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Assessment of Hydro-geochemical Evolution Mechanism and Suitability of Groundwater for Domestic and Irrigation Use in and Around Ludhiana city, Punjab, India

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ABSTRACT

Groundwater and surface water samples in and around Punjab Agricultural University (PAU) Ludhiana were collected and analyzed for physico-chemical characteristics. The groundwater in the study area was found to be controlled by rock-water interaction, carbonate mineral (calcite and dolomite) weathering and ion exchange processes. The water facies were mainly of Ca-Mg-HCO_3 and Na-HCO_3 types, showing fresh water characteristics. All the groundwater samples were found to be with in the safe limits with respect to the dissolved solids, major cations, major anions and trace elements making it suitable for domestic use. However, the hardness may affect the acceptability of this groundwater for drinking. Most of the groundwater samples are suitable for irrigation, considering salinity hazard, sodicity hazard and bicarbonate hazard. However, magnesium hazard is found to persist in 63% of groundwater samples. The canal water is found to be of good quality for irrigation.

Key words: Hydro-geochemical evolution, Water quality, Domestic and Irrigation use, Salinity hazard, Sodicity hazard, Bicarbonate hazard, Magnesium hazard.

INTRODUCTION

In India, demand for fresh water is increasing rapidly due to population growth and intense agricultural activities. Water scarcity persists even in large parts of the Indo-Gangetic alluvial plains of north and northwest India. These alluvial formations have been extensively exploited for large-scale water supplies for industrial, irrigation and urban uses. A steady and large-scale groundwater loss in the northern India was reported by Tiwari et al., (2009). In Punjab, more than 83% of land is under agriculture. Traditionally, the farmers follow the maize-wheat or sugarcane-maize-wheat cropping pattern. During the last three to four decades, they have shifted to wheat-rice cropping pattern, thereby leading to an increased demand for irrigation water. Groundwater has been the main source of irrigation in these Indo-Gangetic alluvial plains of Punjab region, basically from tube wells. Presently, there are more than one million tube wells in Punjab (Gupta, 2010).

Central Pollution Control Board (CPCB, 2007) reported that groundwater quality of Ludhiana city is good for irrigation and drinking. Apart from CPCB, previous studies on groundwater quality in Ludhiana were mostly focused on heavy metal pollution around Buddha nullah (Garg et al., 2015). High concentration of heavy metals in groundwater were reported, e.g., chromium and cyanide (Chaudhary et al., 2001), and arsenic (Garg et al., 2015; Jain and Kumar, 2007).

The objective of this study is to understand the hydro-geochemistry of the study area and to examine groundwater suitability for domestic and irrigation purposes based on physico-chemical parameters, such as, pH and Electrical Conductivity (EC); major cations such as sodium (Na^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and potassium (K^+); major anions such as chloride (Cl^-), sulfate (SO_4^{2-}), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-), nitrate (NO_3^-) and fluoride (F^-); total hardness (TH), and trace elements including copper (Cu), iron (Fe), manganese (Mn), zinc (Zn), arsenic (As), selenium (Se), and chromium, (Cr). The suitability of groundwater and surface water for irrigation purpose based on parameters such as EC, Sodium percentage (Na^+ %), Sodium adsorption ratio (SAR), Residual sodium carbonate (RSC), Permeability index (PI), Kelly's Ratio (KR) and Magnesium hazard (MH) is also investigated.

Study Area

The study area in and around the PAU campus is located in the central part of Punjab region (Figure 1a-b). It lies between latitudes of 30° 45′ to 31° and longitudes of 75° 45′ to 76°.

