GeoJournal (2020) 85:1151–1174
https://doi.org/10.1007/s10708-019-10015-3

Analysing water-borne diseases susceptibility in Kolkata Municipal Corporation using WQI and GIS based Kriging interpolation

Sk Ajim Ali · Ateeque Ahmad

Published online: 7 May 2019

Abstract The varieties of water-borne disease are caused by pathogens transmitted and spread by different routes. The spread of such infection increases while the water quality affected by external sources. Changes in the quality of water can influence the dynamics of microbial pathogens which can also influence the prevalence and transmission dynamics of water-borne diseases. The present study highlighted on selected chemical parameters of ground water to signify the water quality index and mapping of water-borne diseases susceptibility areas in Kolkata Municipal Corporation, India. The main objective of present study was to demonstrate the significance of geographical information system based Geostatistical technique for identifying water-borne diseases susceptibility by taking different ground water parameters, water quality index and reported water-borne diseases into consideration. Using Kriging interpolation, the spatial map of water parameters, water quality index and reported disease cases were prepared and reclassified by putting risk rank to generate susceptibility map of water-borne diseases. The accuracy of the result was assessed through error estimation and spatial autocorrelation. The result from error estimation, it was found that the root mean square error between diseases susceptibility and selected chemical parameters, water quality index and reported water-borne diseases are 0.0847, 0.1182 and 0.0640 respectively which is always < 1. The correlation of diseases susceptibility with chemical parameters has resulted highly positive ($r^2 = 0.97$) and with water quality index has also resulted positive ($r^2 = 0.82$). The study result also suggests the applicability of geographical information system in other types of diseases susceptibility analysis by setting proper objectives and selecting suitable study criteria with spatial justification.

Keywords Ground water · Chemical parameters · Water quality index · Kriging interpolation · Water-borne diseases · Susceptible areas

S. A. Ali (✉) · A. Ahmad
Department of Geography, Faculty of Science, Aligarh Muslim University, Aligarh, U.P. 202002, India
e-mail: skajimali.saa@gmail.com;
skajimali@myamu.ac.in

Introduction

Water contamination is a very common problem throughout the world (Fawell and Nieuwenhuijsen 2003). Poor water quality causes different health problems. Contaminations of water are directly or indirectly occurred due to anthropogenic activities. In developed countries the problems of water contamination is due to chemical exposure, whereas in developing countries it occurs from agricultural sources (Sharma and Bhattacharya 2017).

Contaminants are different types, mainly come from man-made by-products agriculture and industry, like insecticides, herbicides, pesticides, chemical fertilizers, heavy metals like mercury, copper, chromium, lead, and hazardous chemicals (Ashbolt 2004; Fawell et al. 2006). Disposing of household chemicals wastes like oils, medicines, antiseptics, pool chemicals, insecticides, paints, solvents, batteries, gasoline and diesel fuel can also lead to ground water contamination and severe health problems (Anwar 2003; Kass et al. 2005). Not only anthropogenic activities, sometimes contaminant also occurred through natural process. The ground water moves and infiltrates through pores of sedimentary rocks and different soils may mixed up with various natural compounds, like iron, nitrate, fluoride, chloride, arsenic, magnesium, calcium zinc etc. and therefore high concentration or undesirable level of these naturally occurred components can contaminate the ground water as well, the intake of which causes severe health risk (Mulligan et al. 2001; Rukah and Alsokhny 2004; Charles et al. 2005; Liu et al. 2005; Meenakshi and Maheshwari 2006; Ghrefat et al. 2014).

Water-borne disease (WBD) is termed as infectious disease that spread by pathogenic microorganisms which may mostly transmitted in contaminated water, whether in bathing, washing, drinking, or in the preparation of food (Devipriya and Kalaivani 2012). With giving emphasize on human health, the severe impacts of water-borne diseases are due to lack of improved sanitation facility which directly or indirectly leads to lack of safe drinking water, which currently affects more than one-third of the global population (Ashbolt 2004; Schwarzenbach et al. 2006; Batterman et al. 2009; Devipriya and Kalaivani 2012). The fresh water is really necessity for our good health. But with the development of technology and industrial advancement, fresh water resources throughout the world are threatened with susceptible causes to human health (Chatterjee et al. 1995; Ashbolt 2004; Charles et al. 2005; Bhattacharya 2006; Elimelech 2006). More recently it is estimated that 1/3 of Earth's accessible renewable fresh water is consumptively used for agricultural, industrial and domestic purpose which are considered as major reason for fresh water contamination and causes of more than 2.2 million death per year, out of which about 1.4 million Childrens (Bitton 2014; Ramírez-Castillo et al. 2015; WHO 2015). The water-related diseases can be classified into four categories; i.e. water-borne diseases, water-washed diseases, water-based diseases and water-related diseases (Eisenberg et al. 2001). Water-washed diseases are infections that are caused by poor personal hygiene resulting from insufficient water availability. Water-washed diseases include Shigella, which causes dysentery, scabies, trachoma, yaws, conjunctivitis, skin infections and ulcers. Scabies is a highly contagious skin infection. Waterborne diseases are caused by pathogenic bacteria and microorganisms that are transmitted by water. Disease can be spread while bathing, washing or drinking such water, or by eating food exposed to infected water. Water-borne diseases including cholera, typhoid and dysentery are caused by drinking water containing infectious viruses or bacteria, which often come from human or animal waste (Cesa et al. 2016).

Water-borne pathogens and associated diseases are a major concern on public health (Ramírez-Castillo et al. 2015). Water-borne diseases including diarrhea, cholera, gastrointestinal diseases and other illnesses causes death every day (WHO 2015). Diarrhoea is one of the major public health problems that directly related to water and sanitation. More than 4 billion cases of diarrhoea per year cause 1.8 million deaths, over 90% of them (about 1.6 million) are children under five. Cholera is a serious bacterial infection of the intestinal tract that outbreaks due to unsafe drinking water, improper sanitation and poor hygiene behaviour which causes more than 120,000 reported cholera cases world-wide (UNICEF 2019). Typhoid fever also caused by consumption of contaminated food or water. More than 12 million people are affected by typhoid every year. Trachoma is an eye infection also caused by lack of adequate water supplies and poor sanitation conditions. Report tells that about 6 million people are blind today because of trachoma (UNICEF 2019).

As far as the study area i.e. Kolkata Municipal Corporation (KMC) is concerned, it was found that several residents report about the outbreak of diarrhea during last year due to contamination of the drinking water supplied by municipal authority. Reporting symptoms of the disease came from the adjoining areas of Jadavpur, like Dhakuria and Haltu. About 10 wards of the KMC in the southern and eastern parts of the city have been affected and about 1150 cases reported with diarrhoea (Chakraborty 2018). In case of Kolkata, cholera is changing epidemiologically. The city faced several outbreaks of cholera in different time of the year with peek cases during summer season. A recent combined study on ‘prevalence of cholera in cities of seven developing countries’ has found that Kolkata is the second highest occurrence of such disease. Epidemiologists say that most diarrhoea cases in the city are caused by cholera. There are positive correlation exists between water-borne diseases occurrence and heavy rainfall. Cases of diarrhoea and typhoid have been reported from waterlogged areas in KMC. Recently, southern fringes of the city have been struck with water-borne diseases like diarrhoea and typhoid fever. Out of various types of water-borne diseases found throughout the globe like diarrhea, typhoid fever, cholera, Skin infections, Hepatitis A or E, scabies, trachoma, Conjunctivitis/ear infections, dysentery, yaws, skin infections etc. diarrhea, typhoid and cholera are more common in KMC.

In order to lessen the burden of water-borne diseases, optimal control for transmission of water-borne diseases and active participation of all stakeholders are essential (Devipriya and Kalaivani 2012). Among different diseases control measures, diseases risk zonation and susceptibility assessment can offers efficacy results for better surveillance and control accordingly. Potential diseases risk areas can be detected using remote sensing and GIS techniques that would otherwise be difficult to detect using traditional methods (Gupta and Shriram 2004). Literatures survey proves the applicability and effectiveness of GIS techniques in public health and diseases zonation assessment. GIS was used for identifying the geographical location and distribution of various diseases (Moonan et al. 2004; Bessong et al. 2009; Dhama et al. 2013; George et al. 2013), mapping of risk zonation and stratify risk factors (Daniel et al. 2004; Sarkar et al. 2007; Danson et al. 2008; Mourits et al. 2010; Tu et al. 2014; Qayum et al. 2015; Nazri et al. 2016; Ahmad et al. 2017; Wondim et al. 2017; Ali and Ahmad 2018; Ali and Ahmad 2019a, b), forecasting epidemics (Castronovo et al. 2009; Bergquist and Rinaldi 2010; Eisen and Eisen 2011; DeGrootem et al. 2012; Aimone et al. 2013), Monitoring diseases and developing surveillance strategies (Sanson et al. 1991; Briggs and Elliott 1995; Norstrom 2001; Sipe and Dale 2003; Reinhardt et al. 2008), utilization of health centres and diseases monitoring (Rushton 2003; Mourits et al. 2010; Li et al. 2012), service locations and route optimization to supplies equipments and service and trace the nearest health facility (McKee et al. 2000; Rushton 2003). Control and awareness programs can also be focused toward these areas with more confidence and effectiveness. Hence, it is very urgent to identify the susceptible zones of diseases and prepare surveillance strategies accordingly.

Therefore, geographical information system (GIS) serves as a common tool for merging of multi-disease surveillance activities. Public health resources, specific diseases and other health events can be mapped in relation to their surrounding environment and existing health and social infrastructures. Spatial informations when mapping together, create a potent tool for monitoring and supervision of epidemics. Thus, the main objective of this study was to identify susceptible areas of water-borne diseases. To reach such objective, GIS based Geo-statistical technique (i.e. Kriging interpolation) was applied to properly identify the diseases risk areas using chemical parameters of water and water quality index (WQI) of selected sampled points throughout the study area.

The work done so far

There always a significant relation exists among urban growth, water availability and the problems of water quality in any city. The excessive uses can degrade the quality of water and causes of various water associated diseases. To eradicate such problems of water crisis, the cities can able to treat wasted and used water before distributing to urban users but the treatment and management cost are the major concern faced by major cities especially in developing countries (McDonald et al. 2011). Major threat appears in ground water contamination and water associated problems, when ground water use exceeds the rates of aquifer recharge, as the result ground water table is dropping and contamination rate rising which is main concern to public health. Research result found that ground water is falling about 40 cm/year in some areas of Mexico City (Carrera-Hernandez and Gaskin 2007), since 1980 the water table has fallen 1 m/year in Beijing city (Zhang and Kennedy 2006). The cases are not different in India also. The Central Ground Water Board (CGWB), Govt. of India stated that 56% of well in India has recently declined compare to last 10 years (Ground Water Yearbook 2014). Unchecked urbanisation has only added to the disorder.

Construction is driving groundwater extraction in metropolitan cities which have brought to the brink of a water crisis and many health issues (Lal 2014). Areas neighbouring National Capital Region including Noida and Goutam Budh Nagar, the situation is serious where water level has been decreasing from 0.5 to 2 m per year (Bhowmick 2018). Recently major areas of Kolkata Municipal Corporation (KMC) are facing the same problem of water deficit. Study result revealed that in Kolkata since 2017, ground water level dropped about 14–16 m below ground in Alipore, Ballygunge, Kalighat, Park Circus and Babughat, about 9–11 m in Bansdroni and about 8–9 m in Garia (Gupta 2018). Different studies have been carried out in order to assess the possible impact of such issues and recommend safe strategies for wellbeing environment and good health.

Asadi et al. (2007) attempted to identify suitable zones of water quality index (WQI) using remote sensing and GIS techniques. The study result showed great efficacy of GIS application in monitoring ground water quality in relation to land use and land cover and identified WQI based suitability of water zones for drinking purpose.

Huang et al. (2013) studied to correlate land use types and their impact on water quality using water quality monitoring parameters and remote sensing data. The result showed that there was significant negative correlation between forest land and grassland on water pollution and the built-up area had negative impacts on water quality which indicated healthy vegetated and natural environment has well for water quality and concomitantly dense built-up areas impacted the water quality.

Mohsin et al. (2013) highlighted on drinking water quality and its impact on resident's health based on selected physical and chemical parameters of ground water. The study revealed that EC, TDS, hardness, pH etc. in high concentration and above WHO permissible limits leads to poor water quality and reason of severe water-borne diseases like diarrhea, typhoid, cholera etc.

Yan et al. (2015) emphasized that the identification of water polluted susceptible and risk areas are more important than that of assessment and investigation of water quality and pollution factors. To reach such objective, the Geo-statistical technique and geographical information system (GIS) can be used to visualize the spatial pollution characteristics and identifying potential polluted risky regions with spatial analysis of water parameters like dissolved oxygen (DO), total nitrogen (TN), total phosphorus (TP), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N) and ammonia nitrogen (NH_3-N).

There are various techniques that widely used in assessment of water quality like analytic hierarchy process, complex pollution indices, fuzzy evaluation, Fuzzy quantifying assessment, single factor pollution index, gray evaluation, principal component analysis, artificial neural network, water quality index etc. (Ouyang 2005; Xu 2005; Jiang et al. 2006; Li et al. 2007; Pang et al. 2008; Shankar and Sanjeev 2008; Meng et al. 2009; Yao et al. 2009; Liu et al. 2010). But all these methods have a common limitation with spatial discontinuity of sampling data which cannot offers to identify susceptible and vulnerable regions resulted from polluted surroundings (Yan et al. 2015). This problem can be overcome through the application of GIS technique which provides powerful tool for handling spatial data and performing spatial analysis (Vairavamoorthy et al. 2007). The unique application of GIS is the Geo-statistical analysis and spatial interpolation which help for measuring samples with known values to estimate unknown values to show the spatial pattern of features (Facchinelli et al. 2001). GIS technique and modelling have been used in susceptible analysis and studies related environmental contamination (Ahearn et al. 2005; Chang and Carlson2005; Donohue et al. 2006; Chang 2008; Wan and Wang 2013; Jasmin and Mallikarjuna 2014).

