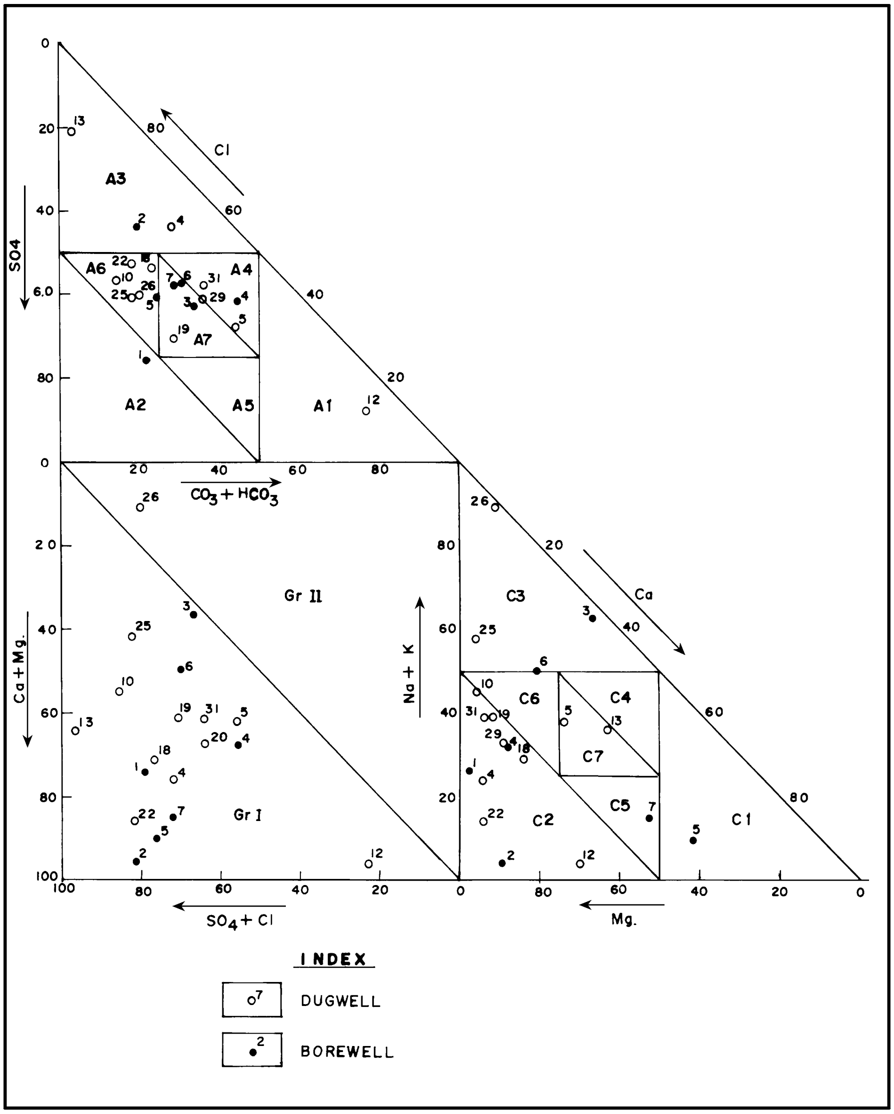

Fig. 7 Plot of chemical constituents of dugwell and borewell water samples of Solapur city, Maharashtra India on Modified Hill–Piper diagram (Romani 1981)

CGWB, CR (PC) DRG. No. 2/2006

178.57 km^2 when there are large open spaces waiting for development to 23% when the city is relatively matured, such as in 1994, with an area of 33.03 km^2 (main city) when the developed area was about 64%. However, indirect recharges due to pluvial soakaways from roofs and paved surfaces, such as roads and pathways, and radical reduction in evapotranspiration compensate such a reduction in recharge (Lerner 1990; Grischek et al. 1996 and Vazquez-Sune et al. 2005).

To make an assessment of the changes in groundwater recharge, it is always better to compare the groundwater recharge received between two time periods with sufficient gap for the same area. Land use details are available for the same area (33.03 km^2) for the years 1980 and 1994, and therefore groundwater recharge received between these two years are compared. Although population has increased from 603,870 to 605,683 between 1980 and 1994, a growth of about 17.64%, there does not seem to be any perceptible change in the groundwater recharge between these two years. The groundwater recharge estimated in 1980 was 5.33 MCM, while in 1994, it is estimated at 5.60 MCM for the same area (33.03 km^2), an increase in recharge of 5%. If immediately outside the city area (presently within the city area) is considered, there is an increase in recharge to an extent of about 3.71 MCM (i.e., 11.60 MCM in 1994−7.89 MCM in 1980), which is an increase in recharge by 47%. Such a rise in recharge in this case can be attributed to wastewater irrigation.

If inhibition of rainfall infiltration due to impervious surfaces due to development and growth of city is considered, there is a decrease in rainfall infiltration between the years 1980 and 1994 to an extent of 0.08 MCM (i.e., 6%) from 1.29 in 1980 to 1.21 MCM in 1994. Between 2003 and 2020, the decrease is likely to be 0.62 MCM (7.88 MCM in 2003−7.26 MCM in 2020) (i.e. 8%). A decrease of 6–8% is negligible and may very well be neglected when a city covers a very large area, to an extent of 178.57 km^2.

The period between 1980 and 1990 was not a high growth period for Solapur in terms of population. Lack of supply of adequate surface water is an important factor for this lean period. The city got expanded in 1992, and arrangements were made to have additional supply of surface water from the Ujjani Dam that currently supplies about 60 MLD of water. After this expansion and additional facilities for surface water in mid-1990s, there has been a rapid flux of people to Solapur city, and the population growth between 1990 and 2001 was about 45%. Addition of population of the adjoining 13 villages has been an important contributor to this population growth, but this addition in population is not the only factor for the city's population growth. The 13 new villages have not yet been supplied with the additional quota of surface water augmented to Solapur city. Till now the 120 MLD of surface water (10 MLD from Ekruk Tank, 50 MLD from the Bhima River at Takli and 60 MLD from the Ujjani Dam reservoir) is supplied to the main city (33.03 km^2) only. Recharge due to rainfall infiltration is generally the same for an equal area between the two different years with a gap of about a decade or two (e.g., 1980 and 1994), but recharge due to transmission losses and wastewater irrigation varies substantially depending on the quantity of water supply and the wastewater generated, which in turn depends on the quantity of water consumed by the city dwellers. Thus, if the groundwater recharge of 3.56 MCM due to transmission losses in 1994 is compared with the 2003 recharge of 6.57 MCM due to these losses, there is an increase in recharge of at least 3 MCM, i.e. an increase of about 84%. Similarly, if the recharge through wastewater irrigation is considered between these two time periods for outside the main city limit (33.03 km^2) (now within the city limit), there is an increase in recharge of 2.28 MCM, i.e., 8.28 MCM in 2003−6 MCM in 1994, which is an increase of ~38%.

With the present area of the city (178.57 km^2) remaining same, if the 2003 (present) recharge of 23.79 MCM is considered and compared with that of 2020, i.e., 41.59 MCM, there is an increase in recharge to an extent of 17.80 MCM, i.e., an increase of about 75%. Between 2003 and 2020, population is expected to rise by 92%, i.e. from 900,000 to 1,725,000 (discussed later). With the increase in population water usages will increase, and the more the water usages, the more will be the generation of wastewater. Again, the more the application of wastewater for irrigation purposes, the more will be the recharge to groundwater.

Groundwater usage through dugwells was prevalent until the late 1970s and early 1980s. In the late 1980s and the early 1990s, borewells became the prevalent structures. City dwellers depended heavily on groundwater during the 1980s and the early 1990s due to lack of sufficient supply of surface water. Usage of groundwater was greatly reduced during the late 1990s due to additional supply of surface water, and the same trend continues now also. Most dugwells got abandoned in late 80s and the borewells in late 1990s. Shallow groundwater levels within the city, e.g., on the road to Shelgi (DW6) (1.11 mbgl), Bhawanipeth (DW4) (2.26 mbgl), Tuljapur Road (DW2) (3.06 mbgl), Majrevadi (DW19) (2.70 mbgl), Nehrunagar (DW20) (2.78 mbgl) and Koynanagar (DW25) (2.76 mbgl), are due to decreasing groundwater abstraction due to higher reliance on surface water. Groundwater level rise due to impact of urbanization has been observed elsewhere in the world, such as Birmingham (Knipe et al. 1993; Greswell et al. 1994); O'Shea 1993 and Nottingham (Barrett 1998).

Hydrogeological studies conducted in Solapur city area by Sudarshana (1988) during the years 1983–1984 and 1984–1985 have shown that groundwater levels in the area south of Solapur city were less than 6 mbgl and in the northern parts 6–9 mbgl. This zonation in water levels is still prevalent in these areas (Fig. 1). Gajbhiye (1977) also studied the area in the years 1975–1976. The changes in water levels of the dugwells he inventoried during March 1975 and the same dugwells inventoried in the present study in February 2003 are shown in Table 5. This table indicates that the groundwater levels are deeper by about 2 m in most areas surrounding Solapur city in 2003 compared to 1975. The possible reason could be groundwater utilization has increased in recent years in these areas mostly for irrigation purposes. The well depths in some cases are shallower mainly due to silting. Many of these wells might have been deepened several times as clearly indicated by the higher depths of these wells in 2003 compared to those in 1997; so the extent of silting is not a clear measure of the silts deposited in these wells over the years.

