Chapter 13

# Impact of Urbanization on Groundwater Quality

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**Chapter Outline**



## 13.1 INTRODUCTION

Urbanization is defined as the process where people living in rural areas move to urban areas. This is facilitated by the growing number of industries and job opportunities in the cities. To accommodate the increasing population and number of businesses the urban areas in many major cities extend beyond the administrative boundaries and into semiurban areas (e.g., Bangkok in Thailand, New Delhi in India, Berlin in Germany). Thus many rural areas are becoming "cities" and many cities are becoming "megacities." The increase in the population living in urban and rural areas from 1960 to 2016 is shown in Fig. 13.1. In 2016 about 54% of the world's population lived in urban areas, with a projected increase to 60% by 2030, and 66% by 2050 (United Nations, 2014). Tokyo tops the list with 38 million people followed by New Delhi, Shanghai, Mumbai, Sao Paulo, Beijing, Mexico City, Osaka, Cairo, and New York (United Nations, 2016). The pace of urbanization is faster in the developing nations of Asia and Africa.

Rapid increase of inhabitants in the urban areas requires proper infrastructure for water supply. At times the water supplies in countries like Bahrain, Denmark, Malta, Oman, Qatar, and Saudi Arabia are solely met by groundwater resources (UNESCO, 2004; Eslamian and Eslamian, 2017). Estimates indicate that half of the world's megacities are dependent on groundwater (Wolf et al., 2006). Many European cities are either completely dependent on groundwater (e.g., Budapest, Copenhagen, Hamburg, Munich, Rome, and Vienna) or receive more than half (e.g., Amsterdam and Brussels) of their water supplies from groundwater (UNESCO, 2004). In Asia, cities such as Lahore, Hanoi, and Kumamoto are solely dependent on groundwater (Takizawa, 2008; Basharat, 2016) and major cities like Dili, Beijing, New Delhi, Bangkok, Jakarta, Bandung, Hanoi, etc., are heavily dependent on groundwater.

The increased demand for water in urban areas is not often immediately met by the development of new or extended water supply systems. Many houses in the cities of developing nations are still deprived of piped water supplies or receive limited water supplies at fixed intervals (Brindha et al., 2014). Due to immediate needs and a deficiency of efficient water supply systems to provide for the growing population, people depend on alternate sources of water, which includes, (1) direct access to surface water or groundwater resources, (2) private water supplies in the form of bottled water, kiosks, water tankers, etc., and (3) public water supplies in the form of standpipes and public taps. A growing number of industries

**GIS and Geostatistical Techniques for Groundwater Science**. https://doi.org/10.1016/B978-0-12-815413-7.00013-4

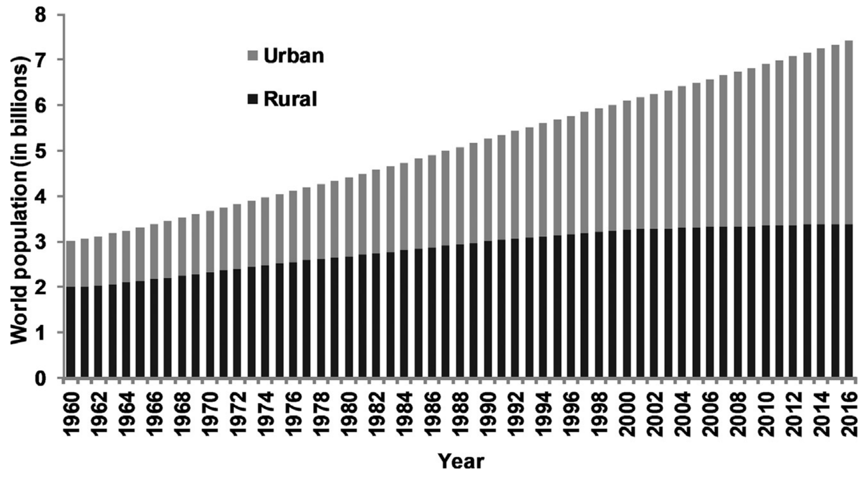


**FIG. 13.1** Urban and rural population of the world, 1960–2016. (Source*: World Bank, 2018. World Population (Total, Urban and Rural). Available online at: https://data.worldbank.org/ (Accessed on 24 December 2018).)*

rely on groundwater as a cheap and quick option. In some cities groundwater extraction for industrial use exceeds that for drinking, such as in Bandung (80%) and Bangkok (60%) (Shrestha and Pandey, 2016).

Lately, an increased reliance on groundwater has led to groundwater depletion at very high rates, the adverse effects of which have been realized in recent decades. The rate of pumping of groundwater has overtaken the rate of replenishment. Groundwater is usually considered to be less vulnerable to pollution compared to surface water, but in recent times it has become increasingly contaminated due to human intervention. Due to the occurrence of groundwater in the subsurface it is vulnerable to pollution from sources located both on the surface and in the subsurface. More in urban areas than in rural areas, groundwater is prone to contamination from multiple sources (domestic, industrial and natural) and with more complex pollutants (fluoride, arsenic, nitrate, heavy metals, organic compounds, etc.).

In this chapter the various sources contaminating urban groundwater are discussed. Selected key contaminants from various sources are described in the subsections. Demarcation of groundwater pollution due to urbanization using geographical information system (GIS) tools is presented through a case study.

## 13.2 POTENTIAL SOURCES OF GROUNDWATER CONTAMINATION

Pollutants in groundwater are generally classified as (1) natural and anthropogenic or (2) physical, chemical, and biological. However, sources of groundwater contamination (Fig. 13.2) can be classified into various types such as (1) natural and anthropogenic, (2) surface and subsurface, (3) point and nonpoint, and (4) rural and urban. This chapter does not classify the sources based on these types, because a pollutant can reach the groundwater environment, especially in urban areas, by multiple pathways. Also, key contaminants from various sources are described within the subsection, but that does not imply that these contaminants are contributed solely from one particular source. For example, arsenic is a toxic pollutant in groundwater of many nations and is chiefly contributed by geochemical processes. Nevertheless, as a by-product of some human activities such as chemical industry, mining operations and agriculture, arsenic can be added to natural waters. The characteristics and pathways of arsenic in groundwater are explained under geogenic sources, as this is the largest contributing source of arsenic.

### 13.2.1 Natural Sources

Arsenic and fluoride are the most common and serious geogenic contaminants of groundwater causing pollution at a large-scale. The occurrence, origin, and chemical reactions of these ions in groundwater are influenced mostly by the local geology, hydrogeology, and geochemistry.

#### *13.2.1.1 Arsenic*

Arsenic in groundwater is largely contributed by natural weathering of minerals from rocks and soil. Urbanization and related human activities accelerate the release of arsenic from the natural environment. An estimated 150 million people from over 70 countries worldwide are exposed to arsenic poisoning by drinking groundwater containing high levels of arsenic (Ravenscroft et al., 2009). Of these, about 110 million people live in 10 Asian countries (South and South-East):

