Science of the Total Environment 575 (2017) 779–790

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Evaluation of index-overlay methods for groundwater vulnerability and risk assessment in Kathmandu Valley, Nepal

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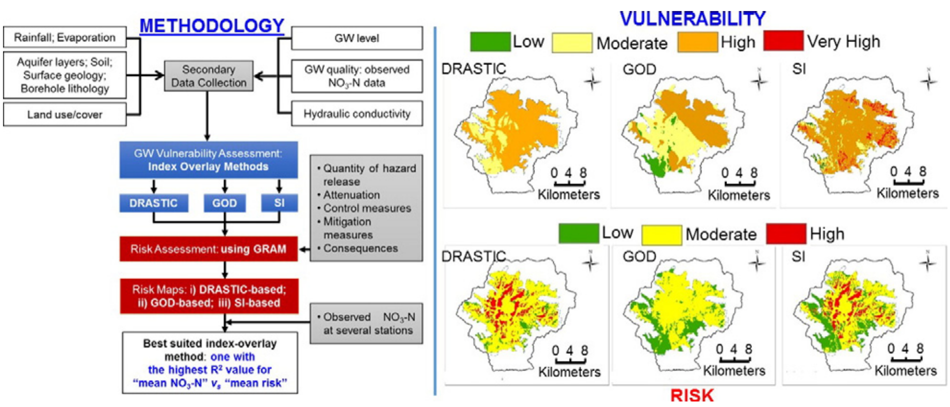
HIGHLIGHTS

- Index-overlay groundwater vulnerability and risk assessment methods were evaluated.
- Sensitivity index (SI) method was found as the most-suited for Kathmandu, Nepal.
- About 15% and 58% areas are under high and moderate vulnerabilities in the area.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 2 September 2016
Accepted 16 September 2016
Available online 30 September 2016

Editor: D. Barcelo

Keywords:
DRASTIC
GIS
GOD
Groundwater
Risk assessment
SI
Vulnerability assessment

ABSTRACT

This study aimed at evaluating three index-overlay methods of vulnerability assessment (i.e., DRASTIC, GOD, and SI) for estimating risk to pollution of shallow groundwater aquifer in the Kathmandu Valley, Nepal. The Groundwater Risk Assessment Model (GRAM) model was used to compute the risk to groundwater pollution. Results showed that DRASTIC and SI methods are comparable for vulnerability assessment as both methods delineate around 80% of the groundwater basin area under high vulnerable zone. From the perspective of risk to pollution results, DRASTIC and GOD methods are comparable. Nevertheless, all the three methods estimate that at least 60% of the groundwater basin is under moderate risk to NO_3-N pollution, which goes up to 75% if DRASTIC or GOD-based vulnerabilities are considered as exposure pathways. Finally, based on strength and significance of correlation between the estimated risk and observed NO_3-N concentrations, it was found that SI method is a better-suited one to assess the vulnerability and risk to groundwater pollution in the study area. Findings from this study are useful to design strategies and actions aimed to prevent nitrate pollution in groundwater of Kathmandu Valley in Nepal.

1. Introduction

Freshwater is under acute stress due to population growth, urbanization and industrial activities. At the same time, available water is

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http://dx.doi.org/10.1016/j.scitotenv.2016.09.141
0048-9697/

contaminated by many pollutants. Groundwater is a major component of freshwater supply in many parts of the world; but it is contaminated from domestic, agricultural or other activities (Russo and Taddia, 2012). In the case of urban areas, inadequate management of wastewater and solid waste are posing significant threats to the groundwater quality and subsequently on public health.

Groundwater is vulnerable to contamination from human activities. Groundwater vulnerability is the tendency of or likelihood for, contaminants to travel and reach a specified location in the groundwater system after it is introduced at some location above the uppermost aquifer. Shallow groundwater zone is more likely to be contaminated from chemical pesticides, fertilizers and industrial wastes. When aquifers become highly polluted, contamination will stay for a long time and hard to remediate due to their large storage, longer residence times and physical inaccessibility (Foster and Chilton, 2003). Furthermore, groundwater contamination is an unnoticeable process and of irreversible nature and too expensive as well as time-consuming, which may constrain efforts aimed at improving groundwater environment (Yu et al., 2010). Groundwater can be polluted by different pollutants like nitrate, ammonia, phosphate, and microbes. Direct disposal of waste material on the river banks and other dumping sites has led to pollution of groundwater as well as surface water from nitrate and other contaminants. For example, shallow aquifer in Kathmandu Valley is contaminated with nitrate because of human-induced sources like untreated waste materials, agricultural fertilizers, and septic tanks (Shrestha et al., 2012). In some cases, naturally occurring denitrification in the aquifer environment by bacteria looking for the source of oxygen may help reduce nitrate level in groundwater (Bittner, 2000). Wisely designed management strategies could be implemented in improving groundwater quality.

Groundwater management encompasses a broad range of activities including prevention of groundwater contamination. Vulnerability and pollution risk assessments to identify risk zones are the very first important steps to generate useful information for devising strategies aimed at groundwater protection to contamination. Delineating vulnerable zones helps water resource managers to divert groundwater development activities to other safer areas and hence can minimize cost of water treatment. There are different methods for groundwater