The groundwater quality parameters like chloride (Cl^-), fluoride (F^-), nitrate (NO_3^-), sulphate (SO_4^{2-}), alkalinity, calcium (Ca^{2+}), magnesium (Mg^{2+}), bicarbonate (HCO_3^-) pH, total dissolved solid (TDS), total hardness (TH) etc. can be analysed and GIS based geostatistical (Kriging) technique can be used for susceptibility mapping of water quality index for knowing the suitability of drinking purpose (Tiwari et al. 2014; Yan et al. 2015; Gharbia et al. 2016; Yadav et al. 2018). Different studies have been carried out for mapping of water-borne diseases in association with water quality parameters (McKee et al. 2000; Ashbolt 2004; Daniel et al. 2004; Gupta and Shriram 2004; Moonan et al. 2004; Sarkar et al. 2007; Danson et al. 2008; Castronovo et al. 2009; Li et al. 2012; Aimone et al. 2013; Dhama et al. 2013; George et al. 2013; Devendra et al. 2014; Ghrefat et al. 2014; Tu et al. 2014; Al-Omran et al. 2015).

It was found during literature survey that major studies emphasized on either GIS based zonation of water quality index or identification of suitable areas of water for drinking purpose (Asadi et al. 2007; Vairavamoorthy et al. 2007; Shankar and Sanjeev 2008; Ramakrishnaiah et al. 2009; Mohsin et al. 2013; Devendra et al. 2014; Tiwari et al. 2014; Gharbia et al. 2016; Yadav et al. 2018). On the other hand, many studies highlighted on application of GIS and spatial analysis for evaluating susceptible zonation of vector-borne diseases or water-borne diseases (Daniel et al. 2004; Moonan et al. 2004; Sarkar et al. 2007; Bessong et al. 2009; Eisen and Eisen 2011; DeGrootem et al. 2012; Li et al. 2012; Aimone et al. 2013; Dhama et al. 2013; George et al. 2013; Tu et al. 2014; Qayum et al. 2015; Ahmad et al. 2017; Ali and Ahmad 2018; Ali and Ahmad 2019a, b). Looking towards the gap, effort was done in the present study to integrate GIS and Geo-statistical method for analysing water-borne diseases susceptible zonation by inter-linking with zonation of water quality index (WQI).

Study area

Kolkata is a typical riverine city located on the east bank of river Hooghly. Kolkata, the capital of Indian state West Bengal is one of the four metropolitan cities of India. It was once surrounded by marshes, tidal creeks, mangroves, swamps and wetlands, but all of these features are now rarely found and have changed with time due to rapid urbanization. Many parts of the city were once under wetland which was reclaimed to house the bourgeoning population. Kolkata Municipal Corporation (KMC) is the largest urban agglomeration of West Bengal state of India (Fig. 1). With an area of 205.07 km^2, KMC is divided into 144 administrative wards under 16 Borough. The average elevation of the city is estimated about 1.5–16 m above MSL. The Monthly mean temperature ranges between 19 and 32 °C. Summers are hot and humid with average temperature 34 °C, and winter with lowest temperature between 9 and 11 °C. The annual mean rainfall is recorded about 1600 mm, but highest rainfall records during the month of July and August. According to latest demographic data (District Statistical Handbook 2014–15), KMC has 44, 96,694 population with population density of 24,306 person/km^2. The data also reveals that KMC is the place of 1,024,928 households with an average density of 755–23,237 households/km^2. In term of population and household density it is observed and calculated that some wards like 26, 23, 62, 134, 18, 41, 19 and 54, where more than 100,000 populations reside. The Sex ratio of KMC is 910 as per latest Census. Here, the literacy rate is 87.14% which is much higher than the national average (74% all India). Kolkata is getting little less dense in compare to last decade. The census data (2011) showed that every new resident of the Kolkata urban area was added in the suburbs. The central city of Kolkata remains very dense still but its population fell from 4,573,000 people in 2001 to 4,487,000 people in 2011. It was estimated that Kolkata, with Gross Domestic Product (GDP) of 150 billion dollars making 3rd rank among South Asian cities just after Mumbai and Delhi. In 2015, The Brookings Institution, a U.S. based think tank in collaboration with JP Morgan ranked Kolkata 2nd among all Indian metros. The economy of Kolkata, to some extent depends on the informal industrial sectors like furniture making, electrical wing, leather works etc. Major portions of the slum population and lower economic class participate in the informal sector of economy. Many environmental issues are repeatedly seen here, including air pollution, water contamination, issues with proper waste management and outbreak of different types of vector-borne and water-borne diseases.

Database and methodology

Looking towards the objective, different steps was followed for identifying susceptible areas of water-borne diseases. Initially, relevant chemical parameters of water were chosen which are more responsible to carry and transmit the water-borne diseases. Then, sampling points were marked and GPS based coordinates were recorded for spatial mapping using ‘x’ ‘y’ input data. Next, interpolation method was run as a part of Geo-statistical technique to know the spatial variation of such chemical parameters. Then, water quality index (WQI) was calculated and spatial map of WQI was prepared and finally, effort was done to signify how far the water-borne diseases affected areas are correlated with poor water quality index zones, to verify the result of present study.

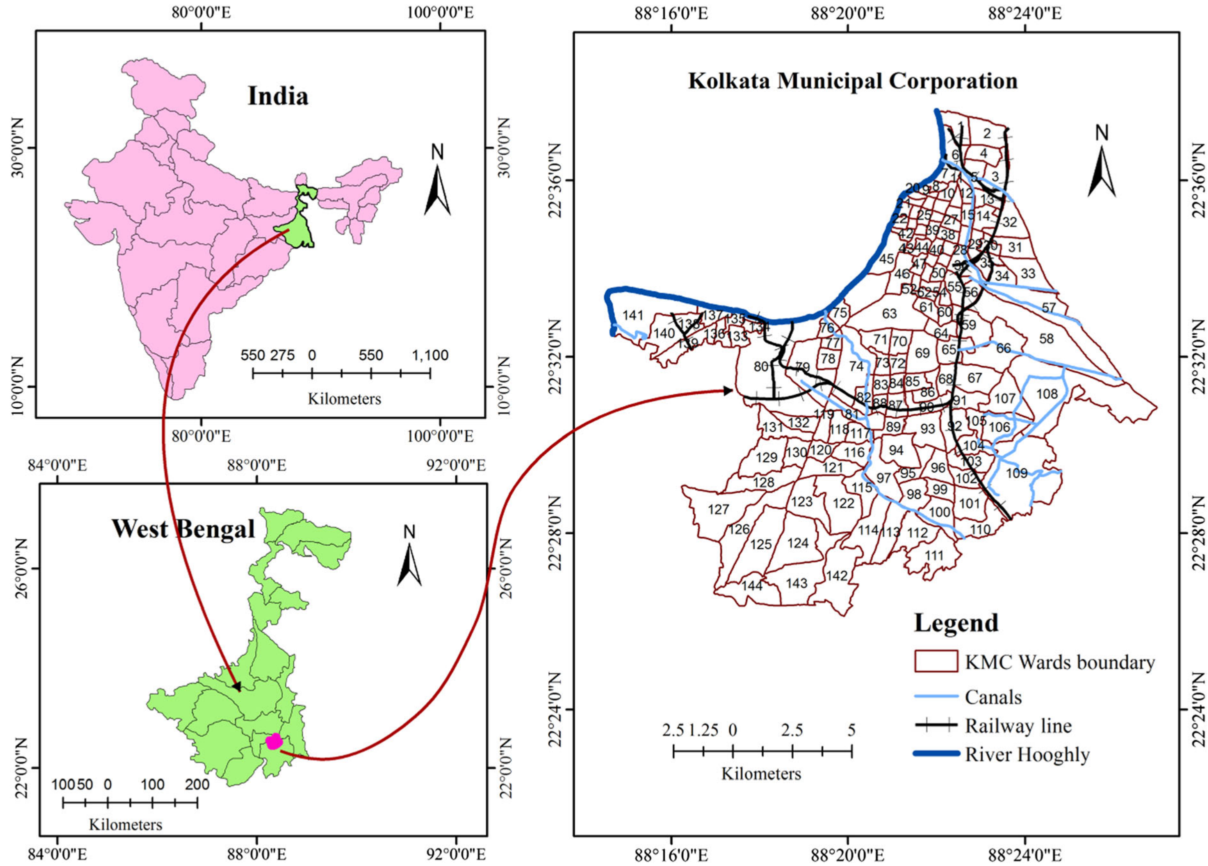


Fig. 1 Location map of the study area

Selection of chemical parameters

Naturally, many chemical compounds are found in ground water including Aldrin, Ammonia-N, Arsenic, BOD, Boron, Cadmium, Calcium, Chloride, Chromium total, COD, Conductivity, Copper, Fluoride, Iron, Lead, Magnesium, Mercury, Nickel, Nitrate N, pH, Potassium, sodium, Total coliform, TDS, TSS, turbidity, zinc, etc. Out of these parameters, some were selected based on literature survey and previous study findings which have significant role in water-borne diseases occurrence. The selected chemical parameters were Arsenic, Ammonia-N, Chloride, Fluoride, Nitrate-N, pH, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Turbidity and Zinc.

Arsenic is classified as a metalloid, inhalation of inorganic arsenic cause lung cancer in smelter workers (Enterline et al. 1987). Arsenic also share a peculiar property in that each may cause lung cancer following ingestion via drinking water (Smith and Steinmaus 2009). The most common reason for long-term exposure of arsenic is contaminated drinking water. Long-term exposure of arsenic can result in darker skin (black spot), stomach pain, diarrheal disease, heart disease, shock and cancer also. It is said that the *Ammonia* molecule is a nutrient vital for life, but excessive ammonia accumulation in organism may cause alteration of metabolism or increases in body pH. Contaminated concentrations of ammonia in humans may cause loss of stability, convulsions, unconsciousness, and death also.

Indication of general increase in *chloride* concentrations in groundwater and drinking-water has been found (WHO 1978). Chloride levels in unpolluted waters are often below 10 mg/litre and sometimes below 1 mg/litre, but above acceptable limit and prolonged ingestion of large amounts considered as harmful (Department of National Health and Welfare 1987). The outbreaks of water-borne diseases caused by a variety of water contaminants, but some few in particular are main concern. Among many other contaminants, *coliform* straining and emerging pathogens in drinking water which transmits water-borne diseases like cholera, typhoid fever and bacillary dysentery (Cabral 2010; Dore 2015).

Ingestion of excess *fluoride* can cause of fluorosis which affects the teeth and bones. The most common reason for long-term exposure is contaminated drinking water with high levels of fluoride. Moderate amounts can cause to dental problems, but long-term ingestion of large amounts can cause to potentially severe skeletal problems (WHO 1993). Unexpectedly, low amounts of fluoride intake benefit to prevent dental caries (WHO 1996a, b). *Nitrate* is one of the common groundwater pollutants in rural areas. Excessive levels of Nitrate can cause 'blue baby' disease. Blue baby syndrome can also be caused by nitrates in drinking water leading to methemoglobinemia (Fewtrel 2004). Usually pH (power of hydrogen) has no direct impact on water consumers; it is one of the essential operational water-quality parameters. But exposure to extreme pH values caused irritation to the eyes and mucous skins. Eye irritation and exacerbation of skin disorders have been related with pH values more than 11.

Total dissolved solids (TDS) is the term used to define the inorganic salts and small amounts of organic matter present in water. Early studies found inverse relationships between TDS concentrations in drinking water and the incidence of cancer (Burton and Cornhill 1977), coronary heart disease (Schroeder 1960), arteriosclerotic heart disease (Schroeder 1966), and cardiovascular disease (Sauer 1974; Craun and McGabe 1975). Total mortality rates were reported to be inversely correlated with TDS levels in drinking-water (Crawford et al. 1968; Craun and McGabe 1975). *Total Suspended Solids* in water may include silt, decomposing plant and animal matter, industrial wastes, and sewage. High proportions of suspended solids in water can cause many problems. Excessive suspended solids are often related with higher levels of disease-causing microorganisms such as germs, parasites and some bacteria, which can cause indications like nausea, cramps, diarrheal disease and associated headaches. *Turbidity* refers to cloudiness of water. Turbidity has no health effects, but can interfere with disinfection and provide a medium for microbial growth. Turbidity may indicate the presence of disease-causing organisms. *Zinc* is a vital nutrient for body growth and development, but above standard level can causes may health problems. Drinking water having high levels of zinc can lead to stomach cramps, nausea, vomiting and sometimes accompanied by bleeding and abdominal cramps (Elinder 1986; WHO 1996a, b).

Data source

The present study was based on both primary and secondary data sources. The secondary data includes chemical parameters of water. The above mentioned chemical parameters in water were collected from the central laboratory of West Bengal Pollution Control Board (http://www.wbpcb.gov.in/). There are total 8 ground water sampling points throughout Kolkata Municipal Corporation. These points were considered for collecting the water quality data (Fig. 2). It is a difficult task for any individual researcher to collect water from different tube well or any other source (i.e. bore hole) throughout the study area because from water collection to post-test processing in any private testing laboratory, is considered as time consuming and too much expensive. Sometimes, the results also become questionable. Hence, instead of collecting water from different tube well by personal survey, the study considered and used the data from Government sources (central laboratory of WBPCB) because these data are considered as authentic and accurate also.