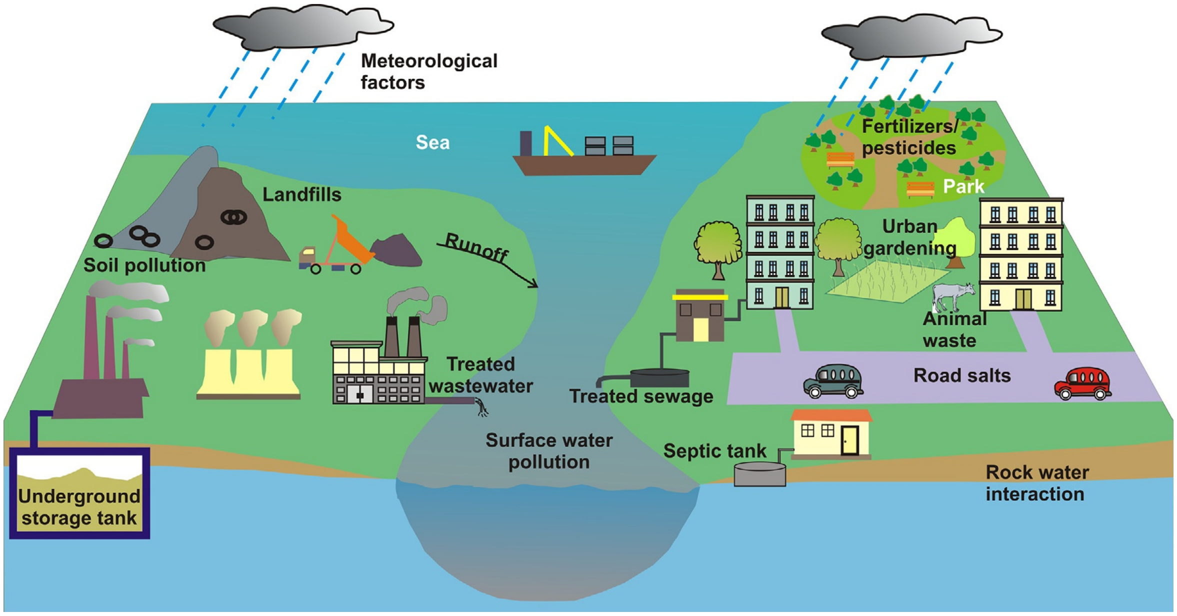


**FIG. 13.2** Sources of groundwater contamination.

Bangladesh, Cambodia, China, India (West Bengal), Laos, Myanmar, Nepal, Pakistan, Taiwan, and Vietnam (Brammer and Ravenscroft, 2009). Smith et al. (2000) described the groundwater contamination by arsenic in Bangladesh as the largest and worst poisoning of a population in history. Cities such as Hanoi (Vietnam) located in one of these contaminated hotspots face serious consequences, as the Hanoi municipal water supply system depends on groundwater exploited from a polluted confined aquifer as the only water source for its domestic water supply (Nga, 2008). These highly contaminated aquifers contain arsenic at levels up to 112 μg/L (Nga, 2008), which exceeds the World Health Organization limit (10 μg/L) (WHO, 1993) by many times. An additional infrastructure is essential to treat the groundwater before supplying the local population.

Arsenic primarily occurs as arsenopyrite and is commonly associated with sulfide minerals. Orpiment, realgar, and arsenic-rich iron oxyhydroxide also release arsenic in the groundwater (Garelick et al., 2008). Four geochemical reactions namely, reductive dissolution, alkali desorption, sulfide oxidation, and geothermal activity, predominantly determine the occurrence and distribution of natural arsenic (Ravenscroft et al., 2009). Crops irrigated with arsenic contaminated groundwater lead to an accumulation of arsenic in the soil and in the end-products. In south and southeast Asia, the rice, which is the staple crop, is irrigated with groundwater, which has further enhanced the arsenic content of the rice (Williams et al., 2006; Pal et al., 2009). This may not only pose a risk to the population that consume these crops, but is also a threat to food production due to the toxic levels of arsenic accumulated in the irrigated soil.

Based on the pH and redox conditions, arsenic occurs in two oxidation states in the environment: arsenic (III) or arsenite and arsenic (V) or arsenate. Arsenite is more toxic than arsenate. Long-term exposure to low doses of arsenic (such as drinking arsenic contaminated groundwater) can lead to arsenicosis. This is a serious and irreversible health issue and the adverse health effects include skin lesions, circulatory disorders, neurological and respiratory complications, diabetes, and hepatic and renal dysfunction (Chen et al., 2009). Arsenic is a known carcinogen causing cancer of skin, lung, liver, bladder, and prostate. Acute toxicity may lead to death.

### *13.2.1.2 Fluoride*

Fluoride, like arsenic, causes mass contamination of groundwater affecting around 200 million people from among 25 nations all over the world (Ayoob and Gupta, 2006). It is more pronounced in Africa (Kenya, Ghana, Tanzania, Malawi, Uganda, Sudan, South Africa, Ethiopia, and Algeria) and Asia (India, China, Pakistan, Thailand, Japan, and Sri Lanka). Fluoride naturally occurs in groundwater due to the weathering of fluoride-rich rocks. Long residence times of groundwater in aquifers with fluoride-rich rocks and slow movement of groundwater increases fluoride concentrations in groundwater (Brunt et al., 2004). Commonly occurring fluoride bearing minerals are fluorite, apatite, and mica. It is also present in biotite, amphibole (e.g., tremolite and hornblende), cryolite, epidote, fluorapatite, fluormica, topaz, sellaite, clays, villuanite, and phosphorite (Brindha and Elango, 2011). High fluoride concentrations in groundwater are associated with alkaline pH, high sodium, high bicarbonate, and low calcium contents. Hence most fluoride-rich groundwater has a characteristic sodium-bicarbonate water type.

Volcanic rocks enhance the concentration of fluoride and, thus, volcanic ash is also rich with fluoride. These volcanic ashes are highly soluble and cause fluoride contamination in groundwater. Though these geogenic sources are the largest contributor of fluoride, it also enters the groundwater through anthropogenic sources. Combustion of fossil fuels; production of cement, glass, ceramic, brick, plastics, tiles, and phosphate fertilizers; and industrial processes such as smelting, dyeing, and industrial wastewater, are additional sources.

Fluoride is essential for healthy bones and teeth, while in excess it causes fluorosis. As a public-health initiative, many countries have adopted fluoridation of the public water supply as an effective tool to reduce dental carries. Usually the fluoride level is adjusted to 1 mg/L in the public water supply. About 378 million people from 25 countries have access to artificially fluoridated water through the public water supply (The British Fluoridation Society, 2012). However, the percentage of population benefiting from this varies from <1% to 100%. Developed nations like Singapore and Hong Kong supply fluoridated water to 100% of the population. More than half of the population are consuming optimally fluoridated water (<1.5 mg/L) through the public water supply and from natural sources, such as in Australia (80%), Brunei (95%), Chile (70%), the Irish Republic (73%), Israel (70%), Malaysia (76%), New Zealand (61%), and the United States of America (USA) (66%) (The British Fluoridation Society, 2012). Though the positive effect of fluoride on teeth is accepted, the method used, i.e., mass medication of the population is argued against by certain groups as unethical. Dental products are also fluoridated to reduce dental carries and strengthen teeth. A moderate amount of fluoride intake causes dental fluorosis, i.e., discoloration of teeth from yellow to brown or black in the form of spots or streaks. But long-term exposure to fluoride-rich drinking water can cause crippling skeletal fluorosis, renal dysfunction, and kidney stones. In addition, high fluoride consumption disrupts the normal functioning of the respiratory, digestive, nervous, excretory, and reproductive systems (Meenakshi and Maheshwari, 2006).

#### *13.2.1.3 Total Dissolved Solids*

Salinization is an increase in the total dissolved solids (TDS) of the aquifer caused by natural or anthropogenic factors. The processes and sources of salinization vary for inland and coastal aquifers. In urban areas located inland, salinization may be due to geogenic or anthropogenic factors (Fig. 13.3). Saline water naturally underlies freshwater aquifers at greater depths in some regions (Martens and Wichmann, 2007). When the water from these saline aquifers is discharged onto the surface, the fresh water aquifers may also be contaminated. It is also possible that the salt water and fresh water mixes in the subsurface and the salinity of fresh water aquifer is increased. The salinity of aquifers depends on the distribution and rates of precipitation, evapotranspiration and recharge rates, type of aquifer material and its characteristics, residence time, flow velocities, and nature of the discharge areas (Richter and Kreitler, 1993). Aquifers in contact with salt deposits also turn saline due to natural rock-water interaction processes. Water pumped from these saline aquifers cannot be directly used for water supply or industrial purposes. Australia, being a dry continent, is highly affected by salinization, therefore groundwater in many parts of the country is naturally saline. Major anthropogenic sources of inland salinization in urban areas include irrigation of dry areas that lack proper drainage, increased evaporation and decreased precipitation facilitated by climate change, excessive groundwater pumping, wastewater with a high salt content being disposed of carelessly by industries onto the surface, etc (Foster and Chilton, 2003, Zimmermann-Timm, 2007). Irrigation and heavy groundwater pumping-induced salinization is commonly reported in India and Pakistan.