Impacts of land use changes have been studied by Ritter and Chirnside (1984) and Qi and Luo (2006). In Solapur city, how much land use changes between the years 1980 and 1994 have contributed to the ground water recharge is difficult to quantify, but the expansion of residential areas by 34%, mixed uses by 61%, industries by 10% and commercial areas by 78% has distributed the water supply network in different parts of the city resulting in the increased groundwater recharge due to transmission losses of surface water. Expansion of transport facilities by 60%, reduction of public utilities by 75%, agricultural land by 40% and vacant land by 38% would have certainly reduced the direct rainfall infiltration, but the loss in recharge has been compensated by the additional recharge received due to transmission losses of surface water and irrigation of lands through wastewater, which have direct relationships with the positive growth of the city.

Urbanization has thus increased the groundwater recharge in Solapur city substantially instead of reducing it unlike studies carried out elsewhere in the world by several workers, such as Rismianto and Mak (1994); Hasan (1996); Rao and Thangarajan (1996); Riemann (1997); Butwell (1998); Fung (1998); Pokrovsky et al. (1998); Drouin-Brisebois (1999); Dubruovoskaya and Zemstov (1999); Lam (1999); Ramkhalawan (1999); Chan (2001) and Wellman (2001).

Impact on groundwater quality

Solapur city heavily relies on surface water for drinking, industrial and even irrigation purposes. Groundwater resources are utterly disregarded. Dugwells, which were once the only source of groundwater in the 1960s and 1970s and an important source in the 1980s, are no more in use and are completely abandoned during the past decade. Most of these structures now serve as garbage bins. Borewell technology became popular in the late 1980s and reached its peak in the early 1990s. But, borewells too have limited use now; many of the earlier structures have collapsed/closed. Time is not very far when borewells too may have their extinction in Solapur city

Table 5 Groundwater level changes between the years 1975 and 2003

Location	Well no.	3–11 March 1975		7–9 February 2003		Decline in water levels in 2003 with respect to 1975
		Depth (mbgl)	DTW (mbgl)	Depth (mbgl)	DTW (mbgl)	
Haglur	DW1	9.30	2.40	8.60	6.65	−4.25
Solapur	DW5	4.50	2.00	4.40	2.10	−0.10
Hipparga Bakshi	DW10	8.10	2.97	7.20	4.55	−0.58
Mulegaon	DW12	9.90	9.65	13.45	9.75	−0.10
Tikekarvadi	DW18	10	3.18	7.45	4.15	−0.97
Soregaon	DW22	12.90	5.40	12.75	10.20	−4.80
Degaon	DW26	8.50	4.10	7.00	5.50	−1.40
Kegaon	DW29	8.10	1.50	9.10	2.45	−0.95
Khed	DW30	7.20	3.30	5.50	5.40	−2.10
Gulvanchi	DW31	8.40	3.58	6.80	4.65	−1.07
Bhogaon	DW32	7.70	4.82	9.30	5.90	−1.08
	Average	8.60	3.90	8.32	5.57	−1.67

DTW depth to water level

in the next few decades. Groundwater quality in Solapur city is questionable now in certain pockets, not because of urbanization, but due to the fact that the groundwater structures are not being used now for their intended purposes causing stagnation of groundwater.

In the groundwater originating from basaltic aquifers, generally Ca^{++} concentrations are invariably greater than that of Mg^{++} and Na^{+} (Naik et al. 2001, 2002). But, the fact that Mg^{++} and Na^{+} concentrations are greater than that of Ca^{++} in most of the dugwell and borewell water samples in Solapur city and Na^{+} concentrations are even greater than that of Mg^{++} in many samples, contamination by external sources in certain pockets cannot be ruled out. Das et al. (2005) ascribe anthropogenic reason to higher concentrations of Na^{+} in basalts. Voznaya (1981) opines that industrial and domestic/sewerage wastes give rise to higher concentrations of Mg^{++} in groundwater. Also, in basalts, generally weak acids ($CO_3^{--} + HCO_3^{-}$) dominate the strong acids ($SO_4^{--} + Cl^{-} + NO_3^{-}$). But, in Solapur city strong acids dominate the weak acids, as revealed by Piper diagram (Figs. 5 and 6), suggesting human contamination (Das et al. 2005). Apart from the disuse and misuse of groundwater, other possible sources of pollution could be seepages from unlined sewage lines, domestic drains and leachates from waste dumps. Shepherd (1962); Halliday (1993); Lerner et al. (1999); Eiswirth and Hotzl (1997) and Wolf and Eiswirth (2006) have discussed about the sewer–groundwater interactions elsewhere in the world. Changli et al. (2005) have described the pollution processes acting around the garbage dumps.

Table 6 compares the analytical results of the water samples with those of the drinking water standards defined by the Bureau of Indian Standards (BIS 2003). The table shows that groundwater in Solapur city is generally hard with the Mg^{++} and total hardness (TH) going beyond the BIS desirable limit and even maximum permissible limits in majority of samples. Cl^{-} and SO_4^{--} concentrations in most samples, especially in dugwells, are also beyond the BIS desirable limits. NO_3^{-} is very high in some cases, e.g., at Hipparga Bakshi (DW10) (480 mg/L), Shankarnagar (DW13) (142 mg/L) and Gulvanchi (DW31) (196 mg/L), indicating human contamination in these areas. Human contamination is further corroborated by the presence of high concentrations of Cl^{-} (>250 mg/L), as both NO_3^{-} and Cl^{-} are integral parts of sewage waters. At present, about 42% of dugwell and 29% of borewell water samples show NO_3^{-} concentrations above the BIS standards. These figures may rise in the future since many wells are

Table 6 Status of groundwater quality for drinking purposes in Solapur city as per BIS standards (BIS 2003)

Parameter	BIS standards		Number and percentage of dugwells			Number and percentage of borewells		
	Desirable limit (DL)	Maximum permissible limit (MPL)	Below desirable limit (BDL)	Between desirable limit and maximum permissible limit	Above maximum permissible limit	Below desirable limit (BDL)	Between desirable limit and maximum permissible limit	Above maximum permissible limit
Ph	6.5–8.5	No relaxation	Nil	11 (92%)	1 (8)	Nil	7 (100%)	Nil
TDS	500	2000	1 (8%)	7 (58%)	4 (33%)	Nil	6 (86%)	1 (14%)
TH	300	600	Nil	4 (33%)	8 (67%)	1 (14%)	2 (29%)	4 (57%)
Ca	75	200	11 (92%)	Nil	1 (8%)	3 (42%)	2 (29%)	2 (29%)
Mg	30	100	Nil	4 (33%)	8 (67%)	1 (14%)	3 (43%)	3 (43%)
Cl	250	1000	3 (25%)	8 (67%)	1 (8%)	4 (57%)	3 (43%)	Nil
SO_4	200	400	2 (17%)	5 (42%)	5 (42%)	2 (29%)	4 (57%)	1 (14%)
NO_3	45	No relaxation	7 (58%)	Nil	5 (42%)	5 (71%)	Nil	2 (29%)
F	1	1.5	9 (75%)	2 (17%)	1 (8%)	3 (43%)	4 (57%)	Nil
Cu	0.05	1.5	4 (67%)	2 (33%)	Nil	6 (100%)	Nil	Nil
Fe	0.3	1	4 (67%)	1 (17%)	1 (17%)	4 (63%)	1 (17%)	1 (17%)
Cd	0.01	0.01	3 (50%)	Nil	3 (50%)	4 (67%)	–	2 (33%)
Mn	0.1	0.3	3 (50%)	1 (17%)	2 (33%)	6 (100%)	Nil	Nil
Zn	5	15	6 (100%)	Nil	Nil	6 (100%)	Nil	Nil

All concentrations are in mg/L, except pH soon getting abandoned and are used as waste dumping sites due to greater reliance on surface water.

F^- concentrations are above the desirable limit of 1 mg/L in three water samples from dugwells, namely at Hipparga Bakshi (DW10), Koynanagar (DW25) and Degaon (DW26), and four borewell water samples, namely at Juna Karamba Road (BW1), Dayanand College (BW5), Pachhapeth (BW6) and Majrevadi (BW7). Shelgi Nala also contains an amount of F^- beyond the maximum permissible limit of 1.5 mg/L, which gives an indication that the effluents in Solapur city possibly contain a high amount of F^-. Whether high concentrations (>1 mg/L) of F^- at Degaon (DW26), Koynanagar (DW25) and Juna-Karamba Road (BW1) are due to seepages from the Shelgi Nala effluents (since these effluents are pumped and used for irrigation purposes in these areas) is a difficult task to ascertain, but indications are that the low-lying areas in the city adjoining effluent channels, e.g., Dayanand College (BW5) and Majrevadi (BW7), contain high amount of F^- (>1 mg/L). Hoek et al. (2002); Bhatnagar et al. (2004) and Liu (2005a, b) have studied the impact of the application of sewage water for irrigation purposes. Bhatnagar et al. (2004) opine that although such applications may not be apparently affecting the groundwater quality, in the long run, such activities may prove costly because these effluents are often charged with virus, bacteria and other organisms and may contain toxins and carcinogens. Sperling et al. (2002) have described the urban wastewater treatment technologies and the implementation of discharge standards in developing countries.

In terms of heavy metals not much pollution is detected in both dugwells and borewells, although few samples exceed the desirable limits marginally. At Shankarnagar (DW13), the industrial effluents generated by the industries in MIDC area are actually applied for irrigation purposes. As a result, groundwater in this area has turned dark (blackish color) showing significant quality deterioration.