Along with secondary data, a primary survey was also carried out throughout KMC in order to know the water-borne diseases profile. Stratified Random sampling was considered. Initially 16 Borough and 144 wards were taken, from which 3 wards were selected from each Borough based on their population density, and then 30 households from each ward were selected. Thus total 90 households were considered from each Borough. The primary survey was carried out only to know the status of diseases among sampled households and to validate the study result (Table 1).

Sample collection for water quality analysis

It was found from many literatures that dry and wet season is more susceptible to water-borne diseases (Davies et al. 2015). Flooding and drought condition have potential influence on water-borne diseases, mainly the diarrhoeal disease because flood and

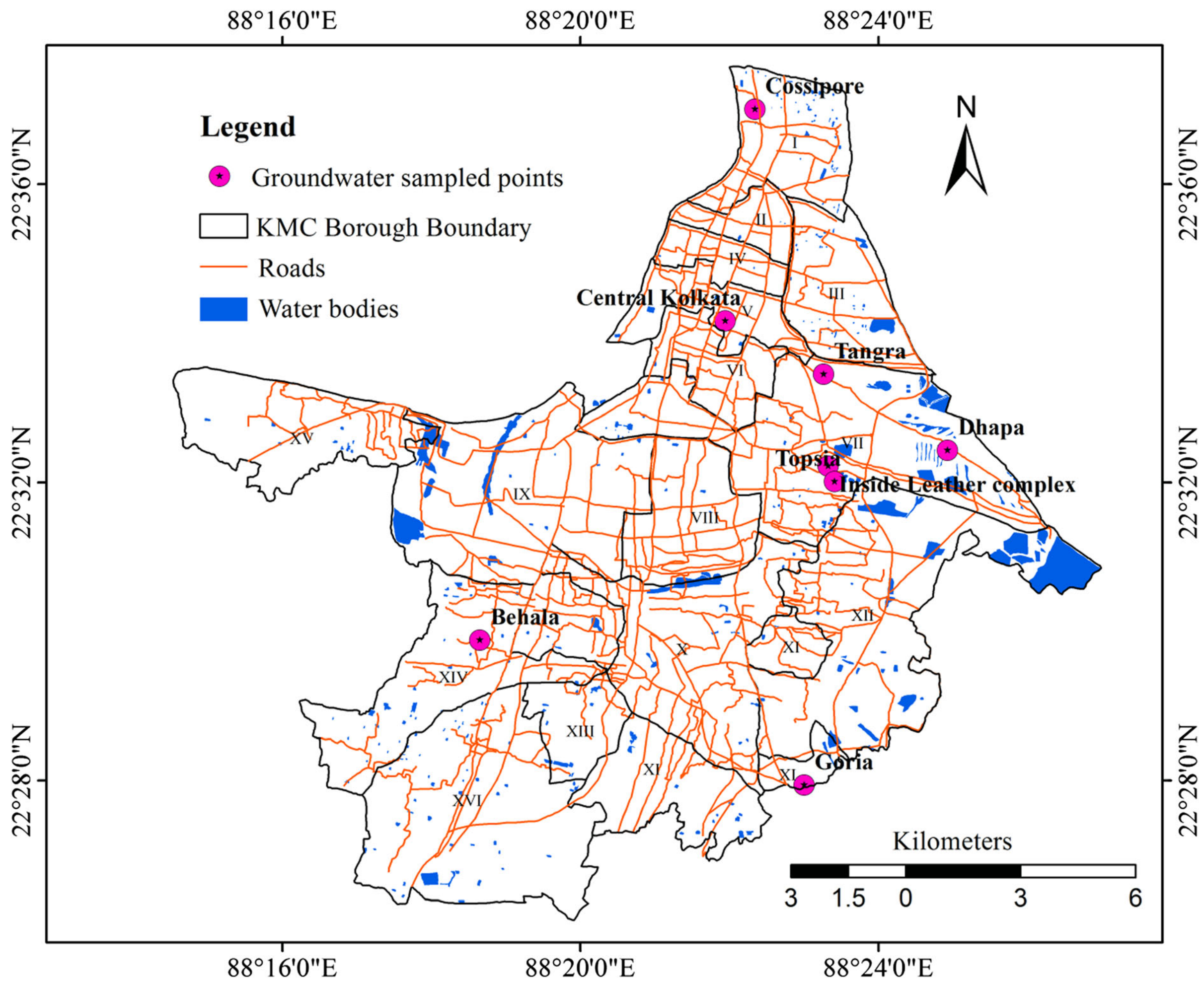


Fig. 2 Location of sampled sites showing eight ground water collection stations of West Bengal Pollution Control Board (WBPCB)

drought make huge changes in water quality and lead to transmit water related diseases (Haines et al. 2006). Extreme weather condition and climate change are also two chief drivers of water-borne diseases (Gentry-Shields and Bartram 2014).

From the primary field survey, it was also found that the outbreaks of diarrhoeal disease was after heavy rainfall and in those areas suffered in water logged since many days. Therefore, it is required to select relevant time for collecting sampled data. Considering published research findings, the water samples of dry season were considered in present study for analysis. The following table depicts the details of sample data that were considered for the further analysis (Table 2).

Kriging interpolation for spatial mapping

Interpolation is a technique through which unknown values can be predicted or estimated from some points of known values. Interpolation techniques are very useful, if availability of data is limited or have to predict treated landscape phenomena (Setianto and Triandin 2013). The main principles of interpolation techniques are autocorrelation which help in assuming that objects adjacent together are more similar than objects far apart. But in case of gap, the boundaries of the interpolated area, extrapolation is also rational. No interpolation technique can be considered as universal for all types of data. Thus, it is essential to aware about the different interpolation methods because different interpolation method on the same data sources lead to

Table 1 Showing the details of household sampling and status of water-borne diseases

Selection of sampled wards			Persons effected with WBDs (per household)			
Wards selected	Population density	Borough no.	1	1–3	3–5	Total
9, 1, 7	59,839, 44,025, 30,391	I	32	13	3	48
18, 20, 15	109,366, 88,607, 51,467	II	29	9	2	40
29, 13, 31	102,794, 50,839, 34,584	III	45	15	10	70
23, 24, 22	124,614, 103,411, 55,096	IV	33	16	2	51
41, 37, 36	106,492, 90,063, 22,368	V	28	19	6	53
62, 53, 55	111,355, 86,743, 35,762	VI	31	14	9	54
56, 59, 57	74,529, 39,959, 12,911	VII	41	23	21	85
88, 83, 69	54,847, 42,711, 23,530	VIII	36	16	14	66
77, 76, 74	93,730, 44,077, 12,486	IX	41	14	9	64
91, 89, 100	38,461, 32,235, 16,167	X	33	12	8	53
104, 103, 110	33,281, 21,339, 15,817	XI	39	11	12	62
107, 101, 108	24,729, 24,424, 18,646	XII	38	23	19	80
117, 119, 122	29,551, 26,398, 13,186	XIII	34	16	10	60
132, 131, 127	28,834, 22,602, 11,128	XIV	25	12	5	42
134, 133, 140	109,990, 42,703, 17,998	XV	38	17	7	62
123, 125, 126	16,706, 12,554, 9769	XVI	27	10	3	40

(1) The wards are sequenced from high to low population density. (2) Water-borne diseases include Diarrhea, Cholera, Typhoid, Scabies, ring worm, impetigo, wounds and other skin disease (3) Total is out of total 90 household from each Borough

Table 2 Ground water sampled data along with location of sampled stations and geographic coordinates

CPCB station code	Station name	Sample date	Latitude and longitude	Human activities
1777	Behala	18-04-2018	22°29′52.98″N and 88°18′39.07″E	Drinking and domestic
1932	Central Kolkata	10-04-2018	22°34′10.13″N and 88°21′56.63″E	Drinking and domestic
1931	Cossipore (N. Kolkata)	10-04-2018	22°37′0.42″N and 88°22′20.58″E	Drinking and domestic
1775	Dhapa	10-04-2018	22°32′25.91″N and 88°24′55.70″E	Bathing and washing
1776	Goria	11-04-2018	22°27′56.45″N and 88°23′0.26″E	Bathing and washing
1935	Inside leather complex	12-04-2018	22°32′13.20″N and 88°23′19.59″E	Drinking and domestic
1773	Tangra	10-04-2018	22°33′27.05″N and 88°23′15.76″E	Drinking and domestic
1774	Topsia	11-04-2018	22°32′0.77″N and 88°23′24.73″E	Bathing and washing

different results (Setianto and Triandin 2013). Among different types of interpolation technique, Kriging interpolation technique was used looking toward its special efficacy.

The most commonly used interpolation method is inverse distance weighting (IDW) method; it determines cell values using a linearly weighted combination of a set of sample points, where weight is a function of inverse distance. IDW assumes the degree of correlations and connections between neighbours is directly proportional to the distance between them which is known as a distance reverse function of every point from neighbouring points (Setianto and Triandin 2013). Basically, IDW will be used where the number of sample points is enough, i.e. at least 14 points with a suitable dispersion in local scale levels (Burrough and McDonnell 1998). Along with, inverse distance weighted, another technique of interpolation is Spline. But these two tools are referred to as deterministic interpolation techniques because they are based on

Table 3 Standard of drinking water parameters along with undesirable effect outside the desirable limit

Parameters	Acceptable limit[a]	Permissible limit[b]	Method of test, Ref. to	Undesirable effect outside the desirable limit
Arsenic	0.01	0.05	IS 3025 (Part 37)	Beyond this, the water becomes toxic
Ammonia-N	0.5	No relaxation	IS 10500	May be carcinogenic above this limit
Chloride	250	1000	IS 3025 (Part 32)	Taste, corrosion and palatability are affected
Fluoride	1	1.5	IS 3025 (Part 60)	High fluoride may cause fluorosis
Nitrate-N	45	No relaxation	IS 3025 (Part 34)	–
pH	6.5–8.5	No relaxation	IS 3025 (Part 11)	Beyond this range the water will affect the mucous membrane and/or water supply system
Total dissolved solids (TDS)	500	2000	IS 3025 (Part 16)	Beyond this limit may cause Gastro intestinal irritation
Total suspended solids (TSS)	Shall not be detectable in any 100 ml sample	–	Indian Standard IS:1622	–
Turbidity	1	5	IS 3025 (Part 10)	Above 5.0, consumer acceptance decreases
Zinc	5	15	IS 3025 (Part 49)	It can cause astringent taste and an opalescence in water

–, undetermined

[a]Requirement

[b]Permissible limit in the absence of alternate source

proportionally surrounding measured values or on specified mathematical formulas that control the smoothness of the resulting surface.

But the interpolation with Kriging (ordinary Kriging), offers accuracy as it consists of Geo-statistical technique and it based on statistical models that comprise autocorrelation. Therefore, Kriging interpolation has not only the ability of producing a prediction surface but also offer accuracy of the predictions. Kriging assumes that the distance between sample points reveals a spatial correlation that can be used to explain variation in the surface. It offers estimation of unobserved location of variable z, based on the weighted average of nearby observed locations of an area (Lillesand et al. 2004). The general formula for kriging is formed as a weighted sum of the data at an unsampled site $z(s_0)$ is defined as;

$$Z(s_0) = \sum_{i=1}^{n} \lambda i z(s_i)$$

where $z(s_i)$ = the measured value at the ith location; λi = an unknown weight for the measured value at the ith location; s_0 = the prediction location, n = the number of measured values.

λ are the weights given to each of the observed samples. These weights sum to unity so that the predictor provides an unbiased estimation;

$$\sum_{i=1}^{n} \lambda i = 1$$

The weights are estimated using the matrix equation;

$$C = A^{-1} * b$$

where A = a matrix of semi-variances between the data points; b = a vector of estimated semi-variances between the data points and the points at which the variable z is to be predicted.; c = the resulting weights

The main tasks to make prediction surface with the Kriging interpolation technique, it is essential to uncover the dependency rules and make the

Fig. 3 Images of related issues in the study area that may consider as possible reasons which can affect the ground water quality and negative consequence on public health. *Note*: **a** Municipal worker cleaning sewerage from Ramnagar locality of Garden Reach, **b** sewerage cleaning points and drinking water tap within 10 m distance in Topsia, **c** a contamination source in Khiddirpore, **d** waste compactor station, the liquate waste directly mix with underground drainage after composting, **e** author in a compactor station at ward 77, borough IX, Mominpur road during primary survey, **f** drinking water supply by KMC to local resident, **g** Childs with diarrhoea in Baghajatin State General Hospital (taken from https://www.firstpost.com). **h** Adults with diarrhoea in Baghajatin State General Hospital (taken from https://m.dailyhunt.in/news). **i** People strike in front of KMC on claiming diarrhoea outbreak after drinking water supplied by KMC (taken from https://www.thehindu)

prediction. To do such, two-steps with Kriging have to follow;

1. It makes the variograms (Semivariogram) and covariance functions to approximate the statistical dependence (i.e. autocorrelation) values that depend on the model of autocorrelation and
2. It predicts the unknown values (i.e. making a prediction).