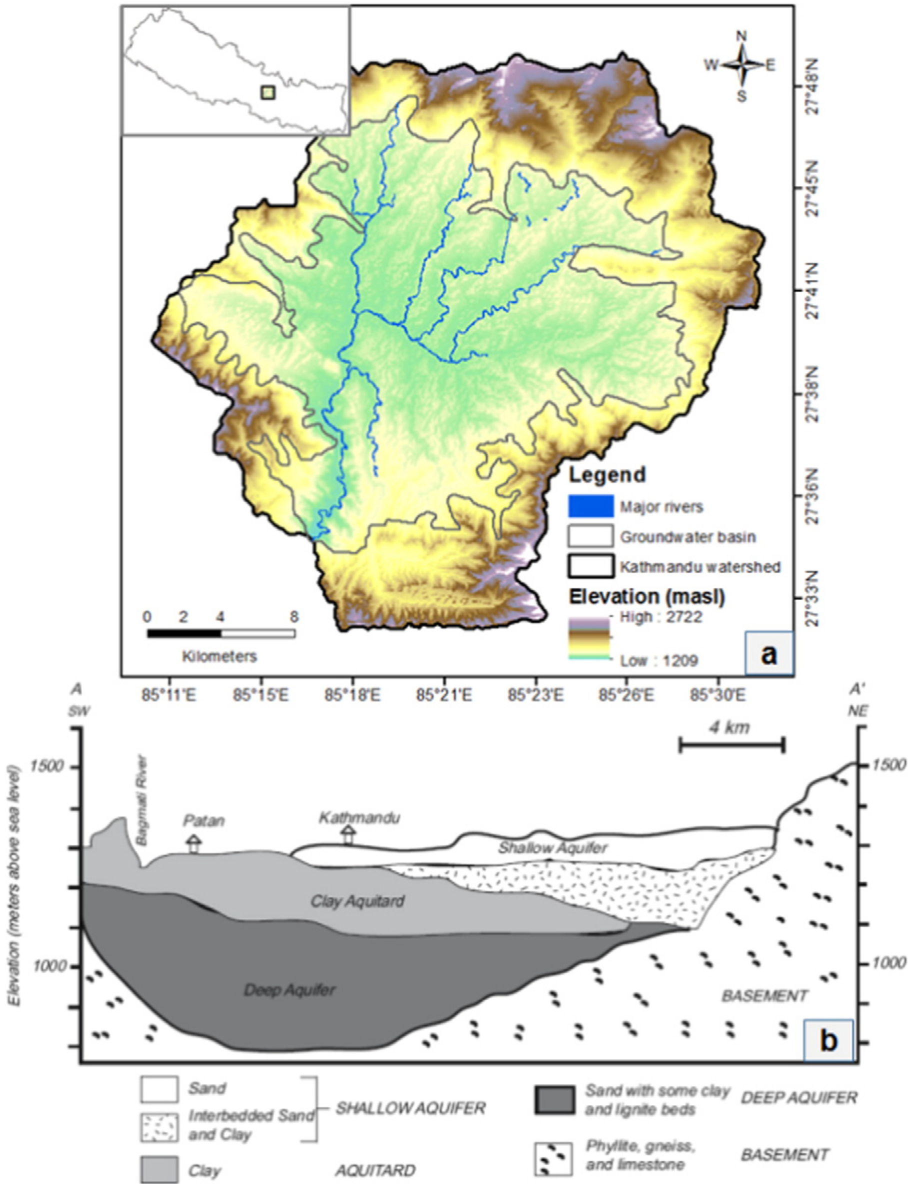

Fig. 1. Location of study area: a) location and topographic details; b) aquifer layers as shown in Warner et al. (2008).

vulnerability assessment such as index-overlay (e.g., DRASTIC, GOD, and SI), statistical, and process-based as summarized in Annex 1 (Supplementary material).

Index-overlay method is the most widely used among the methods of groundwater vulnerability assessment because of simplicity in use, less data requirement, and clarity in description of the vulnerability. In this method, extent of vulnerability is calculated by considering the indices (Huan et al., 2012) and the result is qualitative and relative. The simplest overlay systems use equal weights for all the parameters. More sophisticated systems assign different numerical weights and scores for these parameters based on their contribution to vulnerability (Samey and Gang, 2008; Valle et al., 2015). Moreover, the index-overlay models are less constrained by data shortage and computational difficulties (Barbash and Resek, 1996).

There is a wider application of index-overlay methods in different geographical regions and for various size of aquifers. GOD method is mainly used to map vulnerability of groundwater for the large size aquifer and especially when the data availability is a constraint (Polemio et al., 2009). According to Ribeiro (2000), the Susceptibility Index (SI), can be used to evaluate the groundwater vulnerability from large to medium size aquifers.

Different methods have their own comparative advantages and limitations, and therefore identifying and applying the most suitable one in the area of interest is crucial. One way to deal with is to apply a set of methods, evaluate them, and then select the one that gives the most reasonable results for the study area of concern. Despite wide application of the methods, only little efforts have been made to compare and evaluate various index-overlay methods. For example, Abdelmadjid and Omar (2013) carried out the comparative study in the assessment of groundwater pollution using intrinsic vulnerability methods like DRASTIC, GOD, and SI for the Nil valley groundwater (Jijel, North-East Algeria) and concluded that DRASTIC is most suitable method in the study area and the GOD is the least. However, this study did not present a synthesized information on comparative analysis of the three methods, which could contribute to groundwater literature, in terms of key considerations, advantages/disadvantages, weights used, vulnerability classes, results and other relevant details of the parameters. In addition, that study did not estimate the risk to groundwater pollution.

Another issue is selecting the pollutant of concern while assessing vulnerability. Nitrate (NO_3 - N) is generally taken as an indicator pollutant in many groundwater environments (e.g., Abdelmadjid and Omar, 2013; Krishna et al., 2014) mainly because the major sources of nitrate in groundwater are anthropogenic, such as fertilizer used in the agricultural field or leakage from sewerage system.

In the case of Kathmandu Valley in Nepal (Fig. 1a), where a majority of 2.51 million population residing there rely on groundwater as a main source of water supply (Pandey et al., 2011; Gautam and Prajapati, 2014), groundwater is vulnerable to natural contamination as well as anthropogenic stresses such as uncontrolled groundwater abstraction due to population growth, urbanization, and industrial development. Higher rate of groundwater abstraction compared to natural recharge coupled with inefficient management of solid waste and wastewater from urban areas have increased vulnerability of the groundwater system to depletion and quality deterioration (Pandey et al., 2010). Earlier relevant studies in the area include Pathak et al. (2009), which assessed vulnerability of groundwater using DRASTIC method, and Shrestha et al. (2016), which extended the study further by assessing risk to polluation using the DRASTIC-based vulnerability as exposure pathways. However, none of the studies have attempted to evaluate various methods for vulnerability assessment to come up with the better-suited method for estimating groundwater pollution risk in the area. This study aims at assessment of groundwater vulnerability using three index-overlay methods (i.e., DRASTIC, GOD and SI); assessment of the risks to pollution using the vulnerability maps as exposure pathways; validation of the risk with observed concentraton of NO_3-N as an indicator of pollutant; and finally identification of the better-suited index-overlay method for assessing vulnerability and risk to groundwater pollution in the study area.

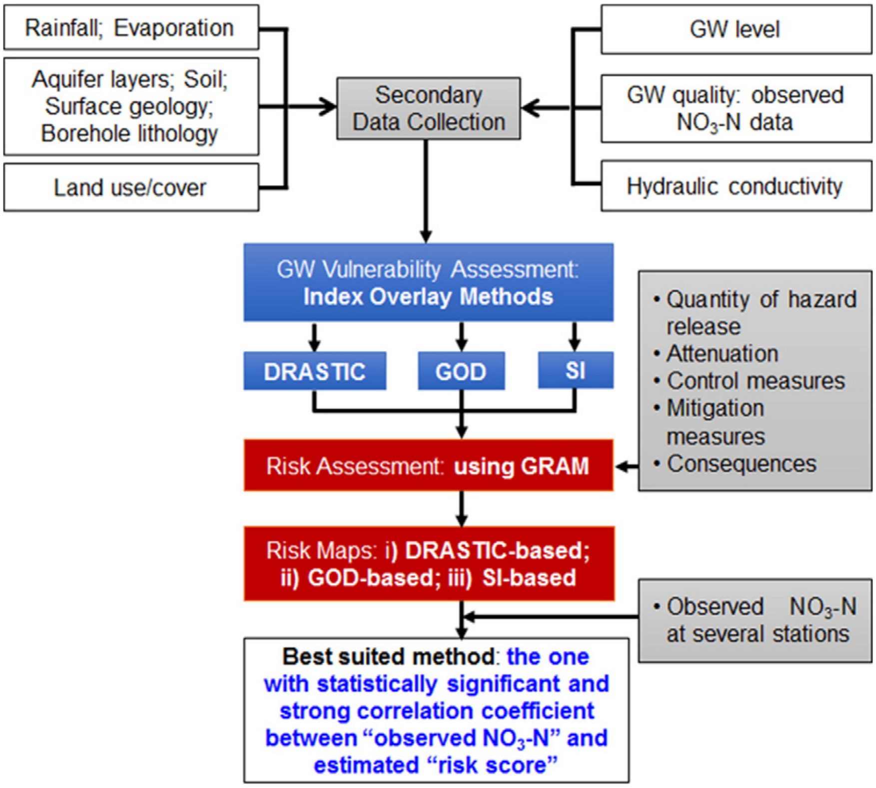

Fig. 2. Methodological framework adopted in this study.

Table 1
Description of and weights to the parameters of the three index-overlay methods.