Unfortunately, the surface water at Ekhruk Tank and the treated water at Bhawanipeth Water Works show high Fe^{++} concentrations of 2.15 and 0.50 mg/L, respectively. Mn^{++} concentrations at these sites are also above the desirable limits although within the maximum permissible limit. The reason for such high concentrations of Fe^{++} and Mn^{++} in these surface water samples is not well known and needs further investigations. High concentrations of these elements even in treated waters at Bhawanipeth Water Works warrant proper filtrations and treatment before releasing the water for drinking purposes. Jou (2004) has given several ways to treat water from higher concentrations of heavy metals.

Deeper groundwater tapped by borewells is, however, better in terms of quality and can still be used for drinking purposes in most areas with caution. Both dugwell and borewell waters are, however, good enough for other household purposes all across the city.

Comparison of water quality data of all the borewells analyzed by the Water Testing Laboratory of SMC at Bhawanipeth Water Works between the periods 1980–1984 and 2002–2003 indicates that the total hardness of deeper groundwater has increased, so do fixed solids and Sulfates possibly due to stagnation/poor circulation of groundwater (Table 7). On the other hand, concentrations of Cl^-, total solids and total alkalinity has decreased. Since the samples analyzed have not been taken from the same borewells, and since the population of the samples analyzed is not the same, it is difficult to compare the concentrations between these time periods with certainty. The concentrations of Cl^-, TH, total solids and SO_4^{--} are higher than BIS desirable limits although within the maximum permissible limits in both these time periods. But their high standard deviations and confidence interval values (Table 7) are indications that quality deterioration is highly localized in Solapur city and cannot be generalized for the city as whole.

A few water samples were collected during this study from the same borewells from where samples were collected during 1981 by individual citizens for analysis by SMC. The comparison in their quality data is shown in Table 8, which shows that there are only marginal increase in Cl^- and NO_3^- concentrations. These increases may possibly be due to anthropogenic reasons. Lerner et al. (1999) and Wakida and Lerner (2005) give several sources of nitrate concentrations in urban groundwater. Similarly, dugwell water samples were collected from the same dugwells from where samples were collected during 1976 by Gajbhiye (1977). A comparison of the analytical results of these samples is given in Table 9. The wells at North Kasbapeth and Mulegaon do not show any perceptible change in quality unlike other wells

Table 7 Comparison of the quality of borewell water samples analyzed during the periods 1980–1984 and 2002–2003, respectively

Parameter	1980–1984 (based on 33 samples)			2002–2003 (based on 107 samples)		
	Mean	Std. dev.	±95% C.I.	Mean	Std. dev.	±95% C.I.
Total solids	1,561	3,012	1,028	1,255	564	107
Fixed solids	557	218	74	986	494	94
TH as $CaCO_3$	538	280	96	689	291	55
Permanent hardness	308	255	87	410	230	44
Total alkalinity as $CaCO_3$	542	619	211	155	55	10
Cl	481	1680	573	259	118	22

All concentrations are in mg/L

Std. dev. standard deviation; *C.I.* confidence interval

Table 8 Comparison of water quality of few borewell water samples collected during 1981 and 2003

	Gold Finchpeth (BW4)		Pachhapeth (BW6)		Dayanand College (BW5)	
	1981	2003	1981	2003	1981	2003
pH	7.9	8.4	7.4	8.14	7.4	7.54
TH as $CaCO_3$	500	450	516	317	625	800
Cl	140	149	160	195	155	234
NO_3	4	35	10	32	<5	26

All concentrations are in mg/L, except pH

Table 9 Comparison of water quality of few dugwell water samples collected during 1976 (Gajbhiye 1977) and 2003

	North Kasbapeth (DW5)		Mulegaon (DW12)		Tikekarvadi (DW18)		Soregaon (DW22)		Gulvanchi (DW31)		Average	
Year	1976	2003	1976	2003	1976	2003	1976	2003	1976	2003	1976	2003
pH	8.5	8.14	8.3	8	8.4	7.7	8.5	7.72	8.5	7.84	8.44	7.88
EC	1,060	1,300	786	780	1,407	2,000	889	2,200	1,882	2,600	1,205	1,776
TDS	588	735	416	410	888	1,165	512	1,240	1,104	1,535	702	1,017
TH	309	405	297	380	272	735	309	970	408	780	319	654
Ca	30	68	30	48	20	68	30	28	25	30	27	48
Mg	57	57	54	63	54	137	57	219	84	171	61	129
Na	0	87	0	5	236	133	0	0	0	206	47	86
CO_3	30	0	24	0	24	0	36	0	24	0	28	0
HCO_3	256	348	220	329	439	293	256	244	354	519	305	347
Cl	128	138	80	28	80	316	104	355	288	316	136	231
SO_4	46	157	Traces	41	268	329	38	370	216	312	142	242

All concentrations are in mg/L, except that of pH and EC (μS/cm) because these wells are still in active use. The well at North Kasbapeth, however, has limited use for Mallikarjun Temple only. The well at Tikekarwadi, which was once used for a textile factory, has now been abandoned. The well at Sonegaon, which was a village drinking well, is no more used for drinking purposes after the village was provided with surface water supply scheme. Similar is the case with the well at Gulvanchi.

Public apathy towards the groundwater system has been the sole reason for its contamination in Solapur main city. The quality of groundwater in the newly added 13 villages, which still use groundwater for various purposes, is generally good and potable barring few abandoned dugwells.

Urbanization may not be blamed for quality deterioration of shallow groundwater. It's the peoples' poor attitude and lack of long-sightedness that has spoiled the system in certain areas in Solapur city.

Future demand on water and solutions

The population of Solapur city is forecasted at 1,259,629 for the year 2012 and 1,532,529 for the year 2017 at a growth rate of 4% per annum by a study carried out by the Gokhale Institute of Politics and Economics, Pune, India (SMC 1997). Taking this growth rate, the population is estimated at 1,723,888 (say 1,725,000) for the year 2020. It is likely that the whole of Solapur will be covered under underground sewerage system by 2020. But as the city grows there will be further influx of rural population from adjoining areas for better employment opportunities, and despite the fact that SMC is trying its best to improve the living conditions in slums, the current trend of 30% of slum dwellers is not likely to decrease in the future. Therefore, taking a water requirement of 40 lpcd for the 30% of population (517,500 people) and 135 lpcd for 70% of population (1,207,500 people), the water requirements of the city as a whole for the year 2020 can be forecasted as follows:

(1) 70% of population connected with tap water supply and sewerage facilities at 135 lpcd	163 MLD
(2) 30% of population depending on water supply stand posts at 40 lpcd	21 MLD
(3) Industrial uses	50 MLD
(4) UFW (transmission losses) (15% of the total supply) 35 MLD	
Grand total	269 MLD

Considering the existing sources of supply, there is availability of 120 MLD of water for Solapur city at present. Thus, it is likely that there will be a shortfall of about 149 MLD (54.39 MCM) of water (i.e., 269−120 MLD) in the year 2020. In most cases forecasts generally overestimate the actual requirements (Gleick 2000), but it is always better to be prepared for the worst.

Ekruk Tank is very old and the tank bed is heavily silted. Not much water, therefore, can be expected from this tank unless massive desilting efforts are made. A maximum of 10 MLD of water may be expected annually from this tank by the year 2020. SMC is soon taking up massive upgradation projects for water supply from the Bhima River at Takli and Ujjani Dam Reservoir (MJP 1998). Therefore, at least about 90 MLD of water from Bhima River at Takli and 100 MLD from the Ujjani Dam can be expected by 2020 making the total water availability of 200 MLD to Solapur city.

Solapur is expected to have a groundwater recharge of 41 MCM during 2020 as estimated previously. In terms of availability of water in liters per day, this quantity will be 113 MLD. This availability is excluding the vast amount of groundwater in reserve in deeper aquifers as explored by CGWB. Thus, the available groundwater resources will be sufficient to cater to the shortfall of 69 MLD (i.e., 269−200 MLD) of surface water supply in 2020. Proper planning should be done, however, as to how best to utilize this vast amount of groundwater resources within the city limits of Solapur. In terms of quality, Jeffrey et al. (2000); Kouraa et al. (2002) and Fatta and Salem (2005) give several water recycling options for urban groundwater. Whitehead et al. (2006) describes the economic aspects of the effect of urban quality improvement. Howard (1997); Bonomi and Cavallin (1997); Morris et al. (1997); Gossell et al. (1999); Johansson et al. (1999); Lee (2000); Lóaiciga and Leipnik (2001); Athanasiadis et al. (2005); Subba Rao and Reddy (2006) have suggested several measures for protection of groundwater and its sustainability in urban environments. Foster (2001) emphasizes upon the interdependence of groundwater and urbanization in rapidly developing cities. Kolsky and Butler (2002) give the performance indicators for urban storm drainage in developing countries. Drangert and Cronin (2004) have described about the use and misuse of the urban groundwater resources and implications for a new management strategy. Howard et al. (2005) give the water safety plans for piped urban supplies in developing countries.

Considering the rapid expansion of Solapur city beyond 2020, it needs to constantly endeavor for exploring new sources of water, whether groundwater or surface water. Groundwater sources may be tapped to the maximum possible by renovating the old dugwells once operational in the city and by drilling appropriate number of deeper borewells at strategic locations in the city. Industries may be encouraged to tap the groundwater sources to the maximum possible for industrial uses. High yielding borewells (yielding >5,000 L/h) may be fitted with motors and may be used for local water supply through stand posts at several locations in the city. Massive projects also need to be taken up for artificial recharge of aquifers for augmentation of the groundwater resources and also for dilution of the harmful chemical constituents in groundwater. Several workers have stressed the importance of rainwater harvesting and water management in urban set-up (Naik 2006; Raju et al. 2006). Sharma et al. (2000) estimated a potential of 3 MCM of additional water availability in Solapur city due to rainwater harvesting based on the rooftop area of 5.35 km^2 in 1991. With the present growth rate, the rooftop area will be about 16.60 km^2 in 2020 with a potential of about 9.80 MCM of harvested rainfall. Steps need to be taken up by SMC for making it mandatory for every new building to have its own rooftop rainwater harvesting structure.