Water Quality Index (WQI) for analysing chemical parameters of water

In developing countries like India due to population increase and rapid urbanization, the availability and quality of groundwater has been affected. The ground water in urban areas commonly contaminated due overexploitation of water and improper waste disposal (Al-Omran et al. 2015). As per World Health Organization (WHO), about 80–85% of all the diseases in human beings are caused by water, specially ground water is major responsible for all types of water-borne diseases. Once the groundwater is polluted, its hard be

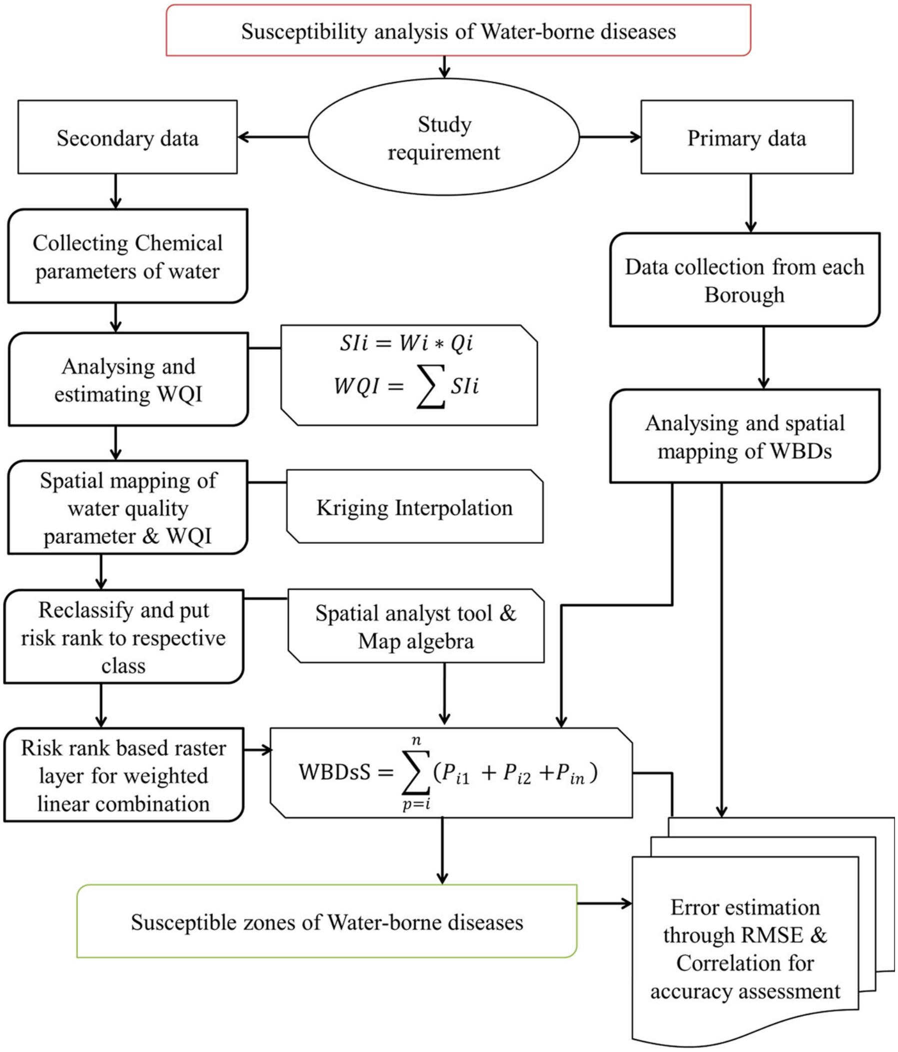


Fig. 4 Study design for analysing water-borne diseases susceptibility in Kolkata Municipal Corporation

restored its quality by preventing the pollutants from the source. Hence, essential to regularly monitor the quality of groundwater and develop methods and means to protect it. Water quality index (WQI) is one of the most common measures to communicate information on the quality of water to the concerned citizens and policy makers (Devendra et al. 2014; Ramakrishnaiah et al. 2009). Water quality index is defined as a ranking that assigned to reflect the composite effect of different water quality parameters. Water quality index is required to calculate in term of suitability of groundwater for human consumption (Avvannavar and Shrihari 2008).

The WQI was calculated in order to know the spatial variation of water quality and their role in occurring different types of water-borne diseases in KMC. For calculating the WQI based on available sampled data on water quality, three parallel steps were followed. First off all, the rank (Rn) of selected parameters was assigned. Thus, rank was given to each of the selected parameters based on their importance in water quality assessment and major role in responsible for water-borne diseases. Next, the relative weight (W_i) was computed using the following equation;

$$W_i = \frac{Rn}{\sum_{i=1}^{n} Rn}$$

where W_i is the relative weight, Rn is the rank of each parameter and n is the number of parameters.

Finally, a quality ranking scale (Qi) for each parameter is assigned by dividing its concentration in each water sample by its standard as per the

Table 4 Analysis of chemical parameters in ground water of sampled stations

Chemical parameters	Unit	Behala	Central Kolkata	Cossipore (North Kolkata)	Dhapa	Goria	Inside leather complex	Tangra	Topsia	IS 10500: 201
Arsenic	µg/l	0	0	0	0	0	7	0	0	0.01
Ammonia-N	mg/l	0.32	0.45	0.44	0.35	0	0	0.34	0	0.5
Chloride	mg/l	149.95	209.93	649.8	499.85	119.96	324.9	349.89	549.83	250
Fluoride	mg/l	0.31	0.42	0.33	0.33	0.64	0.38	0.37	0.48	1
Nitrate-N	mg/l	0.28	0.38	0.26	0.29	0.13	0.25	0.29	0.32	45
pH	Unit	7.61	8.45	8.19	7.95	7.37	7.21	7.96	6.85	6.5
Total dissolved solids (TDS)	mg/l	588	610	944	1326	582	1262	1236	4464	500
Total suspended solids (TSS)	mg/l	4	4	54	8	4	6	28	68	10
Turbidity	NTU	3.93	0.67	4.93	6.11	4.18	0.44	6.28	319	1
Zinc	µg/l	0	240	202	130	0	0	500	100	5
Water Quality Index (WQI)		84.81	719.78	765.44	504.01	81.77	2482.79	1554.40	3842.07	

guidelines laid down in the Bureau of Indian standard (BIS) and the result multiplied by 100. The following simple equation was used;

$$Qi = \frac{Ci}{Si} * 100$$

where Qi is the quality ranking, Ci is the concentration of each parameter in water sample and Si is the Indian drinking water standard respective parameter as per IS10500-2012

Now, for calculating the WQI, the SI value is first determined for each sampled parameter, which is used to calculate the water quality index as per the following equation;

$$SIi = Wi * Qi$$

$$WQI = \sum SIi$$

where SIi is the subindex of ith parameter; Qi is the ranking based on concentration of ith parameter and n is the number of parameters. Based on the above calculation, the WQI are classified into five categories from excellent to unsuitable for drinking.

Water quality standard for drinking purpose

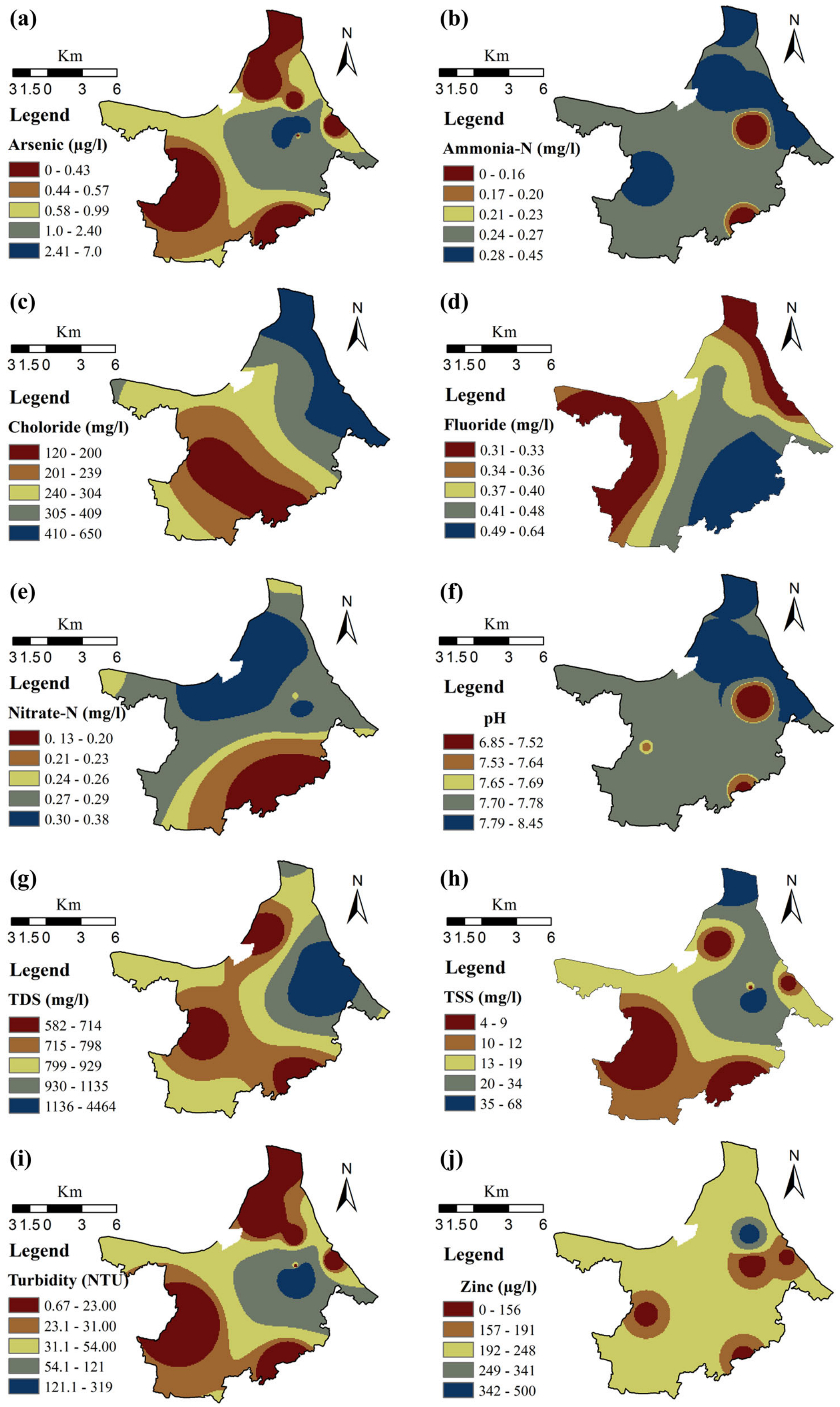
The Bureau of Indian Standards (BIS) has set specifications in IS–10500 and subsequently the revised edition of IS 10500: 2012 in Uniform Drinking Water Quality Monitoring protocol. This standard has two limits i.e. acceptable limits and permissible limit in absence of alternate source. If any parameter surpasses the limit, that water is considered as unfit for human consumption.

Generally, water is defined as unfit for drinking as per BIS, IS-10500-2012, if it is bacteriologically contaminated or if chemical contamination exceeds maximum permissible limits (e.g. excess fluoride [> 1.5 mg/l], Total Dissolved Solids (TDS) [> 2000 mg/l], arsenic [> 0.05 mg/l], nitrates [> 45 mg/l] etc.).

From the sample data, many chemical parameters in different location (which considered for water-borne diseases analysis) excessed the acceptable limits and to some extend permissible limits also. The details of IS standard of these parameters along with negative effect outside the desirable limit is given here (Table 3).

Result and discussion

Water related issues are always a major concern in Kolkata Municipal Corporation. Clear images of water related diseases appear year after year that make the city questionable for water quality. There are many reasons behind the degradation of natural quality of ground water which make it unfit for human consumption. Although it is quite difficult to linear


(a)
Km
3 1.5 0 3 6
Legend
Arsenic (μg/l)
0 - 0.43
0.44 - 0.57
0.58 - 0.99
1.0 - 2.40
2.41 - 7.0
N
(b)
Km
3 1.5 0 3 6
Legend
Ammonia-N (mg/l)
0 - 0.16
0.17 - 0.20
0.21 - 0.23
0.24 - 0.27
0.28 - 0.45
N
(c)
Km
3 1.5 0 3 6
Legend
Choloride (mg/l)
120 - 200
201 - 239
240 - 304
305 - 409
410 - 650
N
(d)
Km
3 1.5 0 3 6
Legend
Fluoride (mg/l)
0.31 - 0.33
0.34 - 0.36
0.37 - 0.40
0.41 - 0.48
0.49 - 0.64
N
(e)
Km
3 1.5 0 3 6
Legend
Nitrate-N (mg/l)
0. 13 - 0.20
0.21 - 0.23
0.24 - 0.26
0.27 - 0.29
0.30 - 0.38
N
(f)
Km
3 1.5 0 3 6
Legend
pH
6.85 - 7.52
7.53 - 7.64
7.65 - 7.69
7.70 - 7.78
7.79 - 8.45
N
(g)
Km
3 1.5 0 3 6
Legend
TDS (mg/l)
582 - 714
715 - 798
799 - 929
930 - 1135
1136 - 4464
N
(h)
Km
3 1.5 0 3 6
Legend
TSS (mg/l)
4 - 9
10 - 12
13 - 19
20 - 34
35 - 68
N
(i)
Km
3 1.5 0 3 6
Legend
Turbidity (NTU)
0.67 - 23.00
23.1 - 31.00
31.1 - 54.00
54.1 - 121
121.1 - 319
N
(j)
Km
3 1.5 0 3 6
Legend
Zinc (μg/l)
0 - 156
157 - 191
192 - 248
249 - 341
342 - 500
N

◀**Fig. 5** Spatial mapping of ground water quality showing the concentration of **a** arsenic, **b** ammonia-N, **c** chloride, **d** fluoride, **e** Nitrate-N, **f** pH, **g** total dissolved solids, **h** total suspended solids, **i** turbidity, **j** zinc

correlate and make responsible any instance for water quality degradation and contamination. But improper drainage and sewerage management, undesired anthropogenic activities with ground water have always negative consequence to human health (Fig. 3). Thus, effort was made to know the major water-borne diseases risk areas in Kolkata Municipal Corporation using the GIS technique and water quality index. For achieving such goal, two types of spatial data was collected i.e. primary survey based previously affected areas with water-borne diseases (Diarrhea, Cholera, typhoid etc.) to prepare the water-borne diseases inventory map and analysis of water quality parameter to calculate the water quality index. The spatial maps of each selected chemical parameter along with the water quality index (WQI) were prepared using Geo-statistical techniques (kriging interpolation). A detail of study design is figured here (Fig. 4).