Parameter	Description (logical relationship to vulnerability)	Weight		
		DRASTIC	GOD	SI
Depth to groundwater table (D)	• Deeper water table imply less chance for contamination to occur	5	1/3	0.186
Recharge (R)	• Higher the recharge, higher the likelihood that it transports the pollutants to groundwater and therefore higher vulnerability to pollution	4	–	0.212
Aquifer media (or aquifer type) (A)	• Indicates saturated zone material property, which affect the flow within the aquifer and controls the pollutant attenuation processes. The larger grain size and the higher porosity within the aquifer contribute to higher vulnerability of groundwater to pollution. • In case of GOD method, it indicates “Groundwater occurrence (G)”	3	1/3	0.259
Soil media (S)	• Indicates condition of upper soil media that controls the amount of recharge that can infiltrate	2	–	–
Topography (T)	• Milder the slope, retention time of surface water is more and likelihood of more recharge to the groundwater system, and effects on passage of a pollutant	1	–	0.121
Impact of vadoze zone (I)	• Indicates condition or characteristics of unsaturated zone material that might have effect on passage and attenuation of the contaminant. It influences aquifer contamination potential in similar way that of aquifer media does, depending upon its permeability and on the attenuation characteristics of the media (Added and Hamza, 2000). • In case of GOD method, lithology in unsaturated zone indicates “overall aquifer class (O)”	5	1/3	–
Hydraulic conductivity (C)	• Higher the value of the hydraulic conductivity, more water and contaminants material may be transmitted into the aquifer	3	–	–
Land use (LU)	• Higher the waste discharges more the chances of contaminant to be transmitted into the aquifer	–	–	0.222

2. Materials and methods

2.1. Study area

The Kathmandu Valley is located in central Nepal between 27° 32′ 13″–27° 49′10″ N latitude and 85°11′31″–85⁰31′38″ E longitude (Fig. 1a) and at a mean elevation of about 1300 m above mean sea level (masl). The surface watershed that covers the valley has the catchment area of 664 km^2. Groundwater basin within the watershed has an area of 327 km^2 only (JICA, 1990), which includes three major cities: Kathmandu, Bhaktapur and Lalitpur. It is a closed basin with gentle slopes towards the center. Groundwater flow is considered to be slow, particularly in the deeper aquifers (Pathak et al., 2009). The surrounding hills rise to >2000 masl. Phulchoki to the south of the valley has the highest elevation at 2762 masl. The total population of the valley in urban and rural area comprises about 2.51 million as per census of 2011. Most parts of the cultivated lands in the valley have changed to urban areas because of high rate of migration from different parts of the country and subsequent activities.

From the perspective of climate, the area falls under the warm temperate zone where the climate is fairly pleasant. Average temperature during the summer varies from 28 to 30 °C, which falls up to an average of 10.1 °C during the winter season. Average annual precipitation in the valley is around 2000 mm.

Due to population growth, urbanization and subsequent water-intensive activities, water demand, specifically groundwater withdrawal from two major aquifer layers (Fig. 1b), has increased significantly over the historical time period and expected to increase further. Increase in population in the valley due to migration from rural to urban area is increasing stress on groundwater resources in the valley. Groundwater is vulnerable to natural contamination as well as anthropogenic stresses such as uncontrolled groundwater abstraction.

2.2. Index-overlay methods of vulnerability assessment

The overall methodology as shown in Fig. 2 consists of computing groundwater vulnerability index using the three index-overlay methods (i.e., DRASTIC, GOD and SI), computing risk to groundwater contamination, developing NO$_3$-N risk map for the area, and finally identifying the most suitable index-overlay method for assessing vulnerability and risk to groundwater pollution in the study area. A comparative description of those methods are provided in Table 1 and criteria used for classifying vulnerability in Table 2.

In each method, the parameter values, representing the model components, were rated to a suitable scale, and multiplied by respective weights, and then aggregated together in the form of an index (e.g., DRASTIC, GOD or SI). Vulnerability classes were then defined based on the composite index values and maps were prepared accordingly. For all the interpolations, ArcGIS Spatial Analyst tool was used. Interpolations were carried out using inverse distance weightage (IDW) and Krigging methods. Finally, interpolation from Krigging that gave the lowest root mean square (RMSE) was adopted.

2.2.1. DRASTIC method

DRASTIC method was developed by the U.S. Environmental Protection Agency (USEPA). As per USEPA, “DRASTIC is an empirical model that calculates the vulnerability of groundwater aquifer on the basis of hydrogeological settings of the study area”. Description of the DRASTIC and suggested weights for the components are shown in Table 1. It is one of the most widely used methods because of its simplicity in concept as well as application.

Each parameter is rated within a range of 1 to 10 as suggested in Aller et al. (1987), the developer of the DRASTIC method. Lower rating means less contribution in overall vulnerability of the groundwater. Groundwater vulnerability map was prepared by overlaying the rated maps of seven parameters (Table 1) and computing the DRASTIC index as the weighted sum of the seven layers using the following equation in a GIS tool. Vulnerability classes were defined as depicted in Table 2.

$$\mathrm{DRASTICindex} = (\mathrm{parameterweight} * \mathrm{parameterrank}) \tag{1}$$

$$\mathrm{DRASTICindex} = D_W D_r + R_W R_r + A_W A_r + S_W S_r + T_W T_r + I_W I_r + C_W C_r \tag{2}$$

Table 2
Criteria for classifying vulnerability level in the three index-overlay methods.

Vulnerability class ➔		Very low	Low	Moderate	High	Very high	Reference
Range of index values	DRASTIC	–	<100	101–140	141–200	>200	Engel et al. (1996)
	GOD	0.0–0.1	0.1–0.3	0.3–0.5	0.5–0.7	0.7–1.0	Abdelmadjid and Omar (2013)
	SI	–	<45	45–64	65–84	85–100	Ribeiro (2000)

Table 3
Criteria for rating the various factors related to the risk assessment.
(Source: Somaratne et al. (2013) and Hagos (2006).)

1) Quantity of hazard release			2) Attenuation score		
Land use	Rating score	Description	Soil type	Rating score	Description
Barren/Vegetation	0.4	Low	Sand	0.80	Low
Cultivated	0.5	Medium	Silt	0.85	Medium
Built-up and water body	0.8	High	Clay	0.90	High

3) Control measures score			4) Mitigation measures score		
Category	Rating score	Description	Category	Rating score	Description
Control measures	0.65	Moderate program	Mitigation measures	0.85	Moderate program

5) Exposure pathway score					6) Consequences score		
Exposure pathway class	Rating	Vulnerability classes			Land use	Rating	Description
		DRASTIC score	GOD score	SI score			
Negligible	0.0	<10	–	<45	Built-up	10.0	High
Low	0.2	10–50	0.0–0.1	45–54	Cultivated	10.0	High
Moderate	0.4	50–100	0.1–0.3	54–84	Vegetation	10.0	High
High	0.7	100–150	0.3–0.7	>84	Water body	10.0	High
Extreme	0.9	>150	>0.7	–	Barren land	2.5	Low

where: D, R, A, S, T, I and C are the seven parameters and the subscripts r and w are the corresponding rating and weights, respectively.

2.2.2. GOD method

This method was developed by Foster (1987) for studying vulnerability of an aquifer against the vertical percolation of pollutants through the unsaturated zone, without considering their lateral migration in the saturated zone (Abdelmadjid and Omar, 2013). It is an empirical system for rapid evaluation of the aquifer vulnerability to contamination. According to Gogu and Dassargues (2000), this method gives reliable results and is more suitable in designing extended areas.