Summary and conclusions

Solapur city with a population of 907,400 increased five-fold in area in the year 1992 after inclusion of 13 new villages under the civic administration of the Solapur Municipal Corporation (SMC). Only 20% of the present city area is fully developed giving ample scope for the future development of the city. Land surface sealing from pukka houses, metalled roads and other such structures has resulted in about 7–23% reduction in direct infiltration of rainfall depending on city's growth. Also, city growth in a span of about a decade or two has caused about 6–8% decrease in recharge from rainfall infiltration. But, indirect recharges due to pluvial soakaways from roofs and paved surfaces, reduced evaporation, leakages from water-supply pipelines and seepage due to the irrigation of agricultural land by wastewater inside the city limits have compensated the effects of surface sealing and have caused additional recharge to groundwater. Shallow groundwater levels inside the main city limits are indications of decreased groundwater abstraction due to higher reliance on surface water and increased groundwater recharge due to additional supply of surface water. However, outside the main city limits, there is a general decline in groundwater levels compared to mid-1970s due to increased groundwater utilization for irrigation purposes.

Groundwaters in Solapur city are generally dominated by alkaline earths (Ca^{++}+Mg^{++}) and strong acids ($SO_4^{--} + Cl^- + NO_3$). Quality deterioration in certain pockets of the city has been due to gross misuse and disuse of stagnant well water. Shallower groundwater has been abused mostly during the past decade due to the use of dugwells as waste dumping sites. Deeper groundwater represented by borewells is, however, of better quality in most parts and can be used for drinking purposes with caution. Both shallower and deeper groundwaters are, however, good enough for use in other household purposes, such as washing and bathing.

Solapur city is poised to have a population of 1,725,000 by 2020 with availability of a quantum of 200 MLD of water while the actual requirement is 269 MLD. The shortfall of 69 MLD can be easily met by groundwater, which has a potential of 113 MLD of water excluding the vast reserve of deeper groundwater. Considering the future demand of water, old dugwells once used for water supply in Solapur city may be renovated and new wells may be constructed at strategic locations. Borewells with a yield of more than 5,000 L/h may be fitted with electric motors and groundwater may be supplied locally from these wells through water supply stand posts for general use purposes. Intensive projects may be taken up for artificial recharge of aquifers and also for dilution of harmful chemical constituents through construction of several water harvesting structures at suitable locations adjoining the city. Rainwater harvesting is an option the SMC may possibly like to make mandatory for the newly constructed buildings within the city.

This paper concludes that there is an increase in groundwater recharge as population in a city grows and more and more water is supplied to the city to meet the growing demands. Impervious surfaces cause only limited decrease in recharge in a young growing city and can very well be neglected. Groundwater quality deterioration is not due to urbanization, but due to general apathy of the public towards this valuable resource. If there is adequate usage of groundwater, its natural circulation would increase and the quality deterioration could be checked.

This paper apprises the city planners and administrators of the effects of urbanization on the ground water regime in a fast growing medium-sized city in a developing country where the infrastructure developments are not in conformity with the rapid growth in population, so that advanced action can be taken up beforehand in similar cities around the world while planning for water supply and sanitation facilities.

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References

Angelakis, A. N., Koutsoyiannis, D., & Tchobanoglous, G. (2005). Urban wastewater and stormwater technologies in ancient Greece. *Water Research*, *39*(1), 210–220.

APHA (American Public Health Association) (1998). *Standards methods for the examination of water and wastewater* (20th ed.). NW Washington, DC: American Public Health Association.

Appleyard, S. J. (1995). The impact of urban development on recharge and groundwater quality in a coastal aquifer near Perth, Western Australia. *Hydrogeology Journal*, *3*(2), 65–75.

Appleyard, S. J., & Bawden, J. (1987). The effects of urbanization on nutrient loads in the unconfined aquifer underlying Perth, western Australia. In *International conference on groundwater systems under stress, Brisbane*. Australian Water Resources Council, pp. 587–595.

Armienta, M. G., Rodriguez, R., Aguayo, A., Ceniceros, N., Villasenor, G., & Cruz, O. (1997). Arsenic contamination of ground water at Zimapan, Mexico. *Hydrogeology Journal*, *5*, 39–46.

Aronica, G., & Lanza, L. G. (2005a). Hydrology in the urban environment. *Hydrological Processes*, *19*(5), 1005–1006.

Aronica, G. T., & Lanza, L. G. (2005b). Drainage efficiency in urban areas: A case study. *Hydrological Processes*, *19*(5), 1105–1119.

Athanasiadis, I. N., Mentes, A. K., Mitkas, P. A., & Mylopoulos, Y. A. (2005). A hybrid agent-based model for estimating residential water demand. *Simulation*, *81*(3), 175–187.

Atwood, D. F., & Barber, C. (1989). The effects of Perth's urbanization on groundwater quality: A comparison with case histories in the USA. In G. Lowe (Ed.), *Swan coastal plain groundwater management conference* (pp. 177–190). Perth: Western Australian Resource Council.

Baechler F. (1999). Urban ground water database, Sydney, Nova Scotia, Australia. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/sydney-ca.html.

Barber, C., Davis, G. B., Therein, J., Bates, L., Patterson, M. B., Pribac, F., et al. (1991). Final Report for project on Assessment of the impact of pollutants on groundwater beneath urban areas. Commonwealth Scientific Industrial and Research Organization, Division of Water Resources, Report no. 91/22, pp. 53.

Barber, C., Otto, C. J., & Bate, L. E. (1996). Evaluation of the relationship between land-use changes and groundwater quality in a water supply catchment, using GIS Technology: The GWELUP Wellfield, Western Australia. *Hydrogeology Journal*, *4*(1), 6–19.

Barker, J. F., Cherry, J. A., Reindard, M., Pankow, J. F., & Zapico, M. M. (1989). Final report: The occurrence and mobility of hazardous organic chemicals in groundwater at several Ontario landfills. Research Advisory Committee Project No. 118 PL for Environment Ontario, p. 148.

Barrett, M. (1998). Urban ground water database, Nottingham, East Midlands, UK. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/nottingham.html.

Barrett, M. H., Hiscock, K. M., Pedley, S., Lerner, D. N., & Tellam, J. H. (1997). The use of marker species to establish the impact of the city of Nottingham (UK) on the quantity and quality of its underlying groundwater. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban environment* (pp. 85–90). Cape Town: Balkema.

Barrett, M. H., Hiscock, K. M., Pedley, S., Lerner, D. N., Tellam, J. H., & French, M. J. (1999). Marker species for identifying urban groundwater recharge sources: A review and case study in Nottingham, UK. *Water Resources Journal*, *33*(14), 3083–3097.

Benkar, E., Davis, G. B., Appleyard, S., Barry, D. A., & Powar, T. R. (1996). Trichloromethane (TCE) contamination in an unconfined sand aquifer underlying a residential area of Perth, Western Australia. *Hydrogeology Journal*, *4*(1), 20–29.

Bhatnagar, R., Joshi, H., & Singhal D. C. (2004). Environmental evaluation of sewage irrigation system, Roorkee. *Journal of Environmental Hydrology*, 12, Paper 11.

BIS (Bureau of Indian Standards) (2003). *Indian standard drinking water specifications IS 10500:1991, edition 2.2 (2003–09)*. New Delhi: Bureau of Indian Standards.

Bocanegra, E. M., Martinez, D. E., Massone, H. E., & Cionchi, J. L. (1993). Exploitation effect and salt water intrusion in the Mar del Plata Aquifer, Argentina. In Custodio & Galofre (Eds.), *Study and modelling of saltwater intrusion into Aquifers*, Proceedings of the 12th SWIM, CIMNE, Barcelona, pp. 177–191.

Bonomi, T., & Cavallin, A. (1997). Application of a hydrogeological model to analyze and manage groundwater processes in the urban groundwater: A case study in the Milan area, Italy. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban area: Problems processes and management* (pp. 91–96). 27th Cong. Int. Assoc. Hydrogeologist (IAH), September 21–27, Nottingham.

Brassington, F. K., & Rushton, K. (1987). Rising water table in central Liverpool. *Quarterly Journal of Engineering Geology*, *20*, 151–158.

Burian, S. J., & Shepherd, J. M. (2005). Effect of urbanization on the diurnal rainfall pattern in Houston (pp. 1089–1103). New York: Wiley.

Burston, M. W., Nazari, M. M., Bishop, P. K., & Lerner, D. N. (1993). Pollution of groundwater in the Coventry Region (UK) by chlorinated hydrocarbon solvents. *Journal of Hydrology*, *149*, 137–161.

Butler, M. J., & Verhagen, B. T. (1997). Environmental isotopic tracing of water in the urban environment of Pretoria, South Africa. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban area: Problems processes and management*. 27th Cong. Int. Assoc. Hydrogeologist (IAH), September 21–27, Nottingham, pp 101–106.

Butwell, B. (1998). Urban ground water database, Ruwaishid, Irbid, Jordan. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/ruwaishid.html.

Campana, N. A., & Tucci, C. E. M. (2001). Predicting floods from urban development scenarios: Case study of the Diluvio basin, Porto Alegre, Brazil. *Urban Water*, *3*, 1–2.

Cardoso, G., Jr. (1996). Urban ground water database, Port Louis, Mauritius. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/rio-de-janeiro.html.