The chemical analysis of ground water that collected from each sampled site along with the Indian Standards are summarised in the following table (Table 4). The sample collected from Behala, South Kolkata shows that except TDS, pH and turbidity, all other parameters are below the IS level. The amount of TDS, pH and turbidity in sampled water was found as 588 mg/l, 7.61 and 3.93 NTU

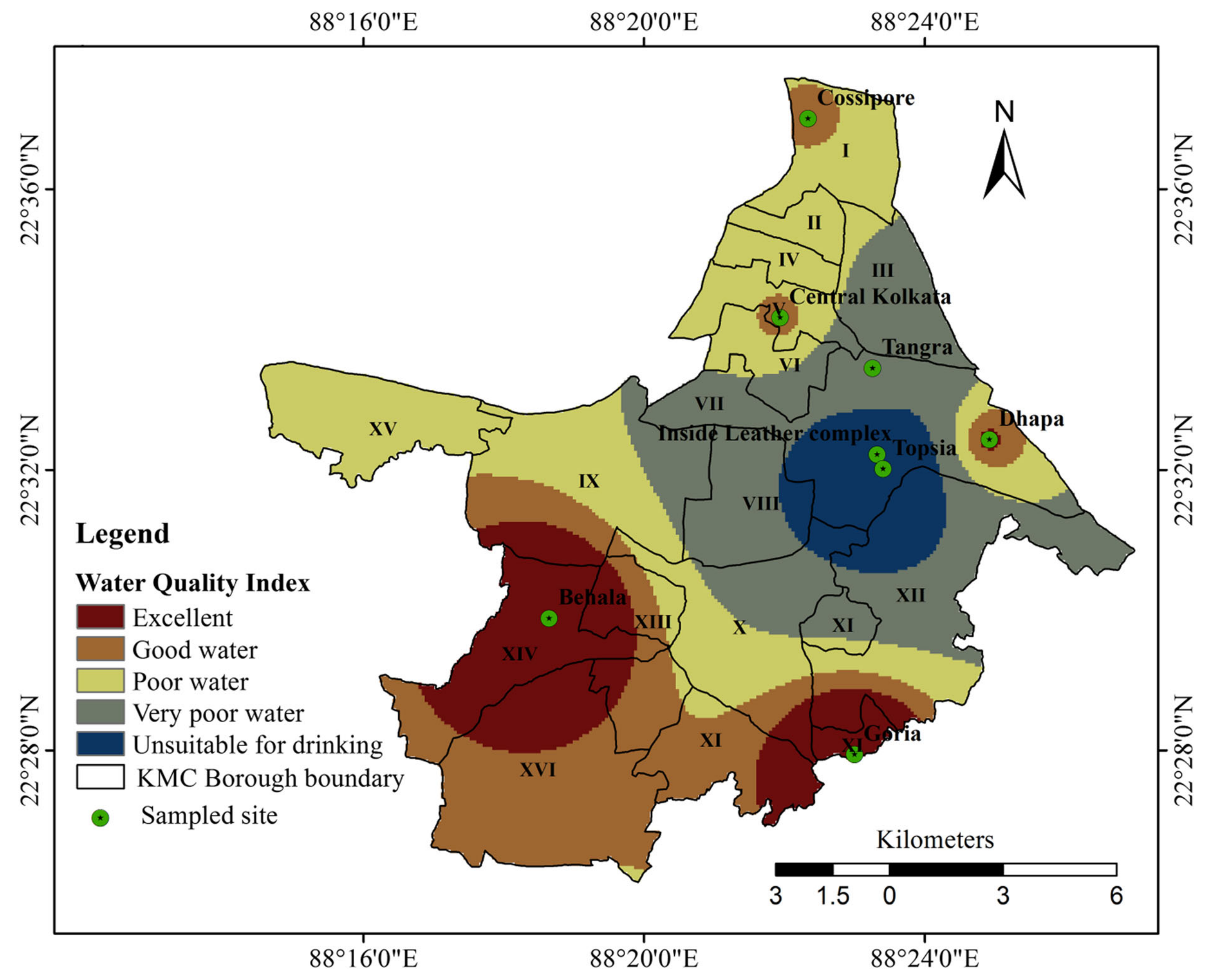


Fig. 6 Spatial map of Water Quality Index of KMC

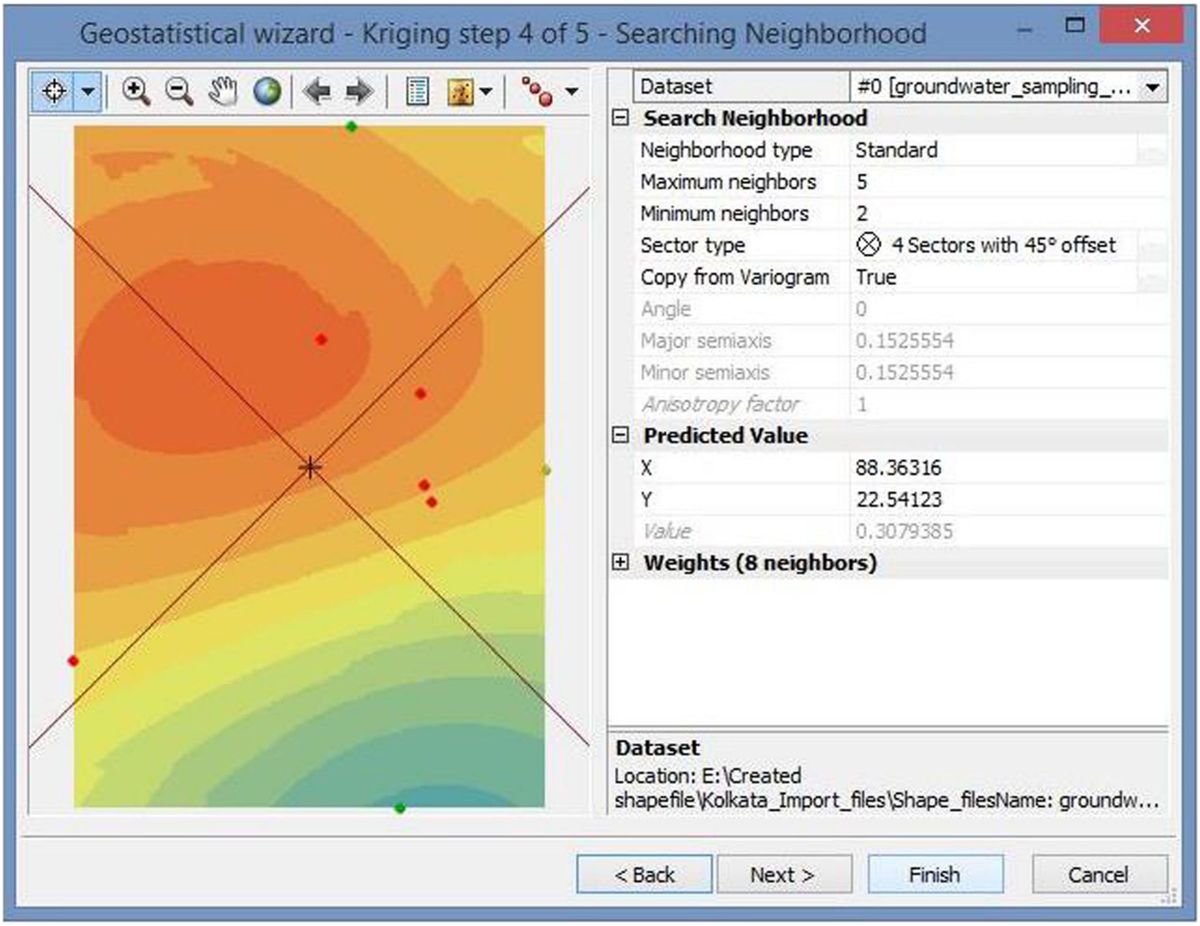


Fig. 7 The setting of Geo-statistical wizard for Kriging interpolation

where the acceptable limit of SI is 500 mg/l, 6.5 and 1 NTU respectively.

In Central Kolkata, the value of Chloride, pH and TDS was found high with 209.93 mg/l, 8.45 and 610 mg/l respectively. The value of Zinc was found excessive high with 240 µg/l whereas the acceptable limit is recommended only 5 µg/l. In case of Cossipore, North Kolkata, the chemical like Chloride, pH, TDS, TSS, Turbidity and Zinc were found high in concentration with value of 499.85 mg/l, 8.19, 944 mg/l, 54 mg/l, 4.93 NTU and 202 µg/l restively.

In Dhapa, East Kolkata, the amount of TDS was seen too high with 1326 mg/l, the concentration of Chloride, turbidity and zinc were also found high with 499.85 mg/l, 6.11 NTU and 130 µg/l respectively. In Goria, except TDS, pH and turbidity, all other chemical parameters are below the range set by Indian Standard. TDS, pH and turbidity in sampled water was found as 582 mg/l, 7.37 and 4.18 NTU where the acceptable limit of SI is 500 mg/l, 6.5 and 1 NTU respectively. A ground water sampling station is located near leather complex, where the value of Arsenic and TDS in ground water was found 7 µg/l and 1262 mg/l respectively which are much more than the acceptable limit. Excepting these two, other chemical parameters were found within or below the acceptable range. In case of Tangra and Tapsia, Chloride, TDS, TSS, Turbidity and zinc were always found much higher than the acceptable range of IS recommendation. Among all ground water stations, the highest TDS was found in Tapsia with 4464 mg/l, the highest Chloride and turbidity in ground water was also found in Tapsia with 549.83 mg/l and 319 NTU respectively. The amount of TSS was also highest (68 mg/l) in Tapsia.

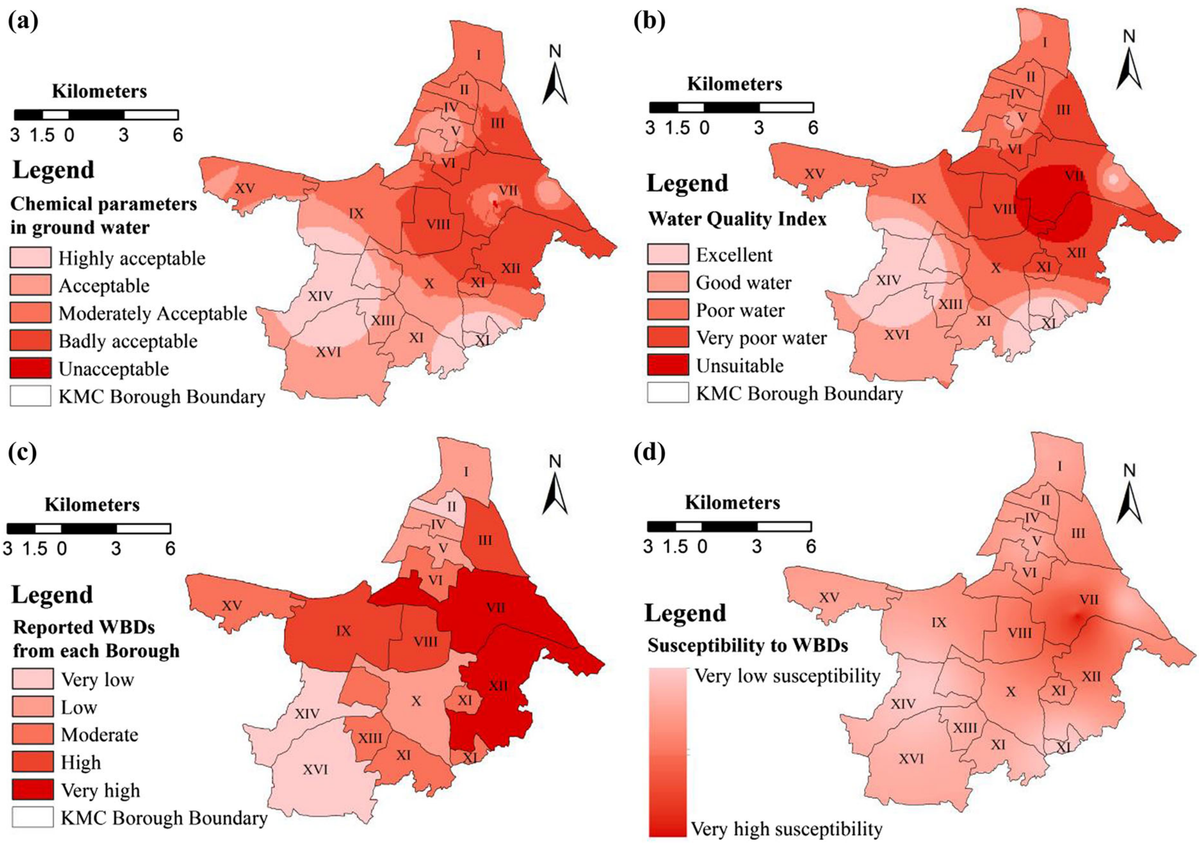


Fig. 8 Input layers for preparing the water-borne diseases susceptibility map **a** concentrations of chemical parameters in ground water, **b** WQI, **c** reported cases of WBDs, **d** susceptible zones of WBDs

As a whole, arsenic was found below detection level in all sample station except inside leather complex. Comparatively, the highest Ammonia-N was found in Central Kolkata, Floride in Goria, Nitrate-N in Central Kolkata, pH in Central Kolkata, TDS, TSS and Turbidity in Tapsia and zinc in Tangra (Fig. 5). Based on these all chemical parameters, the map of water quality index (WQI) was prepared using the Bureau of Indian Standards (BIS) value of specifications in (IS–10500) and above mentioned equations. The WQI were then classified into five categories from excellent to unsuitable for drinking (Fig. 6).