### 13.2.2 Heavy Groundwater Pumping

In coastal urban areas, the majority of salinization is due to seawater intrusion through human influence. Many megacities in the world are located in coastal areas. Nearly 44% of the world's population live within 150 km of the coast (Reed, 2010). The average population densities in these coastal regions are approximately three times higher than the average global population density (Small and Nicholls, 2003). It is estimated that in the year 2030, about 268 million to 286 million people will live in the low-elevation coastal zones with a large portion of the population housed in China, India, Bangladesh, Indonesia, and Vietnam (Neumann et al., 2015). Exponential population growth in these regions increases the demand for public water supply. In many urban coastal areas, groundwater forms the main freshwater source. Coastal aquifers are sensitive to changes in the environment, such as groundwater pumping and recharge due to their low topography. Thus overpumping of groundwater from the coastal aquifers results in seawater intrusion. This is caused by the variation in the density of fresh water and seawater. The high-density seawater moves into the coastal aquifer and forms a wedge shape (Fig. 13.4).

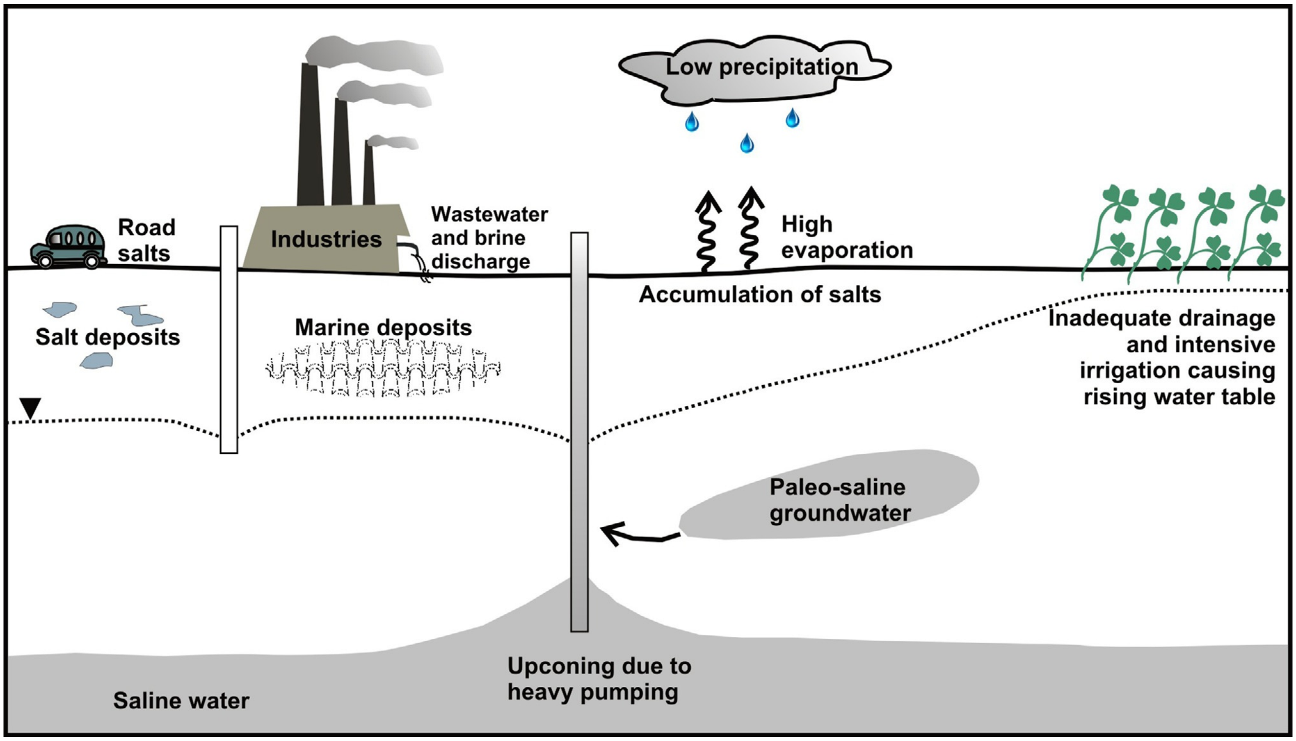


**FIG. 13.3** Sources of inland salinization of groundwater.

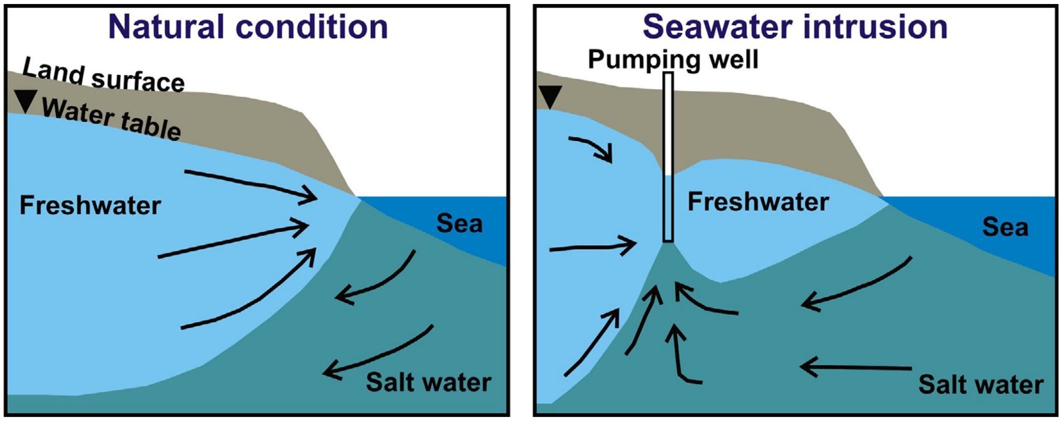


**FIG. 13.4** Conceptual figure of seawater intrusion.

Depending on the intensity of pumping, this wedge can extend for several kilometers inland. These affected aquifers are characterized with high concentrations of chloride, bromide, and sodium.

In Chennai, a coastal city in southern India, the city's water requirement (about 10%) is met from pumping groundwater from the northern part of the city. Due to overpumping in the coastal areas, seawater intrusion has extended inland from 4 km in 1970–1975 (Subramanian, 1975) to 14 km in 2012 (Nair et al., 2015). In 2011 it was found that urban development and subsequent water supply withdrawals had resulted in seawater intrusion in approximately 1200 $km^2$ of the Biscayne aquifer in Florida, USA (Prinos et al., 2014). Seawater intrusion extends >1 km inland in a coastal area in eastern Greece and about 150 $km^2$ of the coastal aquifer has been intruded by saline water due to groundwater extraction through numerous borewells (Kazakis et al., 2016). Nearly 1520 $km^2$ of the coastal area near the Bohai Sea in northern China was affected by salinization due to seawater intrusion in the 1980s and this had increased to approximately 2457 $km^2$ in 2003 (Shi and Jiao, 2014).

Careful planning of groundwater extraction from the coastal aquifers is the preferred method to reduce seawater intrusion. Though alternative methods such as subsurface barriers and managed aquifer recharge are available to control seawater intrusion, they are cost-intensive and time consuming.

## 13.2.3 Industries

Several toxic heavy metals such as lead, cadmium, manganese, mercury, chromium, zinc, iron, aluminum, and copper are used in industrial processes. Industries withdraw a large portion of the groundwater in urban areas, but only a very small portion of this water is truly incorporated within the product. Most of the water used during fabricating is for cooling, washing, or transporting, and it returns to the environment as wastewater, only now it carries huge pollutant loads. Thermal power plants, engineering, paper, textile, and chemical-manufacturing industries are a few of the many industries that consume large amounts of water. Industries may extract water purely from the surface or from both the surface and groundwater, but the contamination from industrial effluents pollutes both these freshwater resources. The ideal practice to discard the effluents resulting from the manufacturing processes is by treating them on-site and disposing of them separately into receiving waters such as ponds, lakes, streams, rivers, and oceans. As a common practice the treated effluents are also disposed of into municipal sewers. The effluents from certain industries that are rich in nutrients (e.g., fertilizer manufacturing, food processing) are diluted and reused directly or by mixing with domestic wastewater for irrigation. This is practiced in countries like Australia, Canada, China, India, Mexico, USA, and the United Kingdom (UK). Regulatory authorities of many countries have stringent standards for the disposal of effluents. Nevertheless, illegal dumping of raw or partially treated effluents is a recurrent practice in developing nations. These effluents eventually find their way into the aquifers along with rainfall recharge and through interaction with surface water.

WHO (2017a) has listed four heavy metals (arsenic, cadmium, lead, and mercury) in its top-10 chemicals of major public concern, as they are carcinogenic. Exposure to arsenic is mainly through drinking groundwater containing high levels of arsenic or from food prepared using this water. Industrial processes contributing to arsenic in groundwater are smelting, metal extraction, processing and purification, manufacture of agro-chemicals (fertilizers, pesticides, herbicides, insecticides, and fungicides), wastewater from industries, etc.