Cavallero, A., Corradi, C., Felice, De., Grassi, P., (1985). Underground water pollution in Milan by industrial chlorinated organic compounds. In *effects of land use upon fresh waters*. Chichester: Ellis Harwood.

CGWB (Central Ground Water Board). (1984). Groundwater resources of the Upper Betwa River basin, India. Indo-British Groundwater Project, Tech Series, Bulletin 1, Central Ground Water Board, Ministry of Water Resources, Government of India, New Delhi.

CGWB (Central Ground Water Board) (1998). Detailed guidelines for implementing the groundwater estimation methodology – 1997 (p. 219). New Delhi: Central Ground Water Board, Ministry of Water Resources, Government of India.

Chan, L. (2001). Urban ground water database, Tianjin, Hubei, China. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/Tianjin.html.

Changli, L., Feng-E, Z., Yun, Z., Shuhong, S., Sheng, Z., Hao, Y., et al. (2005). Experimental and numerical study of pollution process in an aquifer in relation to a garbage dump field. *Environmental Geology*, *48*(8), 1107–1115.

Chebbo, G., Gromaire, M. C., Ahyerre, M., & Garnaud, S. (2001). Production and transport of urban wet weather pollution in combined sewer systems: The 'Marais' experimental urban catchment in Paris. *Urban Water*, *3*, 1–2.

Cheney, C. S., MacDonald, A. M., & Foster, A. (1999). Groundwater responses to urbanization and changing patterns of industrial development in the Wigan metropolitan area, northwest England. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban environment: Selected city profiles* (pp. 111–117). Lisse, The Netherlands: Balkema.

Chilton, J., Hiscock, K., Younger, P., Morris, B., Puri, S., Kirkpatrick, S. W., et al. (Eds.) (1999). *Groundwater in the Urban Environment: Problems Processes and Management, 27th Cong. Int. Assoc. Hydrogeologists (IAH)*, September 21–27, Nottingham, Balkema, Lisse, The Netherlands, p. 682.

Choi, B., Yun, S., Yu, S., Lee, P., Park, S., Chae, G., et al. (2005). Hydrochemistry of urban groundwater in Seoul, South Korea: effects of land use and pollutant recharge. *Environmental Geology Journal*, *48*(8), 979–990.

Coutinho, W. (1998). Urban ground water database, Bridgetown, St. Michael, Barbados. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/bridgetown.html.

Cox, M. E., & Hillier, J. (1994). Impacts on groundwater resources by urban expansion: the Brisbane case, in IAH/IEA Conference on Water Down Under, Adelaide, International Association of Hydrogeologists, 2A, pp. 267–270.

Cox, M. E., Hillier, J., Foster, L., & Ellis, R. (1996). Effects of a rapidly urbanizing environment on groundwater, Brisbane, Queensland, Australia. *Hydrogeology Journal*, *4*(1), 30–47.

Cox, M. E., Moss, A., & Smyth, G. K. (2005). Water quality condition and trend in North Queensland waterways. *Marine Pollution Bulletin*, *51*(1–4), 89–98.

CPHEEO (Central Public Health and Environmental Engineering Organization). (1999). Manual on water supply and treatment, Ministry of Urban Development, New Delhi.

Cross, H. J. (1980). Groundwater contamination by road salt, Nova Scotia, Canada. In R. E. Jackson (Ed.), *Aquifer contamination and protection, UNESCO Studies and Reports in Hydrology* 30, pp. 354–368.

Cruickshank, G., Aquirre, J., Kraemer, D., & Craviota, E. (1980). Bacterial contamination of the limestone aquifer beneath Merida, Mexico. In R. E. Jackson (Ed.), *Aquifer contamination and protection, UNESCO Studies and Reports in Hydrology* 30, pp. 341–345.

Custodio, E. (1997). Groundwater quantity and quality changes related to land and water management around urban areas: Blessing and misfortunes. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the Urban Area: Problems Processes and Management, 27th Cong. Int. Assoc. Hydrogeologist (IAH)*, September 21–27, Nottingham, pp. 11–12.

Czemiel, J. (2000). Phosphorus and nitrogen in sanitary in Kalmar. *Urban Water*, *2*, 1.

Das, A., Krishnaswami, S., Sarin, M. M., & Pande, K. (2005). Chemical weathering in the Krishna Basin and Western Ghats of the Deccan Traps, India: Rates of basalt weathering and their controls. *Geochimica et Cosmochimica Acta*, *69*(8), 2067–2084.

Diaz-Fierros, T. F., Puerta, J., Suarez, J., & Diaz-Fierros, F. V. (2002). Contaminant loads of CSOs at the wastewater treatment plant of a city in NW Spain. *Urban Water*, *4*, 3.

Drangert, J., & Cronin, A. A. (2004). Use and abuse of the urban ground water resource: Implications for a new management strategy. *Hydrogeology Journal*, *12*(1), 94–102.

Drouin-Brisebois, I. (1999). Urban ground water database, Kingston, Kingston and St-Andrew, Jamaica. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/kingston.html.

Dubruovoskaya, L. I., Zemstov, V. A. (1999). Some problems of groundwater near Tomsk, West Siberia, Russia. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *XXVII Congress on groundwater in the urban environment: Selected city profiles, International Association of Hydrogeologists*, Balkema, Rotterdam, 119–123.

Dummer, M., & Straaten, V. (1988). The influence of industrialization and hydrogeology on the quality of ground water and surface water in Bielefeld (case studies). *Symp. on hydrological processes and water management in urban areas*, Duisberg, FRG, April 1988, pp. 423–428.

Dutova, E. M., Nalivaiko, N. G., Kuzevanov, K. I., & Kopylova, J. G. (1999). The chemical and microbiological composition of urban groundwater, Tomsk, Russia. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *XXVII congress on groundwater in the urban environment: Selected city profiles, International Association of Hydrogeologists*, Balkema, Rotterdam, 125–130.

Eisen, C., & Anderson, M. P. (1980). The effects of urbanization on ground water quality Milwauke, Wisconsin, USA. In: Jackson. 378–390.

Eiswirth, M., & Hotzl, H. (1997). The impact of leaking sewers on urban groundwater. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban areas: Problems, processes and management, 27th Cong. Int. Assoc. Hydrogeologists (IAH)*, September 21–27, Nottingham, pp. 399–404.

Esslinger, P. (1998). Urban ground water database, Calgany, Alberta, Canada. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/calgary.html.

Farah, E. A. (1999). Groundwater quality and hydrogeology conditions in the Khartoum area, Sudan. *Journal of Geosciences*, *42*, 45–53.

Fatta, D., & Salem, Z. (2005). Urban wastewater treatment and reclamation for agricultural irrigation: the situation in Morocco and Palestine. *The Environmentalist*, *24*(4), 227–236.

Faye, S. C., Faye, S., Wohnlich, S., & Gaye, C. B. (2004). An assessment of the risk associated with urban development in the Thiaroye area (Senegal). *Environmental Geology*, *45* (3), 312–322.

Fetter, C. W. (1988). *Applied hydrogeology*. Columbus, Ohio: Charles E. Merril.

Fleetwood, A. (1969). Urbant paverkat gundvatten. *Vatten*, *2/69*, 107–112.

Flipse, W. I., Katz, B. G., Linder, J. B., & Markel, R. (1984). Sources of nitrate in groundwater in a sewered housing development, Central Long Island, New York. *Ground Water*, *22*, 418–426.

Ford, M. (1990). Extent, type and sources of inorganic groundwater pollution below the Birmingham conurbation. Unpub. Ph.D. thesis, Earth sciences, University of Birmingham.

Ford, M., & Tellam, J. H. (1994). Source, type and extent of inorganic contamination within the Birmingham aquifer system, UK. *Journal of Hydrology*, *156*, 101–135.

Foster, S. S. D. (1988). Impacts of urbanization on groundwater. In *Symposium on hydrological processes and water management in urban areas*, Duisberg, Germany, April 1988, pp. D1–D24.

Foster, S. S. D. (2001). The interdependence of groundwater and urbanization in rapidly developing cities. *Urban Water*, *3*(3), 185–192.

Foster, S. S. D., & Chilton, P. J. (2004). Downstream of downtown: Urban wastewater as groundwater recharge. *Hydrogeology Journal*, *12*(1), 115–120.

Foster, S. S. D., Morris, B. L., & Lawrence, A. R. (1994). Effects of urbanization on groundwater recharge. In *International Conference on groundwater problems in urban areas*, London, 1993, Institution of Civil Engineers, pp. 43–63.

Fung, L. (1998). Urban ground water database, Beijing, Hubei, China. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/beijing.html.

Fusillo, T. V., Hockreiter, J. J., & Lord, D. G. (1985). Distribution of volatile organic compounds in a New Jersey coastal plain aquifer. *Ground Water*, *23*, 354–360.

Gajbhiye, N. G. (1977). Report on the reconnaitary hydrogeological studies in Solapur-Akalkot area, Solapur District, Maharashtra, Central Ground Water Board, Central Region, Nagpur.

Garrels, R. M., & Christ, C. L. (1967). *Solutions, minerals and equilibria*. New York: Harper and Row.

Gerriste, R. G., Barber, C., & Adeney, J. A. (1990). The impact of residential urban areas on groundwater quality: Swan Coastal Plain, Western Australia, in: Commonwealth Scientific and Industrial Research Organization Division of Water Resources Series. Report no. 3, 28 p.

Gleick, P. H. (2000). The changing water paradigm: A look at twenty-first century water resources development. *Water International*, *25*(1), 127–138.