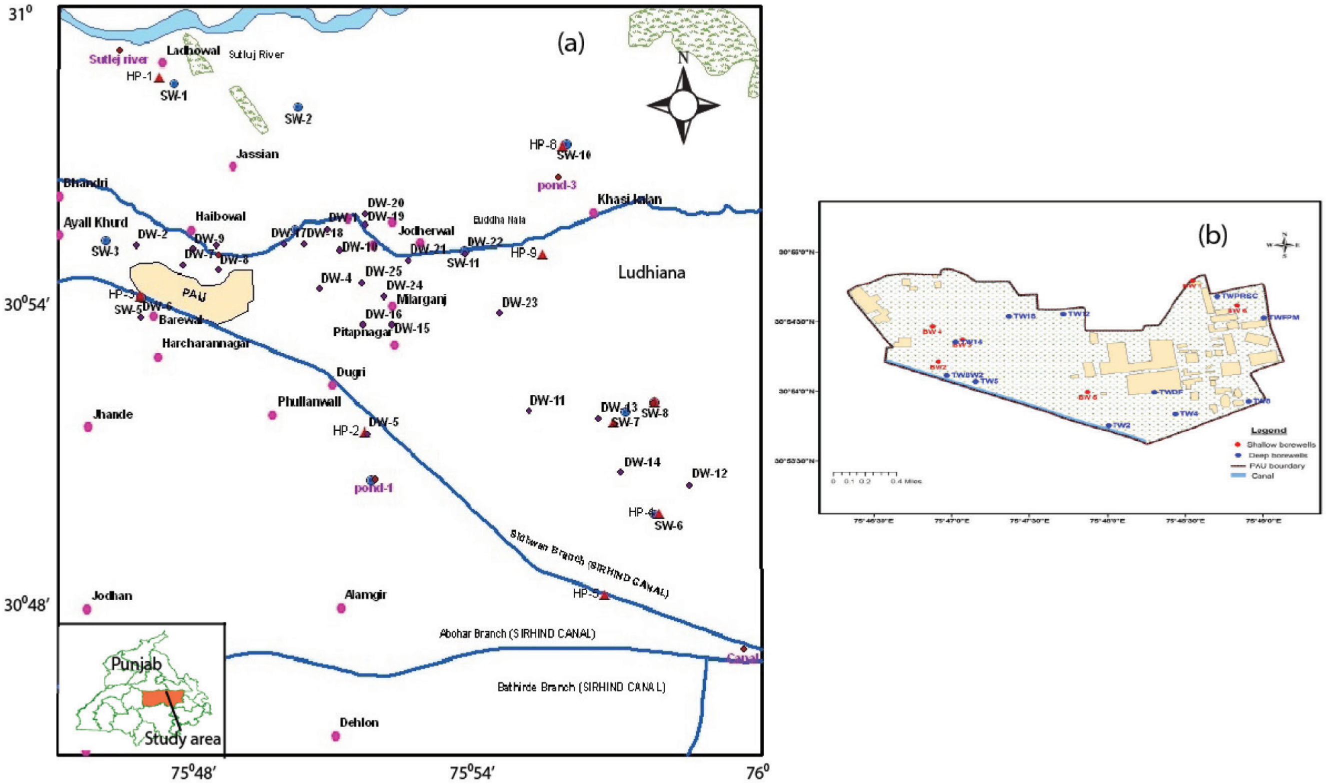

Figure 1. Location of sampling points (a) around PAU campus, Ludhiana city, Punjab, (b) inside the PAU campus.

PAU is located in the south western part of Ludhiana city and is situated at an elevation of 247m above mean sea level. Most part of the area is under anthropogenic activities for the last 30 to 35 years including intensive agriculture and poultry farming (Thind and Kansal, 2002). Irrigation, mainly by tube wells, is supported by canal water in some parts of the area. The EW flowing Sutlej River lies on the northern part of the study area. The Buddha nullah (stream) between Sutlej River and PAU campus runs parallel to the Sutlej River for a fairly large section of its course in the district and ultimately joins the river in the northwestern corner of the district. The stream water witnessed pollution after entering the Ludhiana city due to the city sewerage discharges. The Buddha nullah is reported to be extremely polluted because of the untreated industrial discharge (Singh et al., 2013). Bhalla et al., (2011) reported high concentration of Cr, Fe and Pb in the nullah. The Sirhind canal passes on the south, adjoining the campus.