### *13.2.3.1 Cadmium*

Cadmium is a carcinogen and occurs in the environment as a resultant of industrial processes like smelting and electroplating during the manufacture of alloys, dyes, batteries, fertilizers, and fungicides. The main exposure route for cadmium is through the inhalation of air-borne cadmium particulates and chronic exposure causes lung cancer. Ingestion of cadmium through drinking water affects the renal (kidney disorders), skeletal (bone softening), and respiratory systems. One of the worst cases of large-scale cadmium poisoning was in the Toyama Prefecture in Japan in the early 1900s. The disease is prevalently called as the "itai-itai" (which means "it hurts, it hurts" in Japanese) disease. This caused osteomalacia (softening of bones) and renal tubular dysfunction in humans due to consumption of water with high concentrations of cadmium and of food crops grown with this water. This contamination was due to the disposal of tailings waste containing cadmium from mining and ore processing into the Jinzu River, which served as source for drinking and irrigation water. Groundwater in this area was also polluted due to the infiltration of effluents from unlined sewers and waste-storage ponds (Yoshida, 2002).

### *13.2.3.2 Lead*

Lead is a toxic metal and its presence in drinking water is undesirable, as it is harmful even at low levels of exposure. Although lead occurs naturally in the Earth's crust, its high concentrations in groundwater are mainly due to anthropogenic activities. Lead is discharged in the wastewater as a byproduct from thermal power plants; some engineering processes like smelting and the recycling of batteries; and the manufacture of inks, pigments, cosmetics, utensils, pipes, paints, batteries, gasoline, ceramic, and a wide range of other products. Plumbing systems were in the past made of lead pipes and the corrosion of these pipes led to the occurrence of lead in the drinking water supply. Exposure to lead affects multiple organs in the cardiovascular, hematologic, gastrointestinal, neurologic, renal, and reproductive systems. It has adverse permanent consequences on children's health. Lead poisoning can affect the behavior and learning capabilities of children, reduce their intelligence quotient, delay growth, and cause hearing problems. Acute intake leads to permanent brain and nervous system damage, and even death. Mass lead poisoning is reported mainly in low- and middle-income countries, especially through the inhalation of lead particles from battery recycling and mining (WHO, 2017b).

### *13.2.3.3 Mercury*

Mercury occurs naturally in the elemental form in the environment. When it is transformed into its organic form (methylmercury) it bioaccumulates, especially in aquatic species, i.e., fish and shellfish. Like lead, mercury is also a toxic heavy metal affecting children's neurological development. Fetuses are vulnerable to mercury poisoning through the ingestion of seafood by the mother. Ingestion of mercury affects digestive, immune, and nervous systems. It is used in the manufacture of electronic items (light emitting diode [LED] screens, switches, and batteries), thermometers, pharmaceutical items (dental amalgams, eye ointments, and drops), oil-based paints, and agro-chemicals (fertilizers, fungicides, and algaecides). The worst effects of mass mercury poisoning from industrial wastewater were seen in Minamata City, Japan. This disease, popularly called as the "Minamata disease" was first reported in 1956 (Harada, 1995). A chemical factory producing acetaldehyde was using mercury as a catalyst in its processes. Methylmercury was one of the components of the wastewater and this wastewater was released into the Minamata Bay, affecting the aquatic life. Humans and animals consuming the fish and shellfish were affected by this disease. Though the environmental hazard in Minamata was mostly to marine resources, the waterways carrying the wastewaters also contaminated the soil and groundwater (Ministry of the Environment, Japan, n.d.). Another incidence of mercury poisoning due to the illegal dumping of wastes from a mercury thermometer manufacturing factory was reported in Kodaikanal, India. Mercury contaminated glass scrap was disposed of for recycling and the scrap yards polluted the soil, air, surface water, and groundwater (IPEN, 2016).

### *13.2.3.4 Chromium*

Textile, chrome pigments, paints and alloy production, and industrial processes such as electroplating and welding release chromium containing wastewater. The largest and most important sources of chromium pollution are tanneries. These industries process raw hides and skins to produce leather that is used for producing different finished products. The tanning process increases the durability of leather and this can be of two types: vegetable tanning and chemical tanning. Though using vegetable tannins is environmentally friendly, chemical tanning using chrome salts is preferred as it takes less time. The improper treatment of the industrial wastes leads to chromium contamination of the groundwater. Usually the effluents from many small-scale industries are treated in a common effluent treatment plant and are disposed of into receiving bodies. Nevertheless, the treated effluents do not comply with the standards for the disposal of wastewater and are rich in many ions (Brindha and Elango, 2012a). Many low- and middle-income countries from South Asia, Africa, and Central and South America are affected by chromium pollution from tanneries. India, Bangladesh, Nepal, Pakistan, China, Morocco, Turkey, Mexico, and Brazil are a few of the most affected countries in these regions. The health impacts due to the ingestion of chromium contaminated groundwater involve the gastrointestinal system, while occupational exposure to hexavalent chromium may lead to lung cancer.

### *13.2.3.5 Volatile Organic Compounds*

Volatile organic compounds (VOCs) are carbon containing organic compounds that evaporate readily at room temperature. They are considered to be important environmental contaminants as they are mobile, persistent, and toxic (Squillace et al., 1999). With the multifold increase in the production of synthetic organic chemicals in the past few decades, the presence of VOCs in groundwater and soil has been increasingly reported. VOCs are an integral compound in a large variety of industrial and residential products including paints, inks, dyes, glue, fuel, gasoline, solvents, adhesives, deodorizers, refrigerants, and pesticides. They reach the groundwater mainly through human activities such as industrial wastewater, landfills, leakage and spills, pesticide use, etc. VOCs that are dense nonaqueous phase liquids (DNAPLs) with low solubility and high specific gravity are capable of penetrating deep below the water table and form persistent plumes. Due to their ability to occur in one or more of the four phases (gas, solid, water, and immiscible), remediation of aquifers contaminated with DNAPLs is often difficult, complex, expensive, and constrained by the extent of contamination, type of contaminant, and site-specific characteristics. The identification of VOCs in drinking water sources is of concern due to their carcinogenic, mutagenic, and teratogenic effect on humans. The United States Environmental Protection Agency (USEPA) has estimated that one-fifth of the nation's water supplies was contaminated with VOCs. In Switzerland, 14% of the monitoring sites in the urban areas had VOCs in the groundwater (FOEN, 2016).

### *13.2.3.6 Emerging Organic Contaminants*

Emerging organic contaminants (EOCs) are defined as hazardous compounds that were previously not considered or known to be present in groundwater. Apart from industrial products, these include personal-care products, cosmetics, pharmaceuticals, veterinary products, food additives, engineered nanomaterials, and pesticides (Lapworth et al., 2012). Of these, pharmaceuticals are commonly reported in the groundwater of many countries including Italy, Canada, USA, Spain, Germany, and UK. Pharmaceutical wastes often reach the domestic wastewater disposal network and the wastewater treatment plants are not equipped with the infrastructure to remove these contaminants. Thus the treated wastewater along with the contaminants reach the surface water bodies and eventually pollute groundwater in urban areas. As these EOCs have been only recently discovered in groundwater, monitoring and guidelines for the presence of these compounds in drinking water has not been incorporated into the regulations of all nations. It is also possible that more contaminants have not yet been identified due to the limited availability of analytical facilities. The health implications for humans due to these EOCs are usually high, as they have low biodegradability and are therefore persistent (Kuroda and Fukushi, 2008).

## 13.2.4 Fertilizers

Fertilizers are used to enhance the plant growth and yield. Nitrogen, phosphorus, and potassium are the three major nutrients required by plants. Leaching of these nutrients from fertilizers is a common source of groundwater pollution. These nutrients are generally considered as an agricultural pollutant and are expected to be in high concentrations in non-urban agricultural areas rather than in cities. Nevertheless, use of fertilizers in gardens, parks, and lawns contribute to these pollutants in urban groundwater. Of these nutrients, nitrate contamination in groundwater used for drinking purpose is of highest concern due to the harmful effects on human health. Excess nitrate and phosphate applied to the soil are carried away by urban runoff and cause eutrophication in surface water bodies. This is a condition that causes algal blooms due to the availability of excess nutrients followed by reduced oxygen availability for aquatic flora and fauna, subsequently leading to the death of fish. Potassium-based fertilizers (e.g., potash) generally do not exert adverse effects on the groundwater environment and human health in comparison with other nutrients. Heavy metal and fluoride pollution from fertilizers have also been reported.