Gooddy, D. C., Lawrence, A. R., Morris, B. L., & Chilton, P. J. (1997). Chemical transformations of groundwater beneath unsewered cities. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban areas: Problems, processes and management*, 27th Cong. Int. Assoc. Hydrogeologists (IAH), September 21–27, Nottingham, pp. 405–410.

Gosk, E., Bishop, P. K., Lerner, D. N., & Burston, M. (1990). Field investigation of solvent pollution in the ground waters of Coventry, UK. In K.U. Weyer (Ed.), *IAH conference on subsurface Contamination by immiscible fluids*, Balkema Publ., Rotterdam.

Gossel, W., Herfert, J., Chowanietz, U., & Hermel, U. (1999). Sustainable groundwater management for the Berlin region. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban areas: Problems, processes and management*. 27th Cong. Int. Assoc. Hydrogeologists (IAH), 21–27 September 21–27, Nottingham, pp 139–143.

Gray, S. R., & Becker, N. S. C. (2002). Contaminant flows in urban residential water systems. *Urban Water*, *4*(4), 331–346.

Greswell, R. B., Lloyd, J. W., Lerner, D. N., & Knipe, C. V. (1994). Rising groundwater in the Birmingham area. In W. B. Wilkinson (Ed.), *Groundwater problems in urban areas* (pp. 330–341). London: Thomas Telford.

Grischek, T., Nestler, W., Piechniczek, D., & Fischer, T. (1996). Urban groundwater in Dresden, Germany. *Hydrogeology Journal*, *4*(1), 48–63.

Gutierrez, A. (2001). Urban Ground water database, Valletta, Malta, Malta. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/valletta.html.

Halliday, D. (1993). Sewers as a source of groundwater pollution in the Nottingham District. School of Earth Sciences, University of Birmingham, M.Sc. thesis, 158 p.

Handa, B. K., Goel, D. K., Kumar, A., & Sodhi, T. N. (1983). Pollution of groundwater by chromium in Uttar Pradesh. Technical Annual X, J. Indian Assoc. Water Pollution Control, pp. 167–176.

Hasan, M. K. (1996). Urban ground water database, Dhaka, Bangladesh. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/dhaka.html.

Hem, J. D. (1985). Study and interpretation of the chemical characteristics of natural water. Water Supply Paper - 2254, US Geological Survey.

Herrington, J. (1999). Urban ground water database, Ta'iz, Central Highlands, Yemea. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/taiz.html.

Hoek, W., Hassan, M. U., Ensink, J. H. J., Feenstra, S., Raschid-Sally, L., Munir, S., et al. (2002). Urban Wastewater: A valuable Resource for agriculture: A case study from Haroonabad, Pakistan. International Water Management Institute. Research Report 63.

Houser, C. A. (1999). Urban ground water database, Albuquerque, New Mexico, USA. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/albuquerque.html.

Howard, K. W. F. (1997). Incorporating policies for groundwater protection into the urban planning. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), Groundwater in the Urban Areas: Problems, Processes and Management, 27th Cong. Int. Assoc. Hydrogeologists (IAH), September 21–27, Nottingham, pp. 31–40.

Howard, K. W. F., Eyles, N., Gerber, R. E., Smart, P., & Salvatori, S. (1996a). The Oak Ridges Moraine of southern Ontario: A national resource threatened by urbanization. In E. Eyles (Ed.) Environmental Geology of Urbanised Regions: Geological Association of Canada.

Howard, K. W. F., Eyles, N., & Livingstone, S. (1996b). Municipal landfilling practice and its impact on groundwater resources in and around urban Toronto, Canada. *Hydrogeology Journal*, *4*(1), 64–79.

Howard, G., Godfrey, S., Tibatemwa, S., & Niwagaba, C. (2005). Water safety plans for piped urban supplies in developing countries: A case study from Kampala, Uganda. *Urban Water*, *2*, 3.

Howard, K. W. F., & Israfilov, R. (2002). *Current problems of hydrogeology in urban areas, urban agglomerates and industrial centers*. Dordrecht: Kluwer.

Jacobson, G. (1996a). Urban ground water database, Canberra, Australian Capital Territory, Australia. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/canberra.html.

Jacobson, G. (1996b). Urban ground water database, Kathmandu, Bagmati, Nepal http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/kathmandu.html.

Janet, 1998. Urban ground water database, Honolulu, Hawaii, USA. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/honolulu.html.

Jeffrey, P., Seaton, R., Parsons, S., Stephenson, T., & Jefferson, B. (2000). Exploring water recycling options for urban environments: A multi-criteria modeling approach. *Urban Water*, *1*, 3.

Johansson, P. O., Scharp, C., Alveteg, T., & Choza, A. (1999). Framework for groundwater protection: The Managua groundwater system as an example. *Ground Water*, *37* (2), 204–213.

Jou, C. G. (2004). An efficient technology to treat heavy metal–lead-contaminated soil by microwave radiation. *Journal of Environmental Management*, *78*, 1–4.

Kakar, Y. P., & Bhatnagar, N. C. (1981). Groundwater pollution due to industrial effluents in Ludhiana, India. In W. van Duijvenbooden, Glasbergen and van Lelyveld (Eds.), *Quality of groundwater*. Study in Env. Sci. v. 17, pp. 265–275.

Katz, B. G., Lindner, J. B., & Ragone, S. E. (1980). A comparison of nitrogen in shallow groundwater from sewered and unsewered areas, Nassan County, New York, from 1952 through 1976. *Ground Water*, *18*, 607–618.

Keizer, J. (1998). Urban ground water database, Fredericton, New Brunswick, Canada. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/fredericton.html.

Khadka, M. S. (1993). The groundwater quality situation in alluvial aquifers of the Kathmandu valley, Nepal. *Journal of Australian Geology and Geophysics*, *14*, 207–211.

Kimmel, G. E. (1984). Non-point contamination of ground water on Long Island, New York. In *Groundwater contamination, studies in geophysics* (pp. 120–126). Washington, DC: National Academy.

Knipe, C. V., Lloyd, J. W., Lerner, D. N., & Gresswell, R. (1993). Rising groundwater levels in Birmingham and the engineering implications. Construction Industry Research and Information Association Special Publication. 92, 114 p.

Kolokytha, E. G., Mylopoulos, Y. A., & Mentes, A. K. (2002). Evaluating demand management aspects of urban water policy – A field survey in the city of Thessaloniki, Greece. *Urban Water*, *4*(4), 391–400.

Kolsky, P., & Butler, D. (2002). Performance indicators for urban storm drainage in developing countries. *Urban Water*, *4*(2), 137–144.

Kouraa, A., Fethi, F., Fahde, A., Lahlou, A., & Ouazzani, N. (2002). Reuse of urban wastewater treated by a combined stabilization pond system in Benslimane (Morocco). *Urban Water*, *4*(4), 373–378.

Krill, R. M., & Sonzogni, W. C. (1968). Chemical monitoring of Wisconsin's groundwater. *Journal of American Water Works Association*, *78*, 70–75.

Ku, H. F. H. (1980). Ground water contamination by metal plating wastes, Long island, New York, USA. In R. E. Jackson (ed.), *Aquifer Contamination and Protection, UNESCO Studies and Reports in Hydrology*, 30, pp. 310–317.

Lam, A. (1999). Urban ground water database, Tomsk, West Siberia, Russia. http://www.scar.utoronto.ca/~gwater/IAHCGUA/ UGD/tomsk.html.

Larson, K. J., Basagaoglu, H., & Marino, M. A. (2001). Prediction of optimal safe groundwater yield and land subsidence in the Los Banos-Kettleman City area, California using a calibrated numerical simulation model. *Journal of Hydrogeology*, *242*(1), 79–102.

Lawrence, A. R., Goody, D. C., Kanatharana, P., Meeslip, W., & Ramnarong, V. (2000). Groundwater evolution beneath hat Yai, a rapidly developing city in Thailand. *Hydrogeology Journal*, *8*(5), 564–575.

Lee, T. R. (2000). Urban water management for better urban life in Latin America. *Urban Water*, *2*, 1.

Lee, K. K., Kim, Y. Y., & Sung, I. H. (2001). Urbanization and the groundwater budget, metropolitan Seoul area, Korea. *Hydrogeology Journal*, *9*(4), 401–413.

Lerner, D. N. (1986). Leaking pipes recharge groundwater. *Ground Water*, *24*(5), 654–662.

Lerner, D. N. (1989). Groundwater recharge in urban areas. *Atmospheric Environment*, *24B*(1), 29–33.

Lerner, D. N. (1990). Recharge due to urbanization. In D. N. Lerner, A. S. Issar, & I. Simmers (Eds.), *Groundwater recharge – A guide to understanding and estimating natural recharge*, International Association of Hydrogeologists, 8, 201–214.

Lerner, D. N., & Barrett, M. H. (1996). Urban groundwater issues in the United Kingdom. *Hydrogeology Journal*, *4* (1), 80–89.

Lerner, D. N., Halliday, D., & Hoffman, J. M. (1994). The impact of sewers on groundwater quality. In W. B. Wilkinson (Ed.), *Groundwater problems in urban areas* (pp. 64–75). London: Thomas Telford.

Lerner, D. N., & Tellam, J. H. (1992). The protection of urban groundwater from pollution. *Journal of the Institution of Water and Environmental Management*, *6*(2), 28–37.

Lerner, D. N., Yang, Y., Barrett, M. H., & Tellam, J. H. (1999). Loadings of non-agricultural nitrogen in urban groundwater. In B. Ellis (Ed.), *Impacts of urban growth on surface water and groundwater quality* (pp. 117–123). Wallingford, UK: International Association of Hydrological Sciences 259.