Kriging interpolation as a Geo-statistical method was applied for spatial mapping of ground water in order to know the more vulnerable zones in term of water quality. Kriging is an advanced Geo-statistical technique that creates an estimated/projected surface from a scattered set of known points with z-values. It is essential to measure accuracy and verify the analysis. Hence, spatial modelling which is also known as structural analysis or variography is required to draw. In present work, the ordinary Kriging method and spherical Semivariogram model was used for the same. The Geo-statistical wizard was set with Standard Neighbourhood type (Max neighbours 5 and Min neighbours 2) and 4 sector type with 45° offset. Before finishing the result, the predicted value of x and y was set as 88.3631 and 22.5412 respectively with weight of 8 neighbours (Fig. 7).

The Spherical function type of Kriging was used in present work, the model shows a progressive decrease of spatial autocorrelation until some distance, beyond which autocorrelation is zero. The semivariogram describes the spatial autocorrelation of the measured sample points. It is based on the basic principle of geography i.e. things that are closer are more alike than those farther apart. Thus, measured points that are close will generally have a smaller difference squared.

Table 5 Showing the root mean square error between selected input features and output susceptibility map of WBDs

Class	Pixel area covered in % (CPGW)	Pixel area covered in % (WBDs Susceptibility)	Error	Absolute error	Square of error	Absolute value error/ actual value
Highly acceptable	0.1626	0.2032	0.0406	0.0406	0.0016	0.2502
Acceptable	0.2570	0.3982	0.1411	0.1411	0.0199	0.5491
Moderately acceptable	0.3056	0.2287	− 0.0769	0.07695	0.0059	0.2517
Badly acceptable	0.2043	0.1137	− 0.0905	0.0905	0.0082	0.443
Unacceptable	0.0705	0.0562	− 0.0142	0.0142	0.0002	0.202

RMSE = 0.0847, MAPE = 0.3394

Class	Pixel area covered in % (WQI)	WBDs susceptibility	Error	Absolute error	Square of error	Absolute value error/actual value
Excellent	0.1449	0.2032	0.0583	0.0583	0.0034	0.4023
Good water	0.2068	0.3982	0.1914	0.1914	0.0366	0.9259
Poor water	0.3070	0.2287	− 0.0782	0.0782	0.0061	0.2550
Very poor water	0.2664	0.1137	− 0.1527	0.1527	0.0233	0.5732
Unsuitable	0.0749	0.0562	− 0.0187	0.0187	0.0003	0.2502

RMSE = 0.1182, MAPE = 0.4812

Class	Pixel area covered in % (reported WBDs)	WBDs susceptibility	Error	Absolute error	Square of error	Absolute value error/ actual value
Very low	0.1276	0.2032	− 0.0756	0.0756	0.0057	0.5931
Low	0.3184	0.3982	− 0.0798	0.0798	0.0063	0.2508
Moderate	0.2802	0.2287	0.0515	0.0516	0.0026	0.1839
High	0.1783	0.1137	0.0646	0.0646	0.0041	0.3625
Very high	0.0955	0.0562	0.0393	0.0393	0.0015	0.4116

RMSE = 0.0640, MAPE = 0.3604

Pixel area covered by each respective class is without multiplying by 100

CPGW chemical parameters in ground water, *WQI* water quality index, *WBDs* water-borne diseases, *RMSE* root mean square error, *MAPE* mean absolute percentage error

Susceptibility mapping and accuracy assessment

For susceptibility analysis of water-borne diseases (WBDs), the spatial database, chemical parameters and water quality index were considered to merge using weighted linear combination. Initially, based on survey data, the spatial water-borne diseases map was prepared in form of inventory. Then, all of ten selected water quality parameters were merged into one single layer by map algebra in spatial analysis tool of GIS environment and categorised the single raster into five classes naming highly acceptable, acceptable, moderately acceptable, badly acceptable and unacceptable for drinking purpose by using geometrical interval. Consequently the spatial map of QWI was also classified into five classes i.e. excellent, good water, poor water, very poor water and unsuitable for drinking purpose using the same classification method and the reported WBD cases from each borough was also classified into very low to very high. Then these raster layers were reclassified by putting numerical value from 1 to 5, where highly acceptable for drinking purpose was indicated by 1 and unacceptable for drinking purpose by 5. Parallelly for WQI,

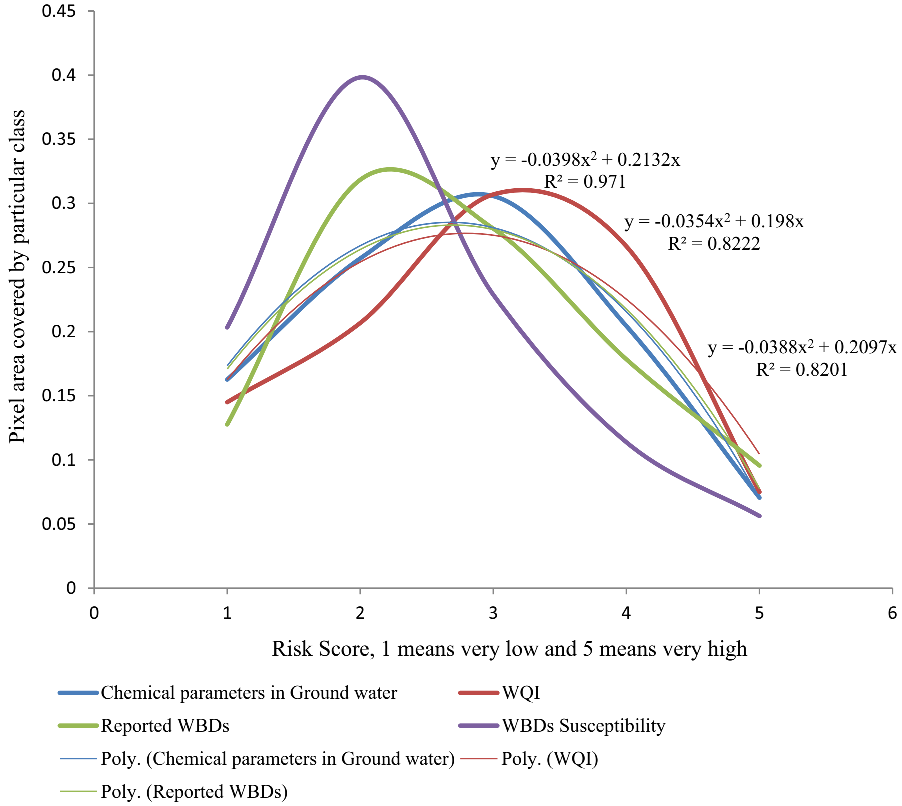


Fig. 9 Correlation of selected chemical parameter in ground water, water quality index and reported water-borne diseases with water-borne diseases susceptibility

excellent class was ranked by 1 and unsuitable for drinking purpose by 5. Inversely high susceptible to WBDs was indicated by 5 and less susceptibility by 1. It means higher rank of water quality index is lower rank to water-borne diseases susceptibility. Now, the spatial map of water-borne diseases susceptibility was prepared (Fig. 8). For the same, the following equation was used in GIS environment;

$$\mathrm{WBDsS} = \sum_{p=i}^{n} (P_{i1} + P_{i2} + P_{in})$$

where WBDsS—water-borne diseases susceptibility; $P_{i1}\ldots P_{in}$—selected parameters and n—total number of parameters chosen for linear combination

For accuracy of the study result, the pixel based root mean square error (RMSE) was estimated between input selected criteria and output final susceptibility map (Table 5). Here, the pixel value covering very high to very low susceptibility were considered as predicted susceptible index (PSI) i.e. dependent variable and the actual pixel value of selected parameters were considered as independent variable. The result from error estimation, it was shown that the RMSE between WBDs susceptibility and selected chemical parameters, water quality index (WQI) and reported water-borne diseases are 0.0847, 0.1182 and 0.0640 respectively. The mean absolute percentage error also calculated among them as 0.3394, 0.4813 and 0.3604 respectively.

Furthermore, the correlation between three aspects of analysis i.e. selected chemical parameter of water, water quality index, reported water-borne diseases from survey with output water-borne diseases (WBDs) susceptibility was calculated to show the relationship between poor water quality and susceptibility to WBDs (Fig. 9). Correlation between 10 selected chemical parameters in ground water (x) and susceptibility to WBDs (y) has resulted highly positive (r^2 = 0.97) and between water quality index (x) and susceptibility to WBDs (y) has also resulted positive (r^2 = 0.82). In both the cases the degree positive of correlation have sharply indicate that acceptable limits of chemical parameters in ground water and excellent QWI have less susceptibility to WBDs and concomitantly poor water quality and unacceptable ranges of chemical parameters in water have higher susceptibility to WBDs.

Therefore, from the RMSE and Correlation analysis it was found that the more water-borne diseases susceptible zones are circulating with very poor zones of QWI and zones of unacceptable ranges of chemical parameters. The primary data also signifies the same findings that eastern parts of the city mainly Borough VII and XII have very high reported WBDs in comparison to other parts.

Conclusion

The present study was carried out to analysis the spatial susceptibility of water-borne diseases in Kolkata Municipal Corporation using water quality index and GIS based Geo-statistical interpolation method. The study showed that GIS offers an effective spatial analyst tool which has the capability of integration, reclassification and overlay for object based weighted result. It is always a parallel consequent of poor water quality to poor health condition and occurring different types of transmissible diseases. Hence, continuous rating of water quality index and proper surveillance on water-borne diseases are required and essential. With the development of GIS technology, the research interest has been increasing towards public health and epidemiology. Mapping of risk zonation, diseases susceptibility analysis, geographical location and distribution of various diseases, monitoring diseases and developing surveillance strategies, service locations and route optimization to supplies equipments, forecasting epidemics etc. are emerging field in GIS.

The present study used the chemical parameters of ground water and water quality index for primarily identifying the weaker zones in term of water quality. Paralally, GIS based Geo-statistical technique was utilised for spatial susceptibility analysis of water-borne diseases and statistical methods like RMSE, MAPE and correlation were used to show the error, accuracy and relation between WQI and WBDs. The study revealed that the more WBDs susceptible zones are encircling with zones of poor WQI and zones of unacceptable ranges of chemical parameters in ground water with showing high degree of positive correlation (> 0.95) and low value of RMSE (< 1). The study result further suggests the applicability of GIS technique in other types of diseases susceptibility analysis by setting proper objectives and electing suitable study criteria with spatial justification.

Acknowledgements We thankfully acknowledge the anonymous reviewers and the editor for their appreciated time, productive comments and suggestions for improving the overall quality of this work.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants and/or animals Human Participants or Animals were not engaged or involved in present research.

Ethical standards Therefore, for this research the compliance with ethical standards is not applicable since only the data on chemical parameter of ground water was collected from central laboratory, West Bengal Pollution Control Board and information regarding water-borne diseases was collected from different households of KMC for showing the accuracy of susceptibility mapping and efficacy of GIS technique.

References

Ahearn, D. S., Sheibley, R. W., Dahlgren, R. A., Anderson, M., Johnson, J., & Tate, K. W. (2005). Land use and land cover influence on water quality in the last free-flowing river draining the western Sierra Nevada, California. *Journal of Hydrology, 313*(3–4), 234–247. https://doi.org/10.1016/j.jhydrol.2005.02.038.

Ahmad, F., Goparaju, L., & Qayum, A. (2017). Studying malaria epidemic for vulnerability zones: Multi-criteria approach of geospatial tools. *Journal of Geoscience and Environment Protection, 5*(5), 30–53. https://doi.org/10.4236/gep.2017.55003.

Aimone, A. M., Perumal, N., & Cole, D. C. (2013). A systematic review of the application and utility of geographical information systems for exploring disease–disease relationships in paediatric global health research: The case of anaemia and malaria. *International Journal of Health Geographics*. https://doi.org/10.1186/1476-072X-12-1.

Ali, S. A., & Ahmad, A. (2018). Using analytic hierarchy process with GIS for Dengue risk mapping in Kolkata Municipal Corporation, West Bengal, India. *Spatial Information Research, 26*(4), 449–469. https://doi.org/10.1007/s41324-018-0187-x.

Ali, S. A., & Ahmad, A. (2019a). Spatial susceptibility analysis of vector-borne diseases in KMC using geospatial technique and MCDM approach. *Modeling Earth Systems and Environment.*. https://doi.org/10.1007/s40808-019-00586-y.