### *13.2.4.1 Nitrate*

Nitrogen is ubiquitous in the environment and the nitrogen cycle, involving a series of biogeochemical processes, contributes to various nitrogen compounds in groundwater. Nitrate, a highly soluble nitrogen compound, occurs as a common surface and groundwater pollutant. An increase in the number of nonagricultural sources of nitrogen due to urban development has led to an increase in the nitrate concentrations in the groundwater of cities (Wakida and Lerner, 2005). Nitrogen bearing rocks containing ammonium-rich minerals and organic nitrogen compounds undergo nitrification under conducive conditions and contribute to nitrate in groundwater (Lowe and Wallace, 2001).

Anthropogenic sources of nitrogen compounds in groundwater are diverse ranging from point sources (e.g., sewage and wastewater treatment plants and landfills), multipoint sources (e.g., leaky sewers), and diffuse sources (e.g., fertilizers and atmospheric deposition) (Wakida and Lerner, 2005; Grimmeisen et al., 2017). Diffuse pollution from the application of fertilizers in agricultural areas is the predominant source of nitrate in groundwater. Agriculture intensification and the overall nature of farmers to utilize more than the required or prescribed level of fertilizers and pesticides expecting high yield is the principle cause of nitrate pollution. Asia (58%) is the largest consumer of nitrogen fertilizers and a large portion of the nitrogen demand comes from China (18%) and India (17%) (FAO, 2015). Nitrate from fertilizers is not just a problem in agricultural areas, but also in urban and peri-urban areas, where fertilizers are used in gardens and golf courses (Winter and Dillon, 2005). Animal waste also has a high nitrogen content. The improper disposal of these animal wastes as piles on unlined surfaces and using them as manure for agriculture can potentially pollute surface and groundwater through stormwater runoff and direct infiltration. Such instances have been reported in urbanized areas. Infiltration of leachate from landfills and from treated wastewater applied to agricultural lands also contaminate the soil and groundwater.

The WHO recommended limit for nitrate in drinking water is 50 mg/L (WHO, 1993). One of the most significant toxicological effects due to high nitrate consumption is methemoglobinemia, which particularly affects infants. This is a condition of the blood that results in cyanosis caused by the reduced ability of the red blood cells to carry oxygen (Fan and Steinberg, 1996). It also causes other health issues such as gastrointestinal infections, recurrent diarrhea, recurrent stomatitis, birth defects, deterioration of the immune system, hypertension, respiratory tract infection in children, and histopathological changes in cardiac muscles, alveoli of lungs, and adrenal glands (Gupta et al., 2008).

### *13.2.4.2 Phosphates*

Phosphorus is one of the key elements necessary for plant growth and it is usually present along with other elements as phosphates, occurring naturally in rocks and mineral deposits. However, anthropogenic activities including sewage and wastewater runoff from agricultural and urban areas (especially from detergents) are the major source of phosphates in groundwater. Unlike nitrate, which primarily occurs in its organic form in soils, phosphorus occurs in organic and inorganic forms. Phosphates are comparatively less soluble than nitrates and are largely retained in soil by adsorption (Domagalski and Johnson, 2012). Therefore, in the past, phosphorus in soil was considered not highly mobile and hence not a major threat to groundwater quality. However, the wide occurrence and determination of phosphates in groundwater has led to the identification of leaching of phosphate fertilizers from the land surface to the groundwater. Africa is the largest exporter and South Asia is the largest consumer of phosphate fertilizers (FAO, 2011). Even at low concentrations, phosphates are likely to cause eutrophication of surface water bodies. Hence the monitoring of phosphate concentrations in the wastewater discharged to water bodies is essential. Permissible limits for phosphates in drinking water have not been proposed (WHO, 1993). They are toxic at very high levels and may cause digestive issues in humans.

## 13.2.5 Sewage Systems and Septic Tanks

Urban groundwater is artificially recharged to a larger percentage with water from leaky water supply systems and sewers. Nitrate and pathogens are the key contaminants from sewage. Grimmeisen et al. (2017) reported nitrate contamination in groundwater in Jordan due to infiltration of septic waste from leaky sewers. Leakage of human wastes from sewers was the major source of contamination from nitrogen compounds in the urban areas of Metro Manila, Philippines and Jakarta, Indonesia (Umezawa et al., 2009).

### *13.2.5.1 Microbial Contamination*

Many water-borne diseases are caused due to ingestion of groundwater containing pathogenic microorganisms. These microscopic pathogens belong to four major groups, bacteria, viruses, protozoa and helminths. Drinking contaminated water is the major cause of large outbreaks of diseases such as cholera, typhoid, diarrhea, dysentery, etc. Nearly 2 billion people worldwide are exposed to drinking water with fecal contamination and this is estimated to cause about 502,000 diarrhea related deaths each year (WHO, 2017c). Children under the age of 5 years are frequent victims and nearly all deaths occur in developing nations.

The mixing of groundwater with sewage is the main source of fecal contamination. Thus microbial contamination of groundwater is closely associated with the local sanitation practices. Sewers in urban areas leak due to improper installation, development of cracks, damage due to disasters (e.g., earthquakes and floods) and land subsidence. The estimated wastewater leak from damaged sewer systems in Germany was several 100 million $m^3$/year (Eiswirth and Hötzl, 1997). Similarly, about 5–8 million $m^3$/year of sewage mixed with groundwater in Hannover, Germany (Mull et al., 1992). The estimated values were much higher in the USA, i.e., 950 million $m^3$/year of wastewater contaminated the groundwater (Pedley and Howard, 1997).

Septic tanks and cesspits are prevalent in developing countries and leaching of wastes from these tanks is another major source. Proper planning of the location, design, operation, and maintenance of these on-site disposal systems is crucial. Shallow groundwater is more susceptible to pollution from these structures compared to deep aquifers. The population density in an area, the density of the disposal systems, and the quality of the materials used for the construction of the on-site disposal systems determine the pollution risk. Discharge of raw or partially treated domestic wastewater into water bodies, its subsequent percolation through the unsaturated zone, and runoff from agricultural areas containing animal and human wastes also add to the contamination. Bacterial and viral contamination in shallow aquifers supplying the public water supply wells were reported in Finland and the USA. Certain microbes serve as indicators of pathogen contamination (e.g., *Escherichia coli*). However, these indicators vary for different pathogen groups. Fate and the transport of pathogens in the subsurface environment is poorly understood due to variation in the behavior of different microbial groups, complex biogeochemical processes, hydrogeological conditions, soil properties, soil heterogeneity, and multiple potential transport pathways.

Many countries disinfect the water before public supply. Chlorination is the simple, most reliable, and cost-effective method adopted. It is a prerequisite in some countries before public water supply (Japan, Israel, USA, UK, and Australia). Some European countries (e.g., Germany, the Netherlands, and Switzerland) have withdrawn this method after reports on the formation of potentially carcinogenic disinfection by-products during the chlorination process were published.

## 13.2.6 Landfills

Ideally the municipal waste generated in cities are recycled and the remnants are either incinerated or disposed of in landfills. The complexity in the management of these wastes is due to their miscellaneous composition including organic wastes, batteries, packaging materials, paper, metal containers, glass, plastics, clothes, electronics, furniture, etc. Often industrial and pharmaceutical wastes containing hazardous substances are disposed of along with municipal waste. The degree of municipal waste generation in a country is influenced by the economic development, urbanization rate, local habits, and climatic conditions (Hoornweg and Bhada-Tata, 2012). The levels of municipal-waste production in some countries are: USA produces 728 kg/person/year (USEPA, 2016a), Denmark produces 789 kg/person/year, Switzerland produces 725 kg/person/year, Germany produces 625 kg/person/year (Eurostat, 2017), Australia produces 565 kg/person/year (Pickin and Randell, 2017), India produces 124 kg/person/year, China produces 372 kg/person/year, Indonesia produces 190 kg/person/year, and Japan produces 624 kg/person/year (Hoornweg and Bhada-Tata, 2012).