Liu, C., Zhang, F., Zhang, Y., Song, S., Zhang, S., Ye, H., et al. (2005a). Experimental and numerical study of pollution process in an aquifer in relation to a garbage dump field. *Environmental Geology*, *48*(8), 1107–1115.

Liu, W., Zhau, J., Ouyang, Z., Soderlund, L., & Liu, G. (2005b). Impacts of sewage irrigation on heavy metal distribution and contamination in Beijing, China. *Environmental International*, *31*(6), 805–812.

Lloyd, J. W., Lerner, D. N., Rivett, M. O., & Ford, M. (1988). Quantity and quality of ground water beneath an industrial conurbation in Birmingham, UK. *Proc. Symp. Hydrological Processes and Water Management in Urban Areas*, Duisberg, FRG, April 24–28. pp. 445–452.

Lóaiciga, H. A., & Leipnik, R. B. (2001). Theory of sustainable groundwater management: an urban case study. *Urban Water*, *3*(3), 217–228.

Loehnert, P. (1998). Urban ground water database, Muenster, North-Rhine–Westfalia. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/muenster.html.

Lok, K. (1999). Urban ground water database, Lima, Costa, Peru. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/lima.html.

Long, D. T., & Saleem, Z. A. (1974). Hydrogeochemistry of carbonate groundwaters of an urban area. *Water Resources Research*, *10*, 1229–1238.

Longstaff, S. L., Aldous, P. J., Clark, L., Flavin, R. J., & Partington, J. (1992). Contamination of the chalk aquifer by chlorinated solvents: A case study of the Lutan and Dunstable area. *Journal of the Institution of Water and Environmental Management*, *6*, 541–550.

Marsh, T. D., & Davies, P. A. (1983). The decline and partial recovery of ground water levels below London. *Proceedings of the Institution of Civil Engineers, Part 1*, *74*, 263–276.

Martinez, D. E., Bocanegra, E. M., Massone, H. E., & Cionchi, J. L. (1993). Groundwater impact of an urban solid waste disposal area in Mar del Plata, Argentina. In Nath & L. Candela (Eds.), *2nd International Conference on Environmental Pollution, Proceedings*, Sitges, Spain, v. 1, pp. 232–239.

Martini, E., Pialli, G., & Sabatini, P. (1980). Bacterial contamination beneath Orvietto, Italy. In R. E. Jackson (Ed.), *Aquifer Contamination and Protection, UNESCO Studies and Reports in Hydrology* 30, pp. 346–349.

Marton, J., & Mohler, I. (1988). The influence of urbanization on the quality of ground water. *Symposium on Hydrological Processes and Water Management in Urban Areas*, Duisberg, Germany, pp. 453–468, April.

Mcfarlane, D. J. (1984). The effect of urbanization on groundwater quality and quantity in Perth, Western Australia, Ph.D. dissertation, 433 p.

Mehta, B. C., Das, S., & Srivastava, S. K. (1994). Environmental hazards of high iron in groundwater of Bhubaneshwar, Orissa. *Regional Workshop on Environmental Aspects of Groundwater Development*, October, Kurukshetra, India.

Merkel, B., Grossman, J., & Uduluft, P. (1988). Effect of urbanization on a shallow Quaternary aquifer. *Proc. Symp. Hydrological Processes and Water Management in Urban Areas*, Duisberg, Germany, April 1988. pp. 461–468.

MJP (Maharashtra Jeevan Pradhikaran). (1998). Remodelling transmission and distribution system of Solapur city and 13 extended villages water supply scheme, executive summary of general report, Maharashtra Jeevan Pradhikaran Circle, Solapur.

MJP (Maharashtra Jeevan Pradhikaran). (1999). Improvements to Solapur sewerage scheme, executive summary, Maharashtra Jeevan Pradhikaran Circle, Solapur.

Molenaar, A., Roeloffzen, A. B., Pepels, A. H. M., Streng, J. M. A., & Uil, H. (1997). A groundwater information system as a tool for environmental management in Rotterdam. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban areas: problems, processes and management*. 27th Cong. Int. Assoc. Hydrogeologists (IAH), September 21–27, pp. 625–630.

Morrill, P. (1998). Urban ground water database, Tokyo, Japan. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/tokyo.html.

Morris, B. L., Lawrence, A. R., & Foster, S. S. D. (1997). Sustainable groundwater management for fast growing cities: mission achievable or mission impossible? In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban area: Problems: Processes and management*, 27th Cong. Int. Assoc. Hydrogeologists (IAH), September 21–27, Nottingham, pp. 55–65.

Naik, P. K. (Ed.). (2006). Rainwater harvesting and water management. *22nd national convention of environmental engineers and national seminar*. The Institution of Engineers (India), November 11–12, Nagpur, 500 p.

Naik, P. K., Awasthi, A. K., Anand, A. V. S. S., & Mohan, P. C. (2001). Hydrogeologic framework of the Deccan terrain of the Koyna River basin, India. *Hydrogeology Journal*, *9*(3), 243–264.

Naik, P. K., Awasthi, A. K., & Mohan, P. C. (2002). Springs in a headwater basin in the Deccan terrain of the Western Ghats, India. *Hydrogeology Journal*, *10*(5), 553–565.

Nazari, M. M., Burston, M. W., Bishop, P. K., & Lerner, D. N. (1993). Urban ground-water pollution: A case study from Coventry, United Kingdom. *Ground Water*, *31*(3), 417–424.

Nelson, S., Kalifa, S., Baumann, F. (1981). Purgeable organics in four groundwater basins, Water Forum 81. American Society for Civil Engineers, pp. 411–418.

Nemeth, G. B., & Uduluft, P. (1982). The effect of urban development and storm sewer drainage on ground water quality and ground water recharge. In R. E. Fratterstone & A. James (Eds.), *Urban drainage systems*, Pitman, pp. 3.103–3.115.

Niemczynowicz, J. (1999). Urban hydrology and water management – Present and future challenges. *Urban Water*, *1*(1), 1–14.

Olania, M. S., & Saxena, K. L. (1977). Groundwater pollution by open refuse dumps at Jaipur. *Journal of Environmental Health (India)*, *19*, 176–188.

O'Shea (1993). Discussion on rising groundwater levels. In W. B. Wilkinson (Ed.), *Groundwater problems in urban areas* (pp. 363–364). London: Thomas Telford.

Otto, C. J., Bates, L., & Barber, C. (1995). Effects of urbanization on Perth's (Western Australia) groundwater resources and quality. In *Groundwater management and strategies using GIS and modeling*, 26th International Association of Hydrogeologists Congress, Edmonton, 1995.

Ozeler, D. U., & Yetis, G. N. (2005). Life cycle assessment of municipal solid waste management methods: Ankara case study. *Environmental International*, *32*(3), 405–411.

Pandit, M. K., & Bhardwaj, V. (2006). Urbanization impact on hydrogeological regime in Jaipur urban block: A rapidly growing urban center in NW India. *The Environmentalist Journal*, *26*(3), 165–173.

Pawar, N. J., Pondhe, G. M., & Patil, S. F. (1998). Groundwater pollution due to sugar-mill effluent at Sonai, Maharashtra, India. *Environmental Geology*, *34*(213), 151–158.

Petrou, M. (1999). Urban ground water database, San Antonio, Texas, USA. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/san-antonio.html.

Piper, A. M. (1944). A graphical procedure in the geochemical interpretation of water analysis. *Transactions, American Geophysical Union*, *25*, 914–923.

Piskin, R. (1973). Evaluation of nitrate content of groundwater in Hall County, Nebraska. *Ground Water*, *11*, 4–13.

Pokarajac, D. (1999). Interaction of wastewater and groundwater management in the city of Bijeljina, Bosnia. *Urban Water*, *1*, 243–255.

Pokrovsky, D. S., Rogov, G. M., & Kuzevanov, K. I. (1998). The impact of urbanisation on the hydrogeological conditions of Tomsk, Russia. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *XXVII congress on groundwater in the urban environment: selected city profiles*, International Association of Hydrogeologists, 2, Balkema, Rotterdam, pp. 217–223.

Qi, S., & Luo, F. (2006). Land-use change and its environmental impact in the Heiche River basin, arid northwestern China. *Environmental Geology*, *50*(4), 535–540.

Raju, N. J., & Reddy, T. V. K. (2007). Environmental and urbanization affect on groundwater resources in a pilgrim town of Tirupati, Andhra Pradesh, South India. *Journal of Applied Geochemistry*, *9*(2), 212–223.

Raju, N. J., Reddy, T. V. K., & Munirathnam, P. (2006). Subsurface dams to harvest rainwater – A case study of the Swarnamukhi River basin, southern India. *Hydrogeology Journal*, *14*, 526–531.

Ramkhalawan, V. (1999). Urban ground water database, Port-of-Spain, Trinidad and Tobago. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/port-of-spain.html.

Rao, G. V. V. S., & Thangarajan, M. (1996). Urban ground water database, Madras, India. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/madras.html.

Razack, M., Drogue, C., & Baitelem, M. (1988). Impact of an urban area in the hydrochemistry of a shallow groundwater (alluvial reservoir), Town of Narbonne, France. *Symposium on hydrological processes and water management in urban areas*, Duisberg, Germany, April 1988, pp. 487–494.

Riemann, U. (1997). Engineering investigation and technological solutions for the groundwater lowering in the city of Dessau, Germany, In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S. W.Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban areas: Problems, processes and management*, 27th Cong. Int.

Assoc. Hydrogeologists (IAH), September 21–27, Nottingham, pp 255–259.