This method takes into consideration of three aspects: Groundwater occurrence (G), Overall aquifer class (O), and Depth of groundwater table (D). The three components (i.e., G, O and D) are represented by the parameters C_a (aquifer type), C_l (lithology in unsaturated zone) and C_d (depth of the groundwater table), respectively. The vulnerability index in this method was calculated by multiplying the three parameters using equal weight (Table 1) and the vulnerability classes were defined as depicted in Table 2.

2.2.3. SI method

The SI method was developed by Ribeiro (2000) in Portugal. It is used to assess vulnerability of vertical agricultural pollution generated mainly by nitrates and secondarily by pesticides. According to Ribeiro (2000), the SI method can be used to evaluate the groundwater vulnerability assessment from large to medium scale (e.g., 1:50,000–1:200,000) aquifers and suited if the pollution is released from agricultural or rural areas. This method is based on five parameters; four of them are identical to the DRASTIC (i.e., D: depth to groundwater table; R: effective recharge; A: aquifer media; and T: topographic slope of the land) and the fifth one is the land use (LU) (Table 1). The four parameters as used in DRASTIC were assigned ratings 10 times the rating of DRASTIC and the LU was rated as did in Ribeiro (2000). The five parameters were aggregated together applying the weights as depicted in Table 1. Then vulnerability classes for SI method were defined as per the criteria as depicted in Table 2.

2.3. Risk assessment

Risk assessment refers to the process of determining potential impacts of any pollutant. It can be determined based on hazard, intrinsic vulnerability of groundwater to contamination, and potential consequences of the contamination event (Zwahlen, 2003). Vulnerability, therefore, is the only one component of risk, the directly related term to the impacts. Groundwater pollution risk assessments help screen out potentially harmful sources and areas threatened by groundwater contamination, which could be an important basis for decision making, such as land zoning and groundwater monitoring. This study has adopted Groundwater Risk Assessment Model (GRAM) (Somaratne et al., 2013), which adopts a "multi-barrier" approach and considers likelihood of release, contaminant pathway, and consequences as related in the Eqs. (3)–(5).

$$\text{Likelihoodofrelease} = \text{Quantity} \times \text{Attenuation} \times \text{ControlMeasures} \times \text{Mitigationmeasure} \tag{3}$$

$$\text{Likelihoodor}\,(\text{Likelihoodofdetection}) = \text{LikelihoodofRelease} \times \text{ExposurePathway} \tag{4}$$

$$\text{Risk} = \text{Likelihoodofdetection} \times \text{Consequences} \tag{5}$$

Table 4
Description of data and sources used in this study. Mbgl is meters below ground level.

Data type: description	Unit	Resolution	Source	Used with (name of model)
Groundwater basin map of the study area	–	Spatial: 30 m × 30 m	JICA (1990)	DRASTIC, GOD, SI
Geological map of Kathmandu Valley	–	Spatial: 30 m × 30 m	Shrestha et al. (1998)	DRASTIC
Digital Elevation Model of Kathmandu Valley (for topography): ArcView/ArcInfo Grid files	–	Spatial: 90 m × 90 m	Survey Department of Nepal	DRASTIC, SI
Soil Map of Kathmandu Valley	–	1:1,000,000	SOTER, Nepal	DRASTIC, GOD
Land use of Kathmandu Valley	–	Spatial: 30 m × 30 m	ICIMOD, Nepal	SI
Borehole lithology	–	Tabular data	Department of Mines and Geology, National drilling company, Groundwater development project/Department of Irrigation	DRASTIC, GOD, SI
Water table depth at 90 locations; NO_3-N concentration in shallow aquifer	mbgl; mg/l	Tabular data	Groundwater development project/Department of Irrigation, Nepal	DRASTIC, GOD, SI
Precipitation and evaporation: point data at metrological stations; year: 2008	mm	Spatial: 5 stations for precipitation and 2 evaporation stations; temporal: monthly	Department of hydrology and meteorology	DRASTIC, SI
Hydraulic conductivity (K)	m/day	–	Pandey and Kazama (2011)	DRASTIC

Four categories for likelihood of release are considered: i) Quantity: release due to nature of the source, amount, type and occurrence; ii) Attenuation: contaminant characteristics, attenuation and degradation capacity; iii) Control measures: best management practices (BMP), regulations and guidelines; and iv) Mitigation measures: emergency plans and effective monitoring.

The likelihood of contamination (or detection) estimated as a multiplication of 'Likelihood of Release' and 'Exposure Pathway' is any unplanned event resulting in consequences and is expressed as a qualitative or quantitative description of probability or frequency. Finally, risk is estimated as a multiple of 'Likelihood of Detection' and 'Consequences'. The likelihood assessment consists of describing the potential of a risk agent release from the source and existence of a pathway, which is the route a contaminant may follow from hazard to the receptor. All the components of risk index were rated as per the suggestion provided in GRAM model documentation.

In this study, the 'quantity' of hazard release map was developed by reclassifying land use map on the basis of score suggested in Somaratne et al. (2013), the developer of GRAM model (see Table 3). Attenuation map was developed by considering the attenuation capacity for