Historically, landfills were places where municipal wastes were dumped without proper planning. During rainfall, the rainwater penetrates through the landfills and leachate is generated. The composition of leachate depends on the (1) climate (rainfall and snowmelt), (2) hydrogeological conditions (groundwater level), (3) waste composition and characteristics (particle size, density, permeability, initial moisture content, and biodegradability), (4) age of the landfill, (5) operation and maintenance (pretreatment, compaction, and vegetation cover), and (6) internal processes (organic matter decomposition) (Rapti-Caputo and Vaccaro, 2006). Typically, the leachate contains a potentially hazardous concentration of many ions, heavy metals, chemicals, toxic substances, organic compounds, and pathogens. Infiltration of the leachate through the vadose zone has resulted in surface and groundwater contamination in many countries, making the groundwater unsuitable. Such cases have been reported in both developed and developing countries, especially due to unlined landfills: Sant'Agostino in Italy (Rapti-Caputo and Vaccaro, 2006), Zhoukou in China (Han et al., 2014), Ranital in India (Samadder et al., 2017), Rishon Lezion in Israel (Aharoni et al., 2017), Londrina in Spain (Lopes et al., 2012), Guadalupe Victoria in Mexico (Reyes-López et al., 2008), and Augsburg, Munich and Gallenbach sites in Germany (Baumann et al., 2006). In recognition of the environmental hazard, landfills are now designed with liners and leachate collection systems that prevent the percolation of leachate and contamination of aquifers.

## 13.2.7 e-Waste

One of the current concerns in waste disposal is "e-waste," comprising of a vast variety of products, including computers, mobile phone, televisions, digital cameras, household appliances, etc. Due to the enhanced rate of production of electrical and electronic products, the short lifespan of these products, and their nonbiodegradable nature, it is a challenge to manage these wastes. Frequent innovations of upgraded models of mobile phones, laptops, and tablets every few months make the previous models obsolete within a short time of their introduction onto the consumer market. In 2014 global e-waste generation was about 42 million tons accounting for 5.9 kg of e-waste per person (Baldé et al., 2015). Developed countries in Europe (15.6 kg/person), Oceania (15.2 kg/person), and America (north, central, and south) (12.2 kg/person) generated the highest e-waste per person (Baldé et al., 2015). E-waste encompasses many toxic metals (e.g., mercury, lead, cadmium, etc.) and hazardous compounds (e.g., polyaromatic hydrocarbons [PAHs]). At present, only a few countries have enacted legislations for the proper disposal of e-wastes. Several less-developed countries have no strict regulations for e-waste management and, hence, many high-income countries get rid of their e-waste by shipping them illegally to low-income countries. These backyard processing centers are not professionally equipped to recycle the e-waste and the inefficient techniques endanger the local environment. Groundwater pollution with multiple pollutants from informal e-waste recycling areas have been widely reported in China, India, Ghana, and Nigeria. The remaining e-wastes from the processing centers also end up alongside municipal solid waste in landfills.

## 13.2.8 Storage Tanks

Storage tanks are tanks that are located either on the surface or subsurface. Underground storage tanks are preferred due to space-constraints on the ground and as they are less vulnerable to vehicular accidents and tampering (Hairston, 1995). These tanks normally hold liquids such as hydrocarbons (petroleum products, gasoline, crude oil, etc.), and other hazardous chemicals. Usually strict guidelines apply for the construction and maintenance of storage tanks. But accidental release of the toxic substances, especially from underground storage tanks, through leaks and cracks caused due to corrosion of the tanks, spillage from tank overfilling (Sacile, 2007), faulty installation, improper operation and maintenance, or negligence (Brindha and Elango, 2014) can lead to seepage through the soil and mixing with groundwater. Remediation of groundwater contaminated with petroleum products and chemicals is often difficult, costly, and time-consuming, taking up to several years. It also usually demands the clean-up of the soil that is soaked with the contaminants. In the USA >530,000 cases of the release of petroleum products from underground storage tanks have been reported, of which 71,000 areas are yet to be cleaned up (USEPA, 2016b). Leaks from an abandoned underground storage tank in southern

India holding petroleum products has led to contamination of groundwater that is used as a source of drinking water (Brindha and Elango, 2014).

### 13.2.9 Polluted Surface Water

Surface water is more vulnerable to anthropogenic pollution. Historically, surface water and groundwater were considered as separate resources and the management of these resources was addressed separately. However, with increased concerns over water resources and the environment, the importance of considering them as a single resource has become increasingly evident (Winter et al., 1998). Interaction between groundwater and surface water is common in all types of fresh surface water bodies such as rivers, streams, lakes, ponds, etc. Pollutants in surface water are prone to infiltration through the soil zone and cause groundwater contamination.

Surface runoff from urban areas carry chemicals from roads, leachate from landfills, nutrients and fertilizers from urban gardening, etc., resulting in surface water pollution. The release of treated or raw wastewater from industries into surface water bodies often results in pollution from toxic substances. Improper disposal of sewage and domestic wastewater into surface water bodies increases the pathogen load. Some of the worst polluted rivers that are of environmental concern include the Ganges and the Yamuna Rivers in India, Yellow River in China, Citarum River in Indonesia, the Marilao and the Pasig Rivers in Philippines, Buriganga River in Bangladesh, Jordan River in Israel, Sarno River in Italy, the Mississippi and the Cuyahoga Rivers in the USA, and the Matanza-Riachuelo River, Argentina.

### 13.2.10 Road Salts

Salt is added to roads and highways in winter to melt the snow and ice by lowering the freezing point of water. Rock salt (sodium chloride) is commonly used as it is effective, easily available, and inexpensive. Once the snow is melted, however, the saline water contaminates the soil, groundwater, and surface water (Fig. 13.3). This has also turned groundwater in many areas to be Na-Cl dominated (Godwin et al., 2003). Several surface water bodies in North America and Europe have reported increased concentrations of sodium and chloride after road salt application during the winter months. On average nearly 5 million tons of road salt is used in Canada every year for de-icing (Environment and Climate Change, Canada, 2017). In the USA, about 21 million tons of road salt is used every year by government and commercial bodies (Sander et al., 2007). Much of this is washed away and pollutes groundwater resources.

### 13.2.11 Impact of Climate Change

Climate influences all life forms and their activities on Earth. Variations in recent climatic conditions, such as global temperatures, extreme rainfall events, cyclones, storms, and heat waves, indicate that climate change is an undeniable reality. Furthermore, the impacts of climate change include extensive melting of snow and ice, sea level rises, and wide spatial and temporal changes in rainfall amounts, wind pattern, and ocean salinity (USGS, 2007). Changes in precipitation, recharge rates, and the availability of water resources will enhance groundwater pumping and the use of agro-chemicals. Sea level rise and its interaction with the groundwater is likely to increase the salinity in the aquifers. Urban areas are at high risk from these extreme weather events (Revi et al., 2014).

The Intergovernmental Panel on Climate Change predicts that increases in water temperature, rainfall intensity, and low-flow period in rivers will affect groundwater quality through an increase in the concentrations of nutrients, salts, pesticides, and pathogens (Bates et al., 2008). Rises in the temperature of surface water bodies will affect water quality through decreased oxygen levels, decreased biological processes, and increased chemical processes. Extreme rainfall events result in floods that may disrupt the sewer systems in cities and can critically pollute groundwater. Floods in southern India caused by high-intensity rainfall within a short timespan have led to the inundation of borewells with sewage contaminated surface water from a river. This increased the concentrations of nutrients and heavy metals, and introduced pathogens into the groundwater (Gowrisankar et al., 2017).

In contrast, extreme droughts increase the residence time of groundwater and enhance water-rock interaction. Decreased flow in rivers reduces the dilution of wastewater and treated effluents and increases toxic substances and fecal contaminants in groundwater. Reduced recharge, increased evapotranspiration, and increased groundwater pumping from shallow groundwater will enhance the salinity (Bates et al., 2008). These effects will be experienced more in the semiarid and arid regions. Short-term droughts, like that during the summer of 2000 in the USA, increased the nutrients and inorganic concentrations in groundwater (Kampbell et al., 2003). Both natural disasters, floods and droughts, caused by climate change increase the risk to human health. Floods increase the risk of cholera and droughts can lead to diarrhea.