Ali, S. A., & Ahmad, A. (2019b). Mapping of mosquito-borne diseases in Kolkata Municipal Corporation using GIS and

AHP based decision making approach. *Spatial Information Research*. https://doi.org/10.1007/s41324-019-00242-8.
Al-Omran, A., Al-Barakah, F., Altuquq, A., Aly, A., & Nadeem, M. (2015). Drinking water quality assessment and water quality index of Riyadh, Saudi Arabia. *Water Quality Research Journal of Canada*. https://doi.org/10.2166/wqrjc.2015.039.
Anwar, F. (2003). Assessment and analysis of industrial liquid waste and sludge disposal at unlined landfill sites in arid climate. *Waste Management, 23*(9), 817–824. https://doi.org/10.1016/S0956-053X(03)00036-9.
Asadi, S. S., Vuppala, P., & Reddy, M. A. (2007). Remote sensing and GIS techniques for evaluation of groundwater quality in Municipal Corporation of Hyderabad (Zone-V), India. *International Journal of Environmental Research and Public Health, 4*(1), 45–52.
Ashbolt, N. J. (2004). Microbial contamination of drinking water and disease outcomes in developing regions. *Toxicology, 198*(1–3), 229–238. https://doi.org/10.1016/j.tox.2004.01.030.
Avvannavar, S. M., & Shrihari, S. (2008). Evaluation of water quality index for drinking purposes for river Netravathi, Mangalore, South India. *Environmental Monitoring and Assessment, 143*(1–3), 279–290. https://doi.org/10.1007/s10661-007-9977-7.
Batterman, S., EIsenberg, J., Hardin, R., et al. (2009). Sustainable control of water-related infectious diseases: A review and proposal for interdisciplinary health-based systems research. *Environmental Health Perspectives, 117*(7), 1023–1032. https://doi.org/10.1289/ehp.0800423.
Bergquist, R., & Rinaldi, L. (2010). Health research based on geospatial tools: A timely approach in a changing environment. *Journal of Helminthology, 84*(1), 1–11. https://doi.org/10.1017/S0022149X09990484.
Bessong, P. O., Odiyo, J. O., Musekene, J. N., & Tessema, A. (2009). Spatial distribution of diarrhoea and microbial quality of domestic water during an outbreak of diarrhoea in the Tshikuwi community in Venda, South Africa. *Journal of Health, Population and Nutrition, 27*(5), 652–659. https://doi.org/10.3329/jhpn.v27i5.3642.
Bhattacharya, A. (2006). Remediation of pesticides polluted water through membranes. *Separation and Purification Reviews, 35,* 1–38. https://doi.org/10.1080/15422110500536151.
Bhowmick, S. (2018). Noida's groundwater level falling by 1.5 metres every year. The Times of India. https://timesofindia.indiatimes.com/city/gurgaon/noidas-groundwater-level-falling-by-1-5-metres-every-year/articleshow/. Accessed on 11 January 2019.
Bitton, G. (2014). *Microbiology of drinking water production and distribution*. Hoboken, NJ: Wiley.
Briggs, A., & Elliott, P. (1995). The use of geographical information systems in studies on environment and health. *World Health Statistics Quarterly, 48*(2), 85–94.
Burrough, P. A., & McDonnell, R. A. (1998). Creating continuous surfaces from point data. In P. A. Burrough, M. F. Goodchild, R. A. McDonnell, P. Switzer, & M. Worboys (Eds.), *Principles of geographic information systems*. Oxford: Oxford University Press.
Burton, A. C., & Cornhill, J. F. (1977). Correlation of cancer death rates with altitude and with the quality of water supply of the 100 largest cities in the United States. *Journal of toxicology and environmental health, 3*(3), 465–478. https://doi.org/10.1080/15287397709529579.
Cabral, J. P. S. (2010). Water microbiology, bacterial pathogens and water. *International Journal of Environmental Research and Public Health, 7*(10), 3657–3703. https://doi.org/10.3390/ijerph7103657.
Carrera-Hernandez, J. J., & Gaskin, S. J. (2007). The Basin of Mexico aquifer system: Regional groundwater level dynamics and database development. *Hydrogeology Journal, 15*(8), 1577–1590. https://doi.org/10.1007/s10040-007-0194-9.
Castronovo, D. A., Chui, K. K., & Naumova, E. N. (2009). Dynamic maps: A visualanalytic methodology for exploring spatio-temporal disease patterns. *Environment and Health, 8*(1), 61. https://doi.org/10.1186/1476-069X-8-61.
Cesa, M., Fongaro, G., & Barardi, C. R. M. (2016). Waterborne diseases classification and relationship with social-environmental factors in Florianópolis city—Southern Brazil. *Journal of Water and Health, 14*(2), 340–348. https://doi.org/10.2166/wh.2015.266.
Chakraborty, A. (2018). *More Kolkata areas affected by diarrhoea*. The Hindu, https://www.thehindu.com/news/cities/kolkata/more-kolkata-areas-affected-by-diarrhoea/article22748252.ece. Accessed on 9 December 2018.
Chang, H. (2008). Spatial analysis of water quality trends in the Han River basin, South Korea. *Water Research, 42*(13), 3285–3304. https://doi.org/10.1016/j.watres.2008.04.006.
Chang, H., & Carlson, T. N. (2005). Water quality during winter storm events in Spring Creek, Pennsylvania, USA. *Hydrobiologia, 544*(1), 321–332. https://doi.org/10.1007/s10750-005-1894-6.
Charles, F. H., Swartz, C. H., Badruzzaman, A. B. M., Nicole, K. B., Yu, W., Ali, A., et al. (2005). Groundwater arsenic contamination on the Ganges Delta: Biogeochemistry, hydrology, human perturbations and human suffering on a large scale. *Comptes Rendus Geoscience, 337*(1/2), 285–296.
Chatterjee, A., Das, D., Mandal, B. K., Chowdhury, T. R., Samanta, G., & Chakraborti, D. (1995). Arsenic in ground water in six districts of West Bengal, India: The biggest arsenic calamity in the world. Part I. Arsenic species in drinking water and urine of the affected people. *Analyst, 120*(3), 643–650. https://doi.org/10.1039/AN9952000643.
Craun, G. F., & McGabe, L. J. (1975). Problems associated with metals in drinking water. *Journal of the American Water Works Association, 67*(11), 593–599. https://doi.org/10.1002/j.1551-8833.1975.tb02307.x.
Crawford, M., Gardner, M. J., & Morris, J. N. (1968). Mortality and hardness of water. *The Lancet*, *291*(7551), 1092. https://doi.org/10.1016/s0140-6736(68)91445-1.
Daniel, M., Kolar, J., & Zeman, P. (2004). GIS tools for tick and tick-borne disease occurrence. *Parasitology, 129*(7), S329–S352. https://doi.org/10.1017/S0031182004006080.
Danson, F. M., Armitage, R. P., & Marston, C. G. (2008). Spatial and temporal modelling for parasite transmission studies and risk assessment. *Parasite, 15*(3), 463–468. https://doi.org/10.1051/parasite/2008153463.
Davies, G. I., McIver, L., Kim, Y., Hashizume, M., Iddings, S., & Chan, V. (2015). Water-borne diseases and extreme weather events in Cambodia: Review of impacts and

implications of climate change. *International Journal of Environmental Research and Public Health, 12*(1), 191–213. https://doi.org/10.3390/ijerph120100191.
DeGrootem, J. P., Larson, S. R., Zhang, Y., & Sugumaran, R. (2012). Application of geospatial technologies for understanding and predicting vector populations and vector-borne disease incidence. *Geography Compass, 6*(11), 645–659. https://doi.org/10.1111/gec3.12003.
Department of National Health and Welfare, Canada. (1987). Guidelines for Canadian drinking water quality. Supporting documentation, Ottawa. http://www.publications.gc.ca/Collection/H48-10-1-46-1997E.pdf. Accessed on January 11, 2019.
Devendra, S., Anju, P., Ashutosh, K., & Sapana, B. (2014). Study of Water Quality Index with the help of remote sensing and GIS for ground water sources between Ganga and Yamuna River Siwalik region in Doon Valley in Outer Himalaya. *International Research Journal of Environmental Sciences, 3*(10), 7–11.
Devipriya, G., & Kalaivani, K. (2012). Optimal Control of multiple transmission of water-borne diseases. *International Journal of Mathematics and Mathematical Sciences, 1,* 16. https://doi.org/10.1155/2012/421419.
Dhama, K., Verma, A. K., Tiwari, R., Chakraborty, S., Vora, K., Kapoor, S., et al. (2013). A perspective on applications of geographical information system (GIS); An advanced tracking tool for disease surveillance and monitoring in veterinary epidemiology. *Advances in Animal and Veterinary Sciences, 1*(1), 14–24.
Donohue, I., McGarrigle, M. L., & Mills, P. (2006). Linking catchment characteristics and her chemistry with the ecological status of Irish rivers. *Water Research, 40*(1), 91–98.
Dore, M. H. (2015). Waterborne disease outbreaks and the multi-barrier approach to protecting drinking water. In *Global drinking water management and conservation.* Springer. https://doi.org/10.1007/978-3-319-11032-5_2.
Eisen, L., & Eisen, R. J. (2011). Using geographic information systems and decision support systems for the prediction, prevention, and control of vector-borne diseases. *Annual Review of Entomology, 56*(1), 41–61. https://doi.org/10.1146/annurev-ento-120709-144847.
Eisenberg, J. N. S., Bartram, J., & Hunter, P. R. (2001). A public health perspective for establishing water-related guidelines and standards. In L. Fewtrell & J. Bartram (Eds.), *Water quality: Guidelines, standards and health*. London: IWA Publishing.
Elimelech, M. (2006). The global challenge for adequate and safe water. *Journal of Water Supply: Research and Technology-AQUA, 55*(1), 3–10. https://doi.org/10.2166/aqua.2005.064.
Elinder, C. G. (1986). Respiratory effects. In Friberg, L., Elinder, C. G., Kjellström, T., et al., (Eds.), *Cadmium and health: A toxicological and epidemiological appraisal. Vol. II. Effects and response* (pp 1–20). Boca Raton, FL: CRC Press.
Enterline, P. E., Henderson, V. L., & Marsh, G. M. (1987). Exposure to arsenic and respiratory cancer. A reanalysis. *American Journal of Epidemiology, 125*(6), 929–938. https://doi.org/10.1093/oxfordjournals.aje.a114631.
Facchinelli, A., Sacchi, E., & Mallen, L. (2001). Multivariate statistic a land GIS-based approach to identify heavy metal sources in soils. *Environment Pollution, 114*(3), 313–324. https://doi.org/10.1016/s0269-7491(00)00243-8.
Fawell, J., Bailey, K., Chilton, J., Dahi, E., Fewtrell, L., & Magara, Y. (2006). *Fluoride in drinking-water*. London: World Health Organization, IWA Publishing.
Fawell, J., & Nieuwenhuijsen, M. J. (2003). Contaminants in drinking water. *British Medical Bulletin, 68*(1), 199–208. https://doi.org/10.1093/bmb/ldg027.
Fewtrel, L. (2004). Drinking-water nitrate, methemoglobinemia, and global burden of disease: A discussion. *Environmental Health Perspectives, 112*(14), 1371–1374. https://doi.org/10.1289/ehp.7216.
Gentry-Shields, J., & Bartram, J. (2014). Human health and the water environment: Using the DPSEEA framework to identify the driving forces of disease. *Science of the Total Environment*. https://doi.org/10.1016/j.scitotenv.2013.08.052.
George, J. M., Chiang, P. H., Tyler Sylk, T., et al. (2013). Use of GIS mapping as a public health tool—From cholera to cancer. *Health Services Insights, 6*(HSI.S10471), 111–116. https://doi.org/10.4137/HSI.S10471.
Gharbia, A. S., Gharbia, S. S., Abushbak, T., Wafi, H., Aish, A., Zelenakova, M., et al. (2016). Groundwater quality evaluation using GIS based geostatistical algorithms. *Journal of Geoscience and Environment Protection, 4*(2), 89–103. https://doi.org/10.4236/gep.2016.42011.
Ghrefat, H., Nazzal, Y., Batayneh, A., Zumlot, T., Zaman, H., Elawadi, E., et al. (2014). Geochemical assessment of ground water contamination with special emphasizes on fluoride, a case study from Midyan Basin, north Western Saudi Arabia. *Environmental Earth Sciences, 71*(4), 1495–1505. https://doi.org/10.1007/s12665-013-2554-1.
Ground Water Yearbook. (2014). Central Ground Water Board. http://www.cgwb.gov.in/documents/Ground%20Water%20Year%20Book%202013-14.pdf. Accessed on March 1, 2019.
Gupta, S. (2018). Worried West Bengal government set to bring in law on groundwater use. The Times of India. https://timesofindia.indiatimes.com/city/kolkata/worried-west-bengal-government-set-to-bring-in-law-on-groundwater-use/articleshow/66112950.cms. Accessed on January 11, 2019.
Gupta, R., & Shriram, R. (2004). Disease surveillance and monitoring using GIS. In *7th Annual international conference Map India 2004*. http://www.gisdevelopment.net/application/health/planning/pdf/mi04054.pdf. Accessed on December 26, 2018.
Haines, A., Kovats, R. S., Campbell-Lendrum, D., & Corvalan, C. (2006). Climate change and human health: Impacts, vulnerability and public health. *Public Health, 120*(7), 585–596. https://doi.org/10.1016/j.puhe.2006.01.002.
Huang, J., Zhan, J., Yan, H., Wu, F., & Deng, X. (2013). Evaluation of the impacts of land use on water quality: A case study in the Chaohu Lake Basin. *The Scientific World Journal, 2013*, 1–7. https://doi.org/10.1155/2013/329187.
Jasmin, I., & Mallikarjuna, P. (2014). Physicochemical quality evaluation of groundwater and development of drinking water quality index for Araniar River Basin, Tamil Nadu, India. *Environmental Monitoring and Assessment, 186*(2), 935–948. https://doi.org/10.1007/s10661-013-3425-7.