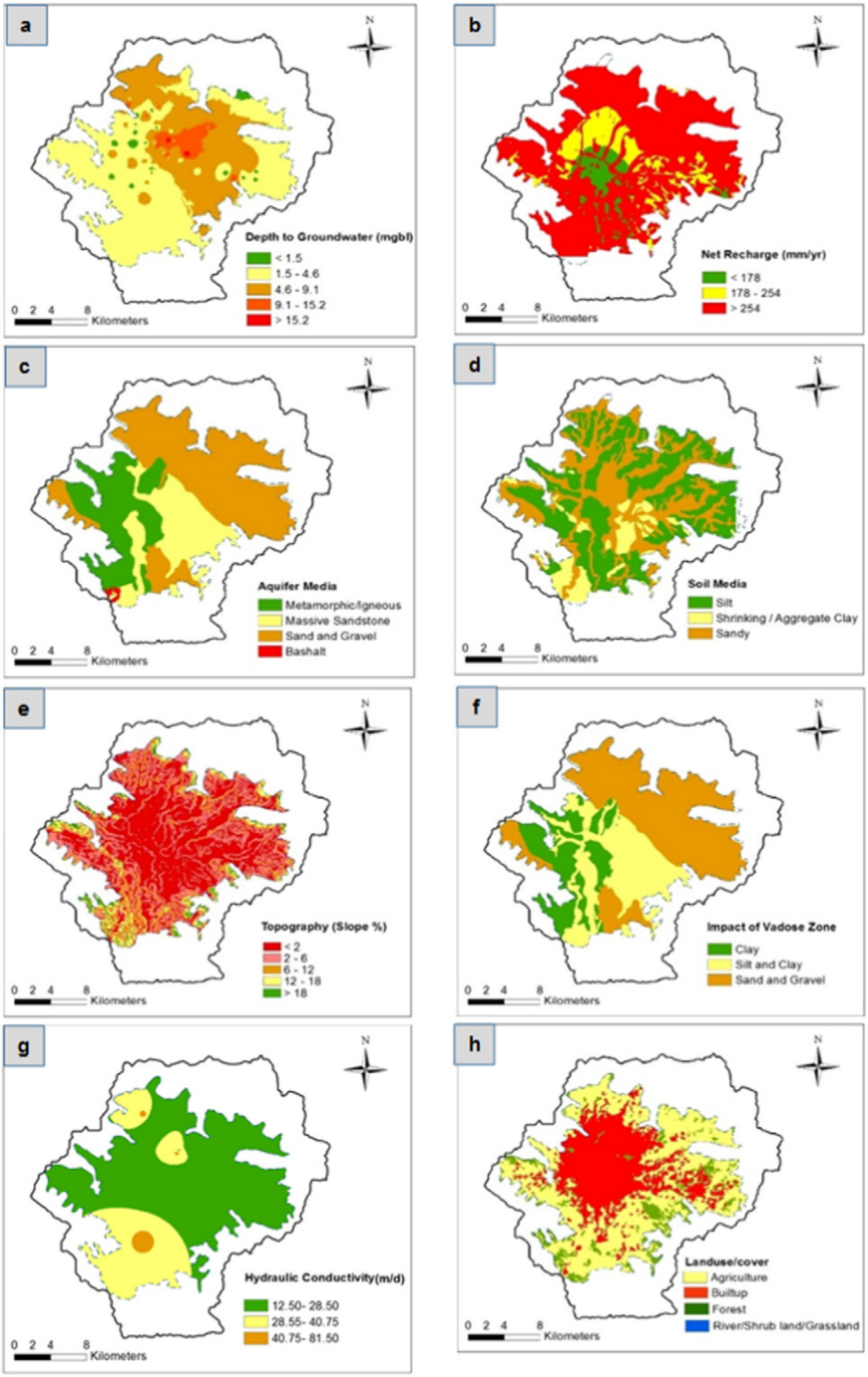

Fig. 3. Spatial distribution in groundwater vulnerability parameters in Kathmandu Valley groundwater basin: a) depth to groundwater table (mbgl); b) recharge (mm/year); c) aquifer media; d) soil media; e) topography (slope); f) impact of vadose zone; g) hydraulic conductivity (m/day); and h) land use/cover.

different soil types as discussed in Hagos (2006) (see Table 3). Rating for control and mitigation measures were selected considering that only moderate programs has taken place in case of Kathmandu Valley. Based on the rating of the four components, spatial distribution in 'likelihood of release' was calculated using raster calculator in a GIS platform following Eq. (3).

Vulnerability map was used as an indicator of 'exposure pathways' for calculating "Likelihood of detection" (Eq. (4)). The exposure pathway was classified into five classes with various ranges of vulnerability scores (as shown in Table 3) to estimate spatial distribution in 'likelihood of hazard detection' (Eq. (4)). Finally, risk map was prepared by aggregating together the raster maps of 'likelihood of detection' and 'consequences of hazard' (Eq. (5)) with three risk levels: low (risk score = 0.0–0.6), moderate (risk score = 0.6–2.5), and high (risk score = 2.5–10.0). The score for the 'consequences of hazard' was provided considering the effect of NO_3-N pollution on human in different land use category (Table 3). The 'consequences of hazard' is the outcome of an event expressed as loss, gain and injury.

2.4. Selecting the better-suited index-overlay method

Observed NO_3-N concentrations at 20 selected locations were used for the purpose. The significance and strength of the correlation between the observed NO_3-N concentrations and risk scores were taken as the basis to select the better-suited index-overlay method for assessing vulnerability and risk to groundwater pollution in the Kathmandu Valley. The risk scores at the points of interest (i.e., NO_3-N observation point) were extracted using ArcGIS tool. The index-overlay method which gives a significant and the strongest correlation was considered as the better-suited method for the study area.

2.5. Data and the sources

Mainly secondary data were collected from various sources including government agencies, private organizations, and personal communications with groundwater experts. Table 4 depicts description of major data, their types, resolution and sources.

3. Results and discussion

3.1. Groundwater vulnerability parameters

Eight parameters depicted in Table 1 are used with the three index-overlay methods for groundwater vulnerability assessment. Fig. 3 shows spatial distribution in those parameters and this section discusses the results.

3.1.1. Depth to groundwater table

This layer was developed based on direct measurement of groundwater levels at 90 shallow wells, both dugwells and tubewells, by Pathak et al. (2009). The observed data was interpolated using inverse distance weightage (IDW) technique. The data was reclassified and given ratings from 1 to 10 depending on the contribution to groundwater pollution. The average depth to groundwater table is 6.85 m whereas minimum and maximum values are 0.5 m and 22.9 m, respectively. Results show that a majority of the basin area (about 59.5%) have groundwater table in a range of 1.5–4.6 m followed by another big chunk of 34.9% within 4.6–9.1 m (Table 5). Therefore, groundwater table in 94.3% of the groundwater basin are in a range of 1.5–9.1 m.

3.1.2. Recharge

Net recharge layer, which refers to the direct infiltration of rainfall into shallow aquifer, was prepared based on following equation: Net recharge = Rainfall − Evaporation − Runoff. Rainfall layer was prepared by interpolating average annual rainfall at 21 rainfall stations in the area; evaporation layer was prepared based on data at only one existing evaporation station located at Tribhuvan International Airport; and runoff layer was prepared by assigning differential runoff coefficients for different land cover/use types (e.g., 0.80 for built up areas, 0.27 for forest, 0.25 for open field/lawn, 0.40 for agricultural field with clay, 0.30 for agricultural field with sand, and 0.15 for water body) (Pathak et al., 2009). The mean annual net recharge values were then reclassified and rated within a range from 6 to 9. Results indicate that some 80% of the groundwater basin area is under higher net recharge areas (i.e., recharge > 254 mm/year) (Table 5). Lower recharge areas (i.e., recharge

Table 5
Vulnerability parameter classes: range of values, ratings and area (km^2). GW is groundwater; mbgl is meters below ground level.

Parameter	Attributes	Attribute values				
Depth to groundwater table (mbgl)	Range	<1.5	1.5–4.6	4.6–9.1	9.1–15.2	>15.2
	Rating for DRASTIC	10	9	7	5	3
	Rating for GOD	1.0	0.9	0.8	0.7	0.6
	Area (% of GW basin)	1.3	59.4	34.9	4.2	0.2
Recharge (mm/year)	Range	<178	178–254	>254		
	Rating	6	8	9		
	Area (% of GW basin)	6.4	13.5	80.1		
Aquifer media (−) [for DRASTIC]	Types	Metamorphic/igneous	Massive sandstone	Sand and gravel	Basalt	
	Rating	3	6	8	9	
	Area (% of GW basin)	24.6	23.2	51.7	0.5	
Aquifer type (−) [for GOD]	Types	Sand & gravel	Silt & clay	Clay		
	Rating	0.6	0.5	0.4		
	Area (% of GW basin)	51.4	29.7	18.9		
Soil media (−)	Types	Silt loam	Shrinking/Aggregated clay	Sandy		
	Rating	4	7	9		
	Area (% of GW basin)	46.0	14.1	39.9		
Topography (slope, %)	Range	< 2	2–6	6–12	12–18	>18
	Rating	10	9	5	3	1
	Area (% of GW basin)	29.0	42.4	19.2	5.1	4.3
Impact of vadose zone (−)	Types	Clay	Silt & clay	Sand & gravel		
	Rating	3	6	8		
	Area (% of GW basin)	19.0	29.6	51.4		
Hydraulic conductivity (m/day)	Range	12.2–28.5	28.5–40.8	40.8–81.5		
	Rating	4	6	8		
	Area (% of GW basin)	71.3	27.2	1.5		
Land use/cover (−)	Types	Agriculture	Builtup	Forest	River	Shrub & grassland
	Rating	90	75	0	50	50
	Area (% of GW basin)	54.7	35.1	9.2	0.2	0.8