## 13.3 CASE STUDY: GROUNDWATER CONTAMINATION IN AN URBAN AREA IN INDIA

Many megacities in India have faced rapid groundwater quality degradation in recent years. Groundwater quality is constantly under threat due to urbanization, improvements in living standards, and an exploding population. In New Delhi, the capital of the country, half of the water consumed is sourced from groundwater (World Bank, 2010). Nitrate, fluoride, and heavy metal pollution is reported consistently every year. Contamination caused by on-site sanitation systems in Indore and Kolkata (formerly Calcutta) (Pujari et al., 2012), tanneries in Chennai (Brindha and Elango, 2012a), and seawater and urban wastewater contamination in Visakapattnam (Rao et al., 2005) are a few examples indicating the diversity of pollutants in groundwater of urban areas in India. All these studies show that systematic monitoring of groundwater quality should be mandatory.

Of the many methods available for the assessment of pollution, remote sensing and GIS serve as useful tools for the interpretation of the data. Spatial maps help to identify the pollution extent and interpolation of the primary data assists in predicting pollutant concentrations even at locations that are inaccessible for sample collection. Additionally, the inherent characteristics of a study area, such as the geology, hydrogeology, and land use, can be overlapped with pollution maps and compared. Due to these advantages, GIS is widely used for groundwater quality mapping. The case study presented serves as an example for the application of GIS in groundwater quality mapping in an urban area in southern India.

### 13.3.1 Study Area

The Tiruchirappalli (also known as "Trichy") district is located centrally in the southern state of Tamil Nadu, India. The administrative headquarters is the city of Tiruchirappalli, which is the fourth most populated city in the state (Census of India, 2011) with a population density of about 5000 persons/km$^2$. With a subtropical climate, this area experiences temperature ranging from 15°C in winter up to 40°C in summer. Monsoon season is from June to September and the average rainfall is 818 mm/year (TWAD Board, 2015).

### 13.3.2 Water Demand and Supply

The water supply for the inhabitants of the city is provided by the Tiruchirappalli City Corporation. The Cauvery River, a perennial river flowing through the city, is the major source for the water supply and in addition to this, groundwater is pumped from borewells (Tiruchirappalli City Municipal Corporation, 2014). Together both sources account for the total water supply of 82.5 million L/day for domestic and commercial use. Irrigation is the predominant use in the areas surrounding the city. With many industries and agricultural activities, water demand is high, therefore there are many private borewells that are used to meet the local needs. Heavy pumping from these wells, especially for commercial use, has led to a decline in the groundwater levels. There are three canals drawing water from the Cauvery River and providing for the irrigation needs. This study focuses on the groundwater quality along one of the canals, the Uyyakondan. This canal flows through the city and it aggregates pollutants due to the dumping of wastes: raw sewage from households, biomedical wastes from hospitals, etc. (Brindha and Kavitha, 2015). Thus it is vital to assess the impact of surface water pollution from the canal on groundwater quality and the suitability of the groundwater for drinking purposes.

### 13.3.3 Sampling Methodology

Groundwater samples from household borewells located near the Uyyakondan canal were collected from 15 locations in January 2014. Samples were collected in precleaned high-density polyethylene bottles of 1 L capacity. Electrical conductivity (EC) of the samples were measured immediately after sampling in the field. Major cations (calcium, magnesium, sodium, and potassium) and anions (chloride and sulphate) were determined by standard procedures (APHA, 1998).

### 13.3.4 Groundwater Quality Mapping

Groundwater and surface water quality in this area has been studied by Brindha and Kavitha (2015). However, this study addressed the water quality at selected locations based on the water quality index (WQI) method. A clear demarcation of the areas contaminated due to poor surface water quality was not achieved. The present study uses GIS techniques to delineate areas with suitable and unsuitable drinking water quality.

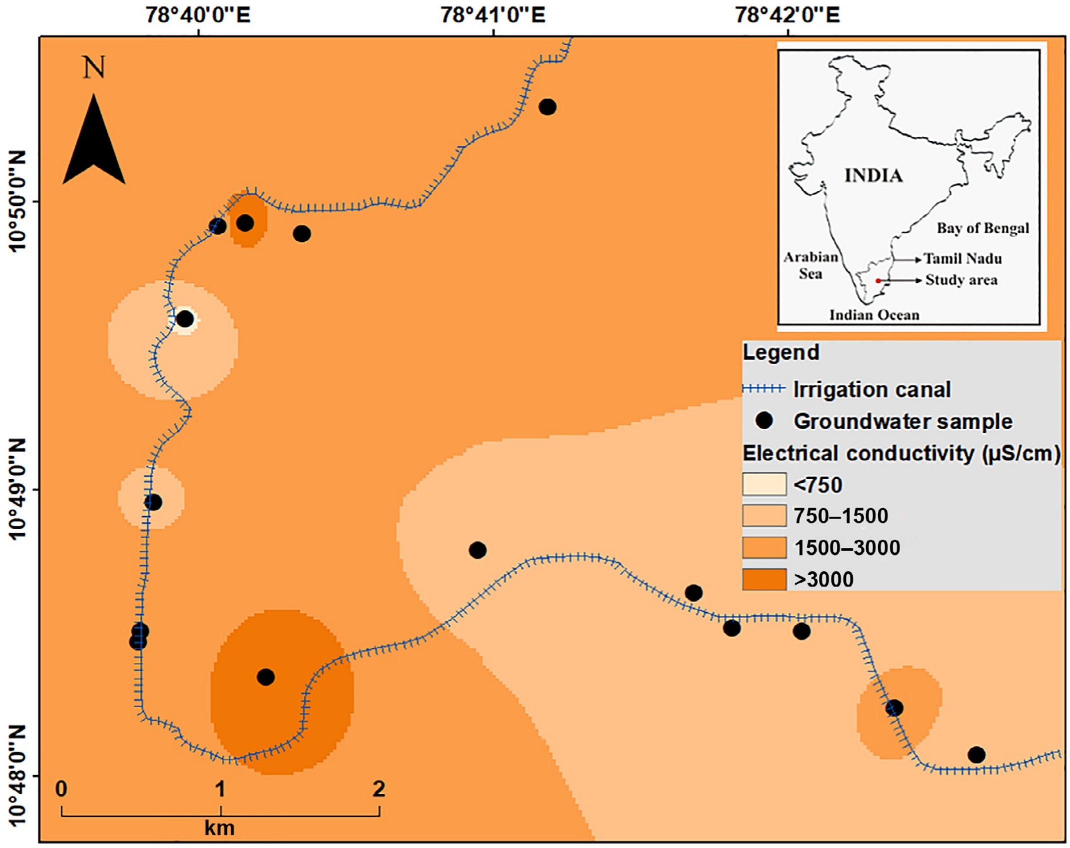


**FIG. 13.5** Location of study area and spatial variation in electrical conductivity of groundwater.

The EC of groundwater varied from 630 to 4500 μS/cm. An EC of <750 μS/cm is suitable, from 750 to 1500 μS/cm is permissible, 1500 to 3000 μS/cm is not permissible, and > 3000 μS/cm is hazardous for drinking. Two samples were hazardous, and the extent of pollution is given in Fig. 13.5. The order of dominance of cations was $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and anions was $Cl^- > SO_4^{2-}$. Sodium chloride was the dominant groundwater type. A comparison of cation and anion concentrations in groundwater with national and international drinking water standards (BIS, 2012; WHO, 1993) indicated a varied number of samples exceeding the permissible limit for each parameter: two locations for calcium, 14 locations for sodium, four locations for potassium, and one location for chloride. Magnesium and sulphate were within the permissible limits for drinking water. This type of classification of results for individual parameters makes it difficult to opt for a suitable management option in an area.

To overcome this, an overlay and index method was adopted for the preparation of a groundwater quality map based on all the parameters. Spatial maps for each parameter were prepared using the inverse distance weighted method, a widely used method for spatial interpolation. Suitable and unsuitable groundwater quality areas for drinking were classified based on the standards. A rank was assigned for the suitable and unsuitable range of measured ion concentrations. The groundwater quality map was arrived at by adding up the ranks of all of the parameters. A detailed description of the steps involved was reported by Brindha and Elango (2012b). Spatial variation in the concentration of various parameters (Fig. 13.6) shows common areas of groundwater contamination. The integrated groundwater quality map shows that groundwater is suitable for drinking purposes in <1 $km^2$ of the study area, poor in 32 $km^2$, and very poor in 5 $km^2$ (Fig. 13.7). Interpolation studies indicate 12 locations where groundwater is unsuitable whereas a previous study reported that groundwater was unsuitable in only six locations (Brindha and Kavitha, 2015). The underestimation was because WQI informs on the quality of the sampled location and does not take into consideration the interaction between the adjacent locations. Groundwater should be avoided for drinking use as demarcated in Fig. 13.7, which also highlights the areas where pollution sources may be introduced into the canal ("very poor" areas in Fig. 13.7) and subsequently into groundwater. However, an on-site field investigation is necessary to confirm this. The present study stresses the importance of cleaning the canal and the implementation of measures to prevent the dumping of waste and sewage into the canal.