Rismianto, D., & Mak, W. (1994). Groundwater problems in Jakarta and their implications for piped water supply. *Symposium Air Jakarta 1994*, Pusat Pengkajian Perkotaan Universitas Tarumanegara, Jakarta (Indonesia).

Ritter, W. F., & Chirnside, A. E. M. (1984). Impact of land use on groundwater quality in Southern Delaware. *Ground Water*, *22*, 38–47.

Rivers, C. N., Barrett, M. H., Hiscock, K. M., Dennis, P. F., Feast, N. A., & Lerner, D. N. (1996). Use of nitrogen isotopes to identify nitrogen contamination of the Sherwood Sandstone aquifer beneath the City of Nottingham, United Kingdom. *Hydrogeology Journal*, *4*(1), 90–102.

Rivett, M. O., Lerner, D. N., & Lloyd, J. W. (1990a). Organic contamination of the Birmingham aquifer. *Journal of Hydrology*, *113*, 307–323.

Rivett, M. O., Lerner, D. N., Lloyd, J. W., & Clark, L. (1990b). Chlorinated solvents in UK aquifers. *Journal of the Institution of Water and Environmental Management*, *4*, 242–250.

Rojas, R., Howard, G., & Bastram, J. (1994). *Groundwater quality and water supply in Lima, Peru. Groundwater quality* (pp. 159–167). London, UK: Chapman and Hall.

Romani, S. (1981). A new diagram for classification of natural waters and interpretation of chemical analysis data. In *International symposium on quality of groundwater, Noordwijkerhout. Studies in environmental science 17*. The Netherlands: Elsevier.

Sahgal, U. K., Sahgal, R. K., & Kaker, Y. P. (1989). Nitrate pollution of ground water in Lucknow area, U.P. In *International workshop on appropriate methodologies for development and management of ground water resources in developing countries* (pp. 871–892). Hyderabad, India: National Geophysical Research Institute (February).

Shahin, M. M. A. (1988). Impacts of urbanization of the greater Cairo area on the ground water in the underlying aquifer. *Proc. symp. hydrological processes and water management in urban areas*, Duisberg, Germany, April, pp. 517–524.

Sharma, V. P. (1988). Groundwater and surface water quality in and around Bhopal city in India. *Proc. symp. hydrological processes and water management in urban areas*, Duisberg, Germany, April 1988, pp. 525–532.

Sharma, M. L., Herne, D. E., Byrne, J. D., & Kin, P. G. (1996). Nutrient Discharge beneath urban lawns to a sandy coastal aquifer, Perth, Western Australia. *Hydrogeology Journal*, *4* (1), 103–117.

Sharma, S. K., Jain, S. K., & Jain, P. K. (2000). Master plan for artificial recharge to ground water in Maharashtra, Central Ground Water Board, Central Region, Nagpur, p. 60.

Shepherd, J. M. (1962). Pollution of groundwater supplies by sewage. *Proceedings of the Society of Water Treatment and Examination*, *11*, 11–16.

Simpson, B., Blower, T., Craig, R. N., & Wilkinson, W. B. (1989). The engineering implications of rising groundwater levels in the deep aquifer beneath London. Construction Industry Research and Information Association Special Publication 69, 116 p.

SMC (Solapur Municipal Corporation). (1997). *Draft development plan of Solapur (1997–2017)*. Solapur: Solapur Municipal Corporation.

SMC (Solapur Municipal Corporation). (2003). *Short note regarding underground drainage system of Solapur City*. Solapur: Solapur Municipal Corporation.

Somasundaram, M. V., Ravindran, G., & Tellem, J. H. (1993). Ground-water pollution of the madras urban aquifer, India. *Ground Water*, *31*(1), 4–11.

Sperling, M., Augusto, C., & Chernicharo, L. (2002). Urban wastewater treatment technologies and the implementation of discharge standards in developing countries. *Urban Water*, *4*(1), 105–114.

Stanley, G. R. (1999). Urban ground water database, Mineola, New York, US. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/mineola.html.

Subba Rao, N., & Reddy, M. P. (2006). Monitoring the groundwater quality in an urban area: An environmental impact assessment and management. *Journal of Applied Geochemistry*, *8*, 37–50.

Subrahmanyam, K. (1996). Urban ground water database, Hyderabad, Andhra Pradesh, India. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/hyderabad.html.

Sudarshana, S. (1988). *Reappraisal hydrogeological studies in parts of Krishna Basin, Solapur District, Maharashtra*. Nagpur: Central Ground Water Board, Central Region.

Sukhija, B. S., Reddy, D. V., & Saxena, V. K. (1989). Study of ground water pollution at Tirumala, Tirupati, India. *Proc. international workshop on appropriate methodologies for development and management of ground water resources in developing countries* (pp. 893–898). Hyderabad, India: National Geophysical Research Institute (February–March).

Thomsen, R., Søndergaard, V.H., & Sørensen, K.I. (2004). Hydrogeological mapping as a basis for establishing site-specific groundwater protection zones in Denmark. *Hydrogeology Journal*, *12*(5), 550–562.

Thomson, J. A. M., & Foster, S. S. D. (1986). Effects of urbanization on ground water of limestone islands: An Analysis of the Bermuda case. *Journal of Institute of Water Engineers and Scientists*, *40*, 527–540.

Tirtomihardjo, H. (1996). Urban ground water database, Jakarta, DKI Jakarta, Indonesia. http://www,scar.utoronto.ca/~gwater/IAHCGUA/UGD/jakarta.html.

Trauth, R., & Xanthopoulus, C. (1997). Non-point pollution of groundwater in urban areas. *Water Resources*, *31*(11), 2711–2718.

Tryon, C. P. (1976). Groundwater quality variation in Phelps County, Missouri. *Ground Water*, *14*, 214–223.

Turin, H. J., Gaume, A. N., Bitner, M. J., Hansen, H. S., & Titus, F. B. (1997). Albuquerque, New Mexico, USA: A sunbelt city rapidly outgrowing its aquifer. In J. Chilton, K. Hiscock, P. Younger, B. Morris, S. Puri, S.W. Kirkpatrick, H. Nash, W. Armstrong, P. Aldous, T. Water, J. Tellman, R. Kimblin, & S. Hennings (Eds.), *Groundwater in the urban area: Problems: processes and management*, 27th Cong. Int. Assoc. Hydrogeologists (IAH), September 21–27, Nottingham.

Vaze, J., & Chiew, F. H. S. (2002). Experimental study of pollutant accumulation on an urban road surface. *Urban Water*, *4*(4), 379–389.

Vazquez-Sune, E., Castillo, O., Sanchez-Vila, X., Alberich, C., & Carrera, J. (2000). Use of anthropogenic tracer to identify sources of groundwater recharge in urban areas in Barcelona. In A. Dessargues (Ed.). *Tracers and modeling in hydrogeology*. IAHS Publ. No. 262, IAHS, Wallingford, UK, pp. 363–369.

Vazquez-Sune, E., Sanchez-Vila, X., & Carrera, J. (2005). Introductory review of specific factors influencing urban groundwater, an emerging branch of hydrogeology, with reference to Barcelona, Spain. *Hydrogeology Journal*, *13* (3), 522–533.

Vossen, W. J., & Huijsmans, T. M. F. (1988). Groundwater pollution by Tilberg's gas plant. *Proc. symp. hydrological processes and water management in urban areas*, Duisberg, Germany, April 1988, pp. 579–584.

Voznaya, N. F. (1981). *Chemistry of water and microbiology*. Moscow: Meer.

Wakida, F. T., & Lerner, D. N. (2005). Non-agricultural sources of ground water nitrate: A review and case study. *Water Research*, *39*, 210–220.

Wellman, D. (2001). Urban ground water database, Port Louis, Mauritius. http://www.scar.utoronto.ca/~gwater/IAHCGUA/UGD/port-louis.html.

Whitehead, E, Hiscock, K. M., & Dennis, P. F. (1999). Evidence for sewage contamination of the Sherwood sandstone aquifer beneath Liverpool, U.K, In B. Ellis (Ed.), *Impacts of urban growth on surface water and groundwater quality* (pp. 179–185). Wallingford, UK: International Association of Hydrological Sciences, 259.

Whitehead, T., Simmonds, D., & Preston, J. (2006). The effect of urban quality improvements on economic activity. *Journal of Environmental Management*, *80*(1), 1–12.

Wolf, L., & Eiswirth, M. (2006). Assessing sewer–ground water interaction at the city scale based on individual sewer defects and marker species distributions. *Environmental Geology*, *49*(6), 849–857.

Yang, Y., Lerner, D. N., Barret, M., & Tellam, J. (1999). Quantification of groundwater recharge in the city of Nottingham, UK. *Environmental Geology*, *38*(3), 183–198.

Zanfang, J., Yingxu, C., Feier, W., & Norio, O. (2004). Detection of nitrate sources in urban groundwater by isotopic and chemical indicators, Hangzhau City, China. *Hydrogeology Journal*, *45*(7), 1017–1024.

Zaporozec, A, & Eaton, T. T. (1996). Groundwater resource inventory in urbanized areas: hydrology and hydrogeology of urban and urbanizing areas. *Proceedings of the AIH annual meeting*, St. Paul, Minnesota, USA.

Zekster, S., & Loaiciga, H. A. (2004). Environmental impacts of ground water overdraft: selected case studies in the southwestern United States. *Environmental Geology*, *47* (3), 396–404.

Zipfel, K., & Horalek, U. (1988). Impacts on groundwater quality and groundwater use in a high populated and industrial urban region. *Symposium on hydrological processes and water management in urban areas*, Duisberg, Germany, April, pp. 607–616.