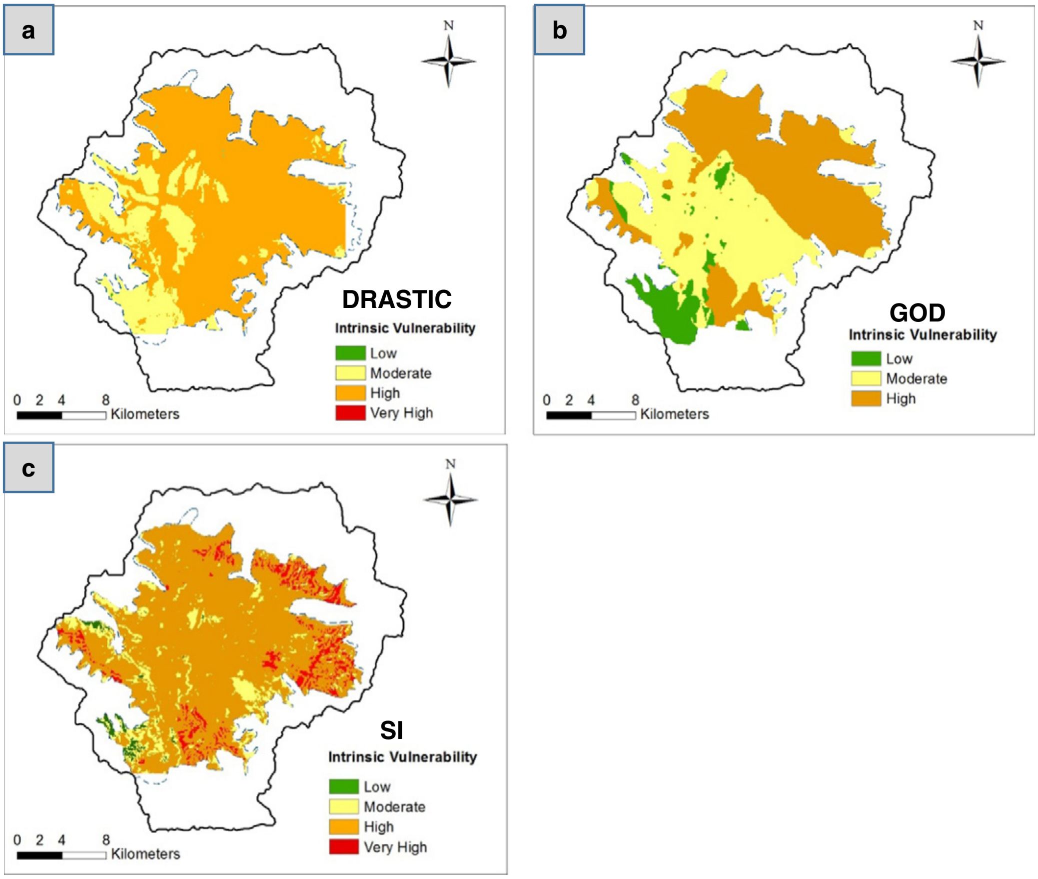

Fig. 4. Intrinsic vulnerability of groundwater to pollution in Kathmandu Valley from: a) DRASTIC; b) GOD; and c) SI.

<178 mm/year), that constitute of only 6.4% of groundwater basin, are located at the central part of the valley.

3.1.3. Aquifer media

This layer was produced from well profile and environmental geological map of Kathmandu Valley. The map was reclassified into four classes and then assigned ratings from 3 to 9. Sand and gravel media, which have large grain size and low attenuation, dominate most of the northern and eastern parts and covers almost half of total area of the groundwater basin.

3.1.4. Soil media

This layer is reproduced from engineering and environmental geological map of Kathmandu Valley. It was reclassified into three classes, and then assigned ratings from 4 to 9 based on their infiltration capacity. Silt and gravel soil types cover most parts of the groundwater basin in the valley. Clay covers about 1/7th of the groundwater basin only and are scattered around central and southern part of the groundwater basin.

3.1.5. Topography

Slope layer derived from Digital Elevation Model (DEM) using ArcGIS was reclassified into five classes and rated with values from 4 to 9. It ranges from zero to >18%. Higher slope areas are concentrated towards the rim of the aquifer boundary and flat slopes are located towards the center of the groundwater basin. >70% of the groundwater basin area is under gentle slope (0–6%). Slope increases outwards from the valley center to over 18% in the surrounding mountains.

3.1.6. Impact of vadose zone

This layer was developed based on well profile and environmental geological map of Kathmandu Valley. It was reclassified into three classes (namely clay; silt and clay; and sand and gravel), each representing different geological units above the groundwater table, and assigned ratings from 3 to 8. The vadose (or unsaturated) zone for north and north-eastern part of the groundwater basin consists of sand and gravel, which cover almost half of the groundwater basin, and other parts consist mainly of silt and clay, which cover nearly 30% of groundwater basin. Therefore, the north and north-eastern parts have a higher rating.

3.1.7. Hydraulic conductivity

This layer was taken from Pandey et al. (2012), reclassified into three classes, and assigned ratings from 4 to 8. The hydraulic conductivity

Table 6
Vulnerability classes and their attributes for three index overlay methods. GW is groundwater.

Vulnerability class	Attributes	Attribute values		
		DRASTIC	GOD	SI
Very Low	Index range	–	0.0–0.1	–
	Area (% of GW basin)	–	0.0	–
Low	Index range	<100	0.1–0.3	<45
	Area (% of GW basin)	0.0	4.1	1.3
Moderate	Index range	101–140	0.3–0.5	45–64
	Area (% of GW basin)	19.6	55.2	11.3
High	Index range	141–200	0.5–0.7	65–84
	Area (% of GW basin)	80.4	40.7	80.9
Very high	Index range	>200	0.7–1.0	85–100
	Area (% of GW basin)	0.0	0.0	6.5

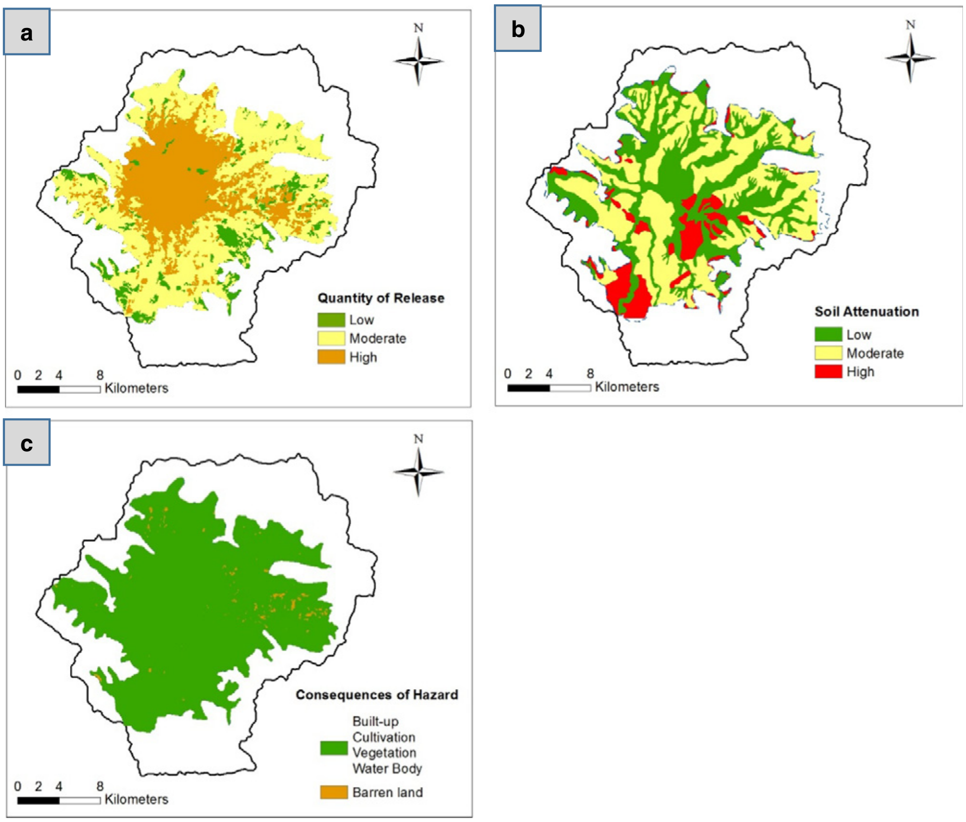

Fig. 5. Risk parameters: a) quantity of hazard release; b) attenuation; and c) consequences.