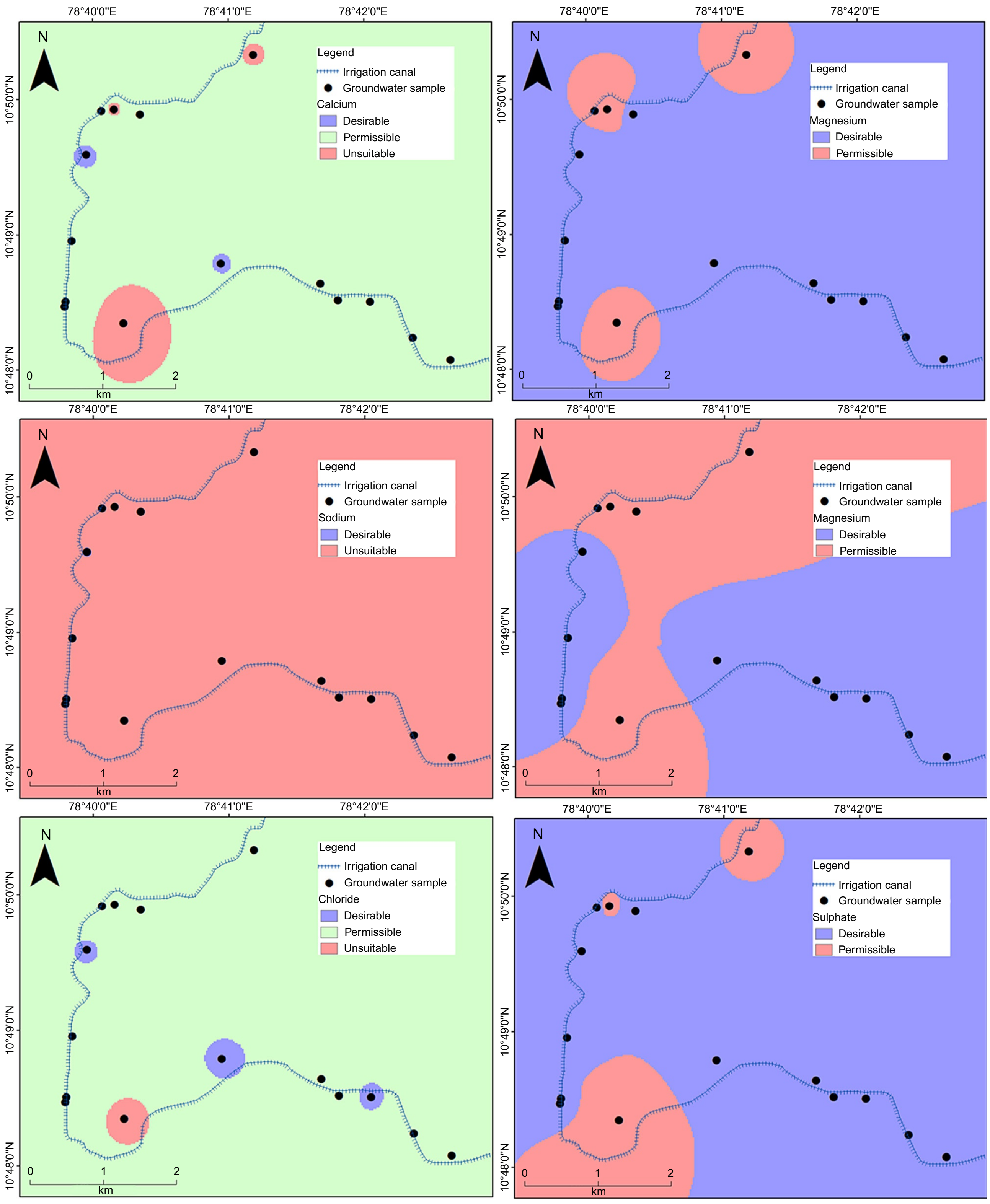


**FIG. 13.6** Spatial variation in the concentration of various parameters in groundwater.

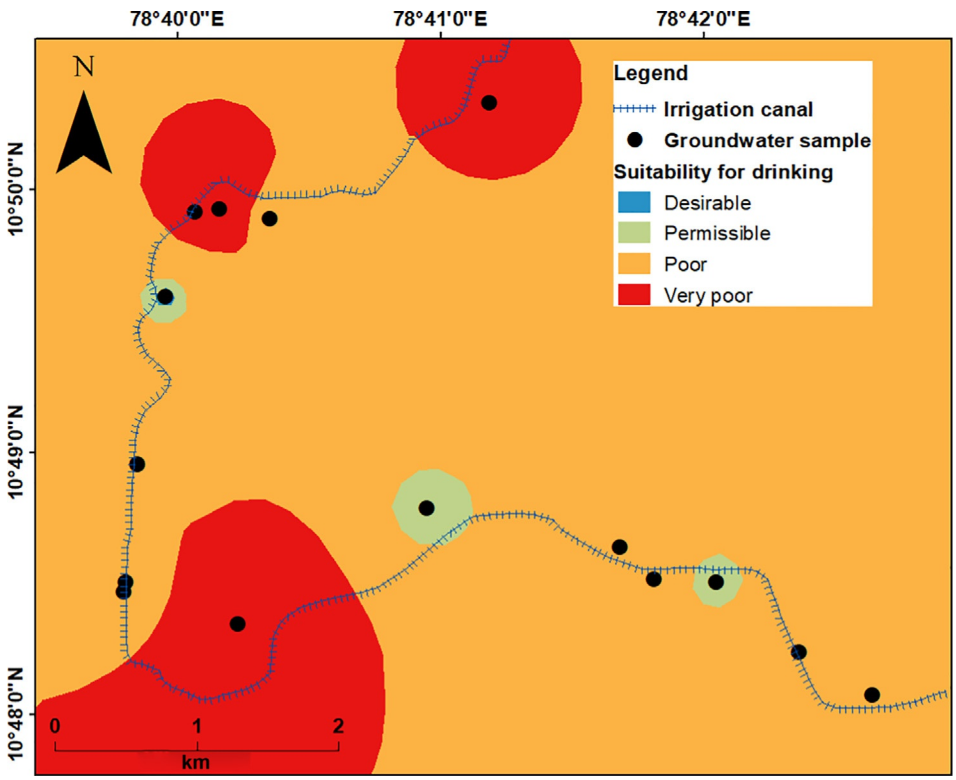


**FIG. 13.7** Groundwater quality map indicating areas suitable and unsuitable for drinking use.

## 13.4 SUMMARY AND RECOMMENDATIONS

Groundwater contamination is a serious problem in many urban areas. Due to multiple pollutants and sources, the management of the resource is usually complex and challenging. With industrialization and urbanization a variety of new pollutants (emerging contaminants) have been discovered, and it is necessary for the municipal wastewater treatments systems to be consistently updated to remove the pollutants, before disposing of the treated wastewater into surface water bodies. Industries should adopt alternate technologies, where possible, by substituting highly toxic with less toxic chemicals and reducing the use of hazardous substances. Protection of the groundwater resource should not be considered as a stand-alone task and an integrated management of groundwater, surface water, and soil resources must be aimed for. All planning operations and polices developed should be coordinated with other policies on management of solid waste, land use, industrial wastewater disposal, etc. Regular monitoring is necessary to keep the pollution under control. Closing the urban water cycle by recycling and reusing wastewater can significantly reduce the excessive extraction of groundwater. Additionally, after appropriate treatment, recycled wastewater can be artificially recharged. Management of these resources must not be restricted to the administrative boundaries of the cities but should include the suburban areas, which are constantly being urbanized. Stringent policies and pollution penalties are required to motivate the rational use of water.

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