Jiang, Y. P., Xu, Z. X., & Yin, H. L. (2006). Study on improved BP artificial neural net works in eutrophication assessment of China eastern lakes. *Journal of Hydrodynamics, 18*(3), 528–532. https://doi.org/10.1016/s1001-6058(06)60107-8.

Kass, A., Yechieli, G. Y., Vengosh, A., & Starinsky, A. (2005). The impact of freshwater and wastewater irrigation on the chemistry of shallow groundwater: A case study from the Israeli Coastal aquifer. *Journal of Hydrology, 300*(1–4), 314–333. https://doi.org/10.1016/j.jhydrol.2004.06.013.

Lal, N. (2014). India's groundwater drops to critical levels. Thethirdpole.net. www.thethirdpole.net/en/2014/10/14/indias-groundwater-drops-to-critical-levels/. Accessed on March 1, 2019.

Li, T., Cai, S. M., Yang, H. D., Wang, X. L., Wu, S. J., & Ren, X. Y. (2007). Fuzzy comprehensive-quantifying assessment in analysis of water quality: A case study in Lake Honghu, China. *Environmental Engineering Science, 26*(2), 451–458. https://doi.org/10.1089/ees.2007.0270.

Li, X. J., Fang, L. Q., Wang, D. C., Wang, L. X., Li, Y. P., Li, Y. L., et al. (2012). Design and implementation of geographical information system on prevention and control of cholera. *Zhonghua Liu Xing Bing Xue Za Zhi, 33*(4), 431–434.

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2004). *Remote sensing and image interpretation* (5th ed.). Singapore: Wiley.

Liu, J. T., Gao, J. F., & Jiang, J. H. (2010). Application of different fuzzy assessment methods of water quality assessment in Dianchi Lake. *Environmental Pollution & Control, 32*(1), 20–25.

Liu, A., Ming, J., & Ankumah, R. O. (2005). Nitrate contamination in private wells in rural Alabama, United States. *Science of the Total Environment, 346*(1–3), 112–120. https://doi.org/10.1016/j.scitotenv.2004.11.019.

McDonald, R. I., Douglas, I., Revenga, C., Hale, R., Grimm, N., Gronwall, J., et al. (2011). Global urban growth and the geography of water availability, quality, and delivery. *Ambio, 40*(5), 437–446. https://doi.org/10.1007/s13280-011-0152-6.

McKee, K. T., Shields, T. M., Jenkins, P. R., Zenilman, J. M., & Glass, G. E. (2000). Application of a geographic information system to the tracking and control of an outbreak of shigellosis. *Clinical Infectious Diseases, 31*(3), 728–733. https://doi.org/10.1086/314050.

Meenakshi, & Maheshwari, R. C. (2006). Fluoride in drinking water and its removal. *Journal of Hazardous Materials, 137*(1), 456–463. https://doi.org/10.1016/j.jhazmat.2006.02.024.

Meng, W., Zhang, N., Zhang, Y., & Zhang, B. H. (2009). Integrated assessment of river health based on water quality, aquatic life and physical habitat. *Journal of Environmental Science, 21*(8), 1017–1027. https://doi.org/10.1016/s1001-0742(08)62377-3.

Mohsin, M., Safdar, S., Asghar, F., & Jamal, F. (2013). Assessment of drinking water quality and its impact on residents health in Bahawalpur City. *International Journal of Humanities and Social Science, 3*(15), 114–128.

Moonan, P. K., Bayona, M., Quitugua, T. N., Oppong, D. D., Jost, K. C., Burgess, J. G., et al. (2004). Using GIS technology to identify areas of tuberculosis transmission and incidence. *International Journal of Health Geographics*. https://doi.org/10.1186/1476-072X-3-23.

Mourits, M. C. M., van Asseldonk, M. A. P. M., & Huirne, R. B. M. (2010). Multi criteria decision making to evaluate control strategies of contagious animal diseases. *Preventive Veterinary Medicine, 96*(3–4), 201–210. https://doi.org/10.1016/j.prevetmed.2010.06.010.

Mulligan, C. N., Yong, R. N., & Gibbs, B. F. (2001). Remediation technologies for metal contaminated soils and groundwater: An evaluation. *Engineering Geology, 60*(1–4), 193–200. https://doi.org/10.1016/s0013-7952(00)00101-0.

Nazri, C. D., Ahmad, A. H., Latif, Z. A., & Ismail, R. (2016). Application of GIS-based analytical hierarchy process as a tool for dengue risk assessment. *Asian Pacific Journal of Tropical Disease, 6*(12), 928–935. https://doi.org/10.1016/s2222-1808(16)61158-1.

Norstrom, M. (2001). Geographical information system (GIS) as a tool in surveillance and monitoring of animal diseases. *Acta Veterinaria Scandinavica, 42*(Suppl 1), S79. https://doi.org/10.1186/1751-0147-42-s1-s79.

Ouyang, Y. (2005). Evaluation of river water quality monitoring station by principal component analysis. *Water Research, 39*(12), 2621–2635. https://doi.org/10.1016/j.watres.2005.04.024.

Pang, Z. L., Chang, H. J., Li, Y. Y., Zhang, N. Q., Du, R. Q., & Hu, L. Q. (2008). Analytical hierarchy process (AHP) evaluation of water quality in Danjiangkou reservoir-source of the middle line project to transfer water from south to north, China. *Acta Ecologica Sinica—International Journal, 28*(4), 1810–1819.

Qayum, A., Arya, R., Kumar, P., & Lynn, A. M. (2015). Socio-economic, epidemiological and geographic features based on GIS integrated mapping to identify malarial hotspots. *Malaria Journal, 14*(1), 192. https://doi.org/10.1186/s12936-015-0685-4.

Ramakrishnaiah, C. R., Sadashivaiah, C., & Ranganna, G. (2009). Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India. *E-Journal of Chemistry, 6*(2), 523–530.

Ramírez-Castillo, F. Y., Loera-Muro, A., Jacques, M., Garneau, P., et al. (2015). Waterborne pathogens: Detection methods and challenges. *Pathogens, 4*(2), 307–334. https://doi.org/10.3390/pathogens4020307.

Reinhardt, M., Elias, J., Albert, J., Frosch, M., Harmsen, D., & Vogel, U. (2008). Epi Scan GIS: An online geographic surveillance system for meningococcal disease. *International Journal of Health Geographics, 7*(1), 33. https://doi.org/10.1186/1476-072x-7-33.

Rukah, A., & Alsokhny, K. (2004). Geochemical assessment of groundwater contamination with special emphasis on fluoride concentration, North Jordan. *Chemie Der Erde-Geochemistry, 64*(2), 171–181. https://doi.org/10.1016/j.chemer.2003.11.003.

Rushton, G. (2003). Public health, GIS, and spatial analytic tools. *Annual Review of Public Health, 24*(1), 43–56. https://doi.org/10.1146/annurev.publhealth.24.012902.140843.

Sanson, R., Pfeiffer, D., & Morris, R. (1991). Geographic information systems: Their application in animal disease control. *Revue Scientifique et Technique de l'OIE, 10*(1), 179–195. https://doi.org/10.20506/rst.10.1.541.

Sarkar, R., Prabhakar, A. T., Manickam, S., Selvapandian, D., Raghava, M. V., Kang, G., et al. (2007). Epidemiological investigation of an outbreak of acute diarrhoeal disease using geographic information systems. *Transactions of the Royal Society of Tropical Medicine and Hygiene, 101*(6), 587–593. https://doi.org/10.1016/j.trstmh.2006.11.005.

Sauer, H. I. (1974). Relationship between trace element content of drinking water and chronic disease. In *Trace metals in water supplies: Occurrence, significance and control*. University of Illinois Bulletin (Vol. 71(108), p. 39).

Schroeder, H. A. (1960). Relation between mortality from cardiovascular disease and treated water supplies. Variation in states and 163 largest municipalities. *Journal of the American Medical Association, 172*(17), 1902. https://doi.org/10.1001/jama.1960.03020170028007.

Schroeder, H. A. (1966). Municipal drinking water and cardiovascular death rates. *Journal of the American Medical Association, 195*(2), 81–85. https://doi.org/10.1001/jama.195.2.81.

Schwarzenbach, R. P., Escher, B. I., Fenner, K., et al. (2006). The challenge of micropollutants in aquatic systems. *Science, 313*(5790), 1072–1077. https://doi.org/10.1126/science.1127291.

Setianto, A., & Triandin, T. (2013). Comparison of Kriging and inverse distance weighted (IDW) interpolation methods in lineament extraction and analysis. *Journal of Southeast Asian Applied Geology, 5*(1), 21–29.

Shankar, B. S., & Sanjeev, L. (2008). Assessment of water quality index for the groundwaters of an industrial area in Bangalore, India. *Environmental Engineering Science, 25*(6), 911–915.

Sharma, S., & Bhattacharya, A. (2017). Drinking water contamination and treatment techniques. *Applied Water Science, 7*(3), 1043–1067. https://doi.org/10.1007/s13201-016-0455-7.

Sipe, N., & Dale, P. (2003). Challenges in using geographic information systems (GIS) to understand and control malaria in Indonesia. *Malaria Journal, 2*(1), 36–43. https://doi.org/10.1186/1475-2875-2-36.

Smith, A. H., & Steinmaus, C. M. (2009). Health effects of arsenic and chromium in drinking water: Recent human findings. *Annual Review of Public Health, 29*(30), 107–122. https://doi.org/10.1146/annurev.publhealth.031308.100143.

Tiwari, A. K., Singh, P. K., & Mahato, M. K. (2014). GIS-based evaluation of water quality index of groundwater resources in West Bokaro coalfield, India. *Current World Environment, 9*(3), 843–850. https://doi.org/10.12944/CWE.9.3.35.

Tu, C., Fang, Y., Huang, Z., & Tan, R. (2014). Application of the analytic hierarchy process to a risk assessment of emerging infectious diseases in Shaoxing city in southern China. *Japanese Journal of Infectious Diseases, 67*(6), 417–422.

UNICEF. (2019). Water, sanitation and hygiene—Common water and sanitation-related diseases. https://www.unicef.org/wash/index_wes_related.html. Accessed on January 13, 2019.

Vairavamoorthy, K., Yan, J. M., Galgale, H. M., & Gorantiwar, S. D. (2007). IRA-WDS: A GIS-based risk analysis tool for water distribution systems. *Environmental Modeling & Software, 22*(7), 951–965. https://doi.org/10.1016/j.envsoft.2006.05.027.

Wan, W., & Wang, S. (2013). Areal (2-D) simulation of water flood process in unit well pattern. *International Journal of Chemical and Petroleum Sciences, 2*(2), 1–10.

WHO. (1993). Guidelines for drinking-water quality. Vol. 1. Geneva. https://www.who.int/water_sanitation_health/publications/gdwq2v1/en. Accessed on January 13, 2019.

WHO. (1996a). *Zinc in drinking-water: Background document for development* (2nd ed., Vol. 2). WHO guidelines for drinking-water quality. Geneva.

WHO. (1996b). *Chloride in drinking-water: Background document for development* (2nd ed., Vol. 2). Geneva: WHO Guidelines for Drinking-water Quality.

WHO. (2015). Water sanitation and health. http://www.who.int/water_sanitation_health/diseases. Accessed on January 13, 2019.

WHO Regional Office for Europe. (1978). Sodium, chlorides, and conductivity in drinking water: A report on a WHO working group. EURO reports and studies 2, Copenhagen,

Wondim, Y. K., Alemayehu, E. B., & Abebe, W. B. (2017). Malaria hazard and risk mapping using GIS based spatial multicriteria evaluation technique (SMCET) in Tekeze Basin Development Corridor, Amhara Region, Ethiopia. *Journal of Environment and Earth Science, 7*(5), 76–87.

Xu, Z. X. (2005). Comprehensive water quality identification index for environmental quality assessment of surface water. *Journal of Tongji University (Natural Science), 33*(4), 482–488.

Yadav, K. K., Gupta, N., Kumar, V., Choudhary, P., & Khan, S. A. (2018). GIS-based evaluation of groundwater geochemistry and statistical determination of the fate of contaminants in shallow aquifers from different functional areas of Agra city, India: Levels and spatial distributions. *RSC Advances, 8*(29), 15876–15889. https://doi.org/10.1039/c8ra00577j.

Yan, C. A., Zhang, W., Zhang, Z., Liu, Y., Deng, C., & Nie, N. (2015). Assessment of water quality and identification of polluted risky regions based on field observations and GIS in the Honghe River Watershed, China. *PLoS ONE, 10*(3), e0119130. https://doi.org/10.1371/journal.pone.0119130.

Yao, J. Y., Zhong, Z. Y., & Chen, J. F. (2009). The application of gay cluster and relational analysis in water environmental quality assessment. *Environmental Science and Management, 34*(2), 172–174.

Zhang, L., & Kennedy, C. (2006). Determination of sustainable yield in urban groundwater systems: Beijing, China. *Journal of Hydrologic Engineering, 11*(1), 21–28. https://doi.org/10.1061/(asce)1084-0699(2006)11:1(21).

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.