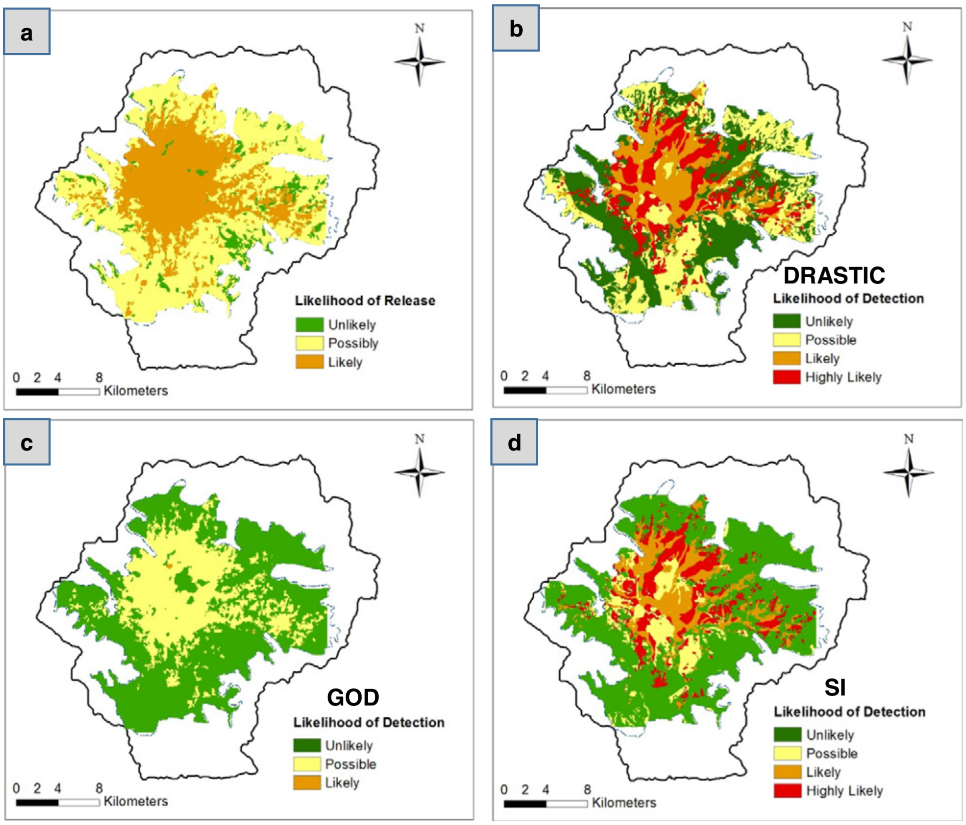

Fig. 6. Likelihoods of release and detection of nitrate in groundwater: a) likelihood of release; b) likelihood of detection (DRASTIC); c) likelihood of detection (GOD); d) likelihood of detection (SI).

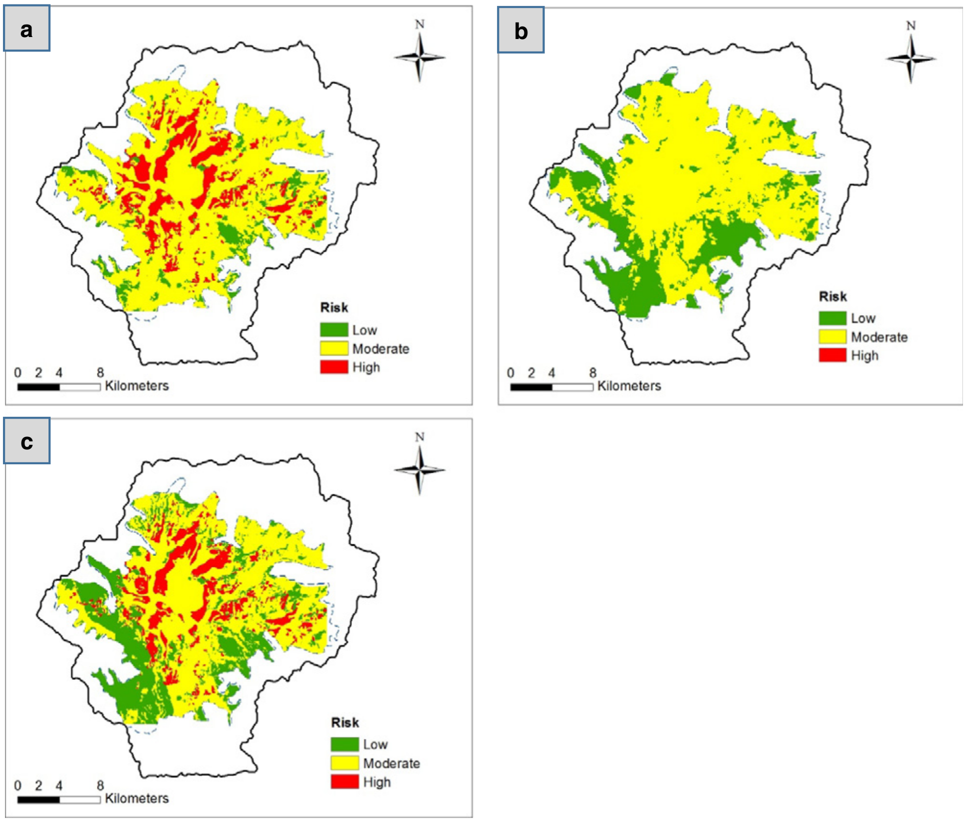

Fig. 7. NO_3-N pollution risk to groundwater in Kathmandu Valley based on three index-overlay methods: a) DRASTIC; b) GOD; and c) SI.

ranges from 12.5 to 44.9 m/day for shallow aquifer. A zone with hydraulic conductivity in a range of 12.2–28.5 m/day occupies 51.4% of the shallow aquifer area, mostly in the northern part of the groundwater basin.

3.1.8. Land use/cover (LULC)

The land use/cover of the area can broadly be classified into agriculture, built-up, forest, and others (i.e., river/shrubland/grassland). The built-up area is mostly located in the central part of the valley, which is then surrounded by agriculture area. Forest areas are found in the periphery of the valley. The agricultural are covers 54.7%, the majority of the groundwater basin, which is then followed by built-up area (~35%) (Table 5). Forest covers only about nine percentage of area.

3.2. Intrinsic vulnerability of groundwater

The intrinsic vulnerability maps using the three index-overlay methods are shown in Fig. 4 and areas under the vulnerability classes and their attributes are depicted in Table 6. Higher vulnerability index refers to higher capacity of the hydrogeological system to move contaminants from surface to groundwater whereas the low vulnerability index indicates that groundwater is better protected from contaminant to reach to groundwater. DRASTIC and SI results show that around 80% of the aquifer areas are under high vulnerable zone; whereas according to GOD, areas under high and moderate vulnerabilities are 40% and 55%, respectively (Table 6). All the methods delineate northern and northeastern parts of the groundwater basin, which consist mainly of sand and gravel, under high or very high vulnerable zones. The factors/parameters leading to high vulnerability in the northern part are high permeability of aquifer media, favorable soil type for pollution movement, high rate of recharge, and high hydraulic conductivity.

3.3. Risk assessment to groundwater pollution

Spatial variation in risk to groundwater pollution in the valley's shallow aquifer was estimated following GRAM methodology discussed in the Section-2. Three risk factors, namely, vulnerability, hazard, and consequences of the hazard, were considered. Results of the spatial variations in risk parameters, two risk dimensions (i.e., likelihood of release, and likelihood of detection), and risks levels using vulnerability (or exposure pathways) from three index-overlay methods are shown in Figs. 5–7, respectively, and risk attributes are depicted in Table 7.

In case of DRASTIC, three levels of risks, namely, low, moderate and high, are visible (Fig. 7a). Almost three-fourth of the aquifer is under moderate risk condition (Table 7). If we compare the risk map with the land use/cover map (Fig. 3h), most of the high risk areas are concentrate in the built-up area, which has a high population density. Sewage and wastewater from these areas may serve as sources of pollution hazard. In case of GOD, the areas under low and moderate risks are 24% and 76%, respectively, which in case of SI-based risk are 26.9% and 58.6%,

Table 7
Groundwater pollution risk classes and their attributes. GW is groundwater.

Risk level	Attributes	Attribute values		
		DRASTIC	GOD	SI
Low	Index range	0.1–0.6	0.1–0.6	0.1–0.6
	Area (% of GW basin)	8.8	23.9	26.9
Moderate	Index range	0.6–2.5	0.6–2.5	0.6–2.5
	Area (% of GW basin)	74.4	76.1	58.6
High	Index range	2.5–10.0	2.5–10.0	2.5–10.0
	Area (% of GW basin)	16.8	–	14.5

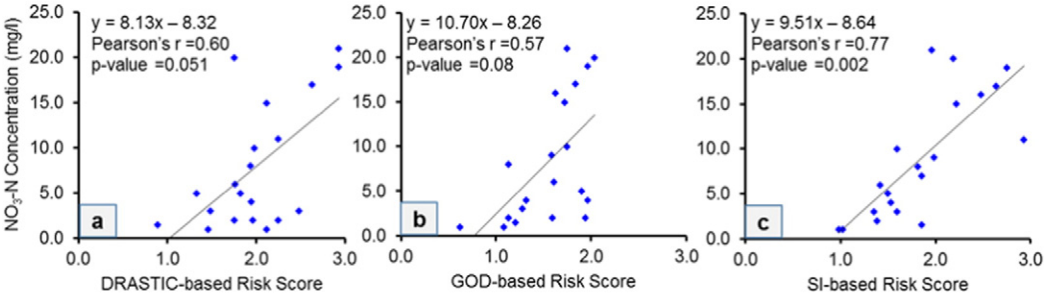

Fig. 8. Relationship between NO_3-N concentrations and risk scores with exposure pathways from: a) DRASTIC; b) GOD; and c) SI.

respectively (Table 7). In general, areas under the moderate risks are more than half for all the three methods.

The results in terms of moderate risk zones are very much comparable for DRASTIC and GOD. However, in case of SI, only 58.6% of the aquifer areas are under moderate risk, which is contrasting with that of DRASTIC and GOD. The reasons for this variation could be consideration of land use/cover in the SI method, which was not considered in the other two methods. Another consistency in the results is that relatively high risk areas by all the three methods were found in the central built-up areas. It indicates that human activities such as unplanned and unprotected sewage disposal are likely be the contributing factor to the nitrate pollution risk in the valley's shallow aquifer. Those activities include but not limited to unplanned and unprotected disposal of sewage and solid waste and leakage for the septic tanks. Another source of nitrate pollution risk could be natural (or soil conditions in the area) because sandy and silty soil, which cover most of the groundwater basin, have relatively higher porosity and they allow contaminated water to pass through it easily.

Results reveal that urban area, in general, has high risk of NO_3-N than agriculture and forest areas. The occurrence of high risk of NO_3-N in urban area might be due to the unplanned disposal of human and animal waste and leakage from the septic tank. Because of the lack of maintenance of groundwater wells and septic tanks, NO_3-N could infiltrate into the shallow aquifers. In this case, leaching from septic tank, domestic wastewater, industrial discharge, poorly constructed and unmanaged sewer lines, and unplanned disposal of human and animal waste are the likely sources of high NO_3-N risk in shallow aquifer. About half of domestic and industrial wastewater generated in Kathmandu Valley is not collected and appropriately treated before disposal due to lack of adequate and effective wastewater infrastructures. In addition to wastewater, Kathmandu Valley generates 579.34 tons of solid waste per day, out of which, only 490 tons are collected (ADB, 2013). In many transfer stations, they are piled for quite sometimes due to untimely collection. This may increase risk of pollution of shallow groundwater from leaching.

3.4. Better-suited index-overlay method for the area

The estimated risk based on GRAM model was evaluated by means of significance and strength of correlation between the risk score and observed NO_3-N concentration at twenty selected wells scattered around the study area. The estimated pollution risk shows a positive linear correlation with NO_3-N concentration (Fig. 8). The degree of relationship between the risk scores and NO_3-N concentrations indicated by Pearson's correlation coefficient (r) shows that the statistically significant and stronger correlation (at 5% level of significance or 95% level of confidence) when the exposure pathways are based on the SI-based vulnerability. It indicates that SI method tends to give better estimation of vulnerability and pollution risk in this study area compared to other two index-overlay methods.

4. Conclusion

This study evaluated three index-overlay methods (i.e., DRASTIC, GOD, and SI) to assess shallow groundwater vulnerability and risk to pollution in Kathmandu Valley of Nepal. All the three methods suggest that north-eastern parts of the groundwater basin, which consist mainly of sand and gravel, are under high or very high vulnerable zones. Based on DRASTIC and SI results, around four-fifth of the groundwater basin area are under high vulnerable zone. Higher vulnerability refers to higher capacity of the hydrogeological system to move contaminants from surface to groundwater whereas the low vulnerability indicates that groundwater is better protected from contaminants from surface.

Further analysis of risk to groundwater pollution using GRAM method revealed that at least three-fifth of the groundwater basin area are under moderate risk, which may go up to three-fourth if DRASTIC – and GOD-based vulnerabilities are considered as exposure pathways. Importantly, most of the high risk areas are concentrated in the built-up or urban areas, which has high population density and generate more amount of wastewater and solid waste. Furthermore, it was found that SI method has a stronger correlation between estimated risk and observed NO_3-N values; indicating better suitability of SI method (compared to others) for the Kathmandu Valley for groundwater vulnerability and risk assessment to groundwater pollution.

As around 75% of the groundwater basin is under moderate risk and 15% under the high risk, it's the high time that the government should keep an eye to the major contributors of pollution and take necessary action to reduce the current risk level and provide good quality drinking water to over 2.51 million people residing in the valley.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.09.141.

Acknowledgements

The authors would like to acknowledge Asian Institute of Technology (AIT), Asian Institute of Technology and Management (AITM) in Nepal, and Center of Research for Environment Energy and Water (CREEW) in Nepal for various levels of support to conduct this study.

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