Geology and Hydrogeology

Ludhiana district is occupied by Indo-Gangatic alluvium of Quaternary age. The subsurface geological formations of the area comprise of sand, silt, clay and kankar in various proportions. The litholog data of bore wells drilled to a depth of 400m by Central Ground Water Board (CGWB) and state government indicate the presence of many sand beds (5 prominent sand horizons) forming the principal aquifers separated by clay beds at various depths. The first aquifer generally occurs between 10 and 30m, the second between 50 and 120m, third between 150-175m, fourth between 200-250m and the fifth between 300-400m. The combined aquifer discharge rate lies between 3-52 lps with 4.3×10^{-4} to 6.98×10^{-4} storativity and transmissivity in the range of 628 to 1120 m^2/day. The sand content of the aquifer in the district varies from 50 to 80%. Clay beds, though thick at places, occur mostly as lenses and pinch out laterally. The granular material becomes coarser with depth. The aquifer at deeper levels acts as semi-confined to confined conditions (CGWB, 2007).

In the study area, groundwater is being pumped from moderate and deep wells (300-400 feet depth) mainly for agricultural purposes. There are about 40 deep wells within the university campus area and innumerable number of agricultural wells with approximate discharge rate of about 50-60 m^3/h. The first aquifer occurring within the depths of 10 and 30m is completely desaturated. The static water level in the shallow observation wells (150-200 feet) in the university campus area varies from 20-26m below ground level.

Materials and Methods

A total of 17 ground water samples from inside the PAU campus and 15 ground water samples from outside the

Table 1. Location of sampling sites and depth of groundwater samples.

Inside PAU campus			Outside PAU campus		
S. No.	Name	Well depth (m bgl)	S. No.	Name	Well depth (m bgl)
1	BW1	150-200	18	HP3	75-100
2	BW2	-do-	19	HP5	-do-
3	BW3	-do-	20	HP6	-do-
4	BW4	-do-	21	HP8	-do-
5	BW5	-do-	22	SW3	250-300
6	BW6	-do-	23	SW4	-do-
7	TW12	250-300	24	SW7	-do-
8	TWFPM	-do-	25	SW9	-do-
9	TWDF	-do-	26	SW10	-do-
10	TWBW2	-do-	27	DW1	350-400
11	TWPRSC	-do-	28	DW5	-do-
12	TW2	350-400	29	DW8	-do-
13	TW4	-do-	30	DW14	-do-
14	TW5	-do-	31	DW23	-do-
15	TW8	-do-	32	DW24	-do-
16	TW14	-do-	33	pond	-do-
17	TW18	-do-	34	canal	-do-

campus and two surface water samples (from the canal and pond) were collected from different depths during March 2009, before the onset of monsoon. The sampling locations are shown in Figure 1a (wells outside campus) and Figure 1b (wells inside campus), and are listed in Table 1. The results of analyses (range and mean value with standard deviation) for groundwater and surface water from inside and outside campus along with World Health Organization (WHO 1996, 2011) guidelines for maximum permissible limit (MPL) and BIS (2003) guidelines for MPL and desirable limit (DL) are presented in Table 2.

The irrigation water quality parameters, such as SAR, % Na^+, RSC, PI, KR and MH are computed from the chemical analytical data of groundwater sample.

RESULTS AND DISCUSSION

Mechanisms controlling groundwater chemistry

Hydro-chemical facies, the Gibb's diagram, and thermodynamic approach were used to understand the geochemical mechanisms that control the groundwater chemistry in the study area.

Gibb's diagram

The groundwater chemistry in an aquifer depends upon the chemical composition of the infiltrating (precipitation/surface) water, rate of evaporation, and chemical composition of rocks present in the aquifer (Gibbs, 1970). In order to assess the groundwater evolution mechanism in and around the PAU campus, the Gibbs ratio I: $Na^+/(Na^+ + Ca^{2+})$ for cations and the Gibb's ratio II: $Cl^-/(Cl^- + HCO_3^-)$ for anions were plotted with respect to TDS in Figure 2a and 2b respectively. The data on the Gibbs diagram suggest that groundwater chemistry is mainly controlled by water-rock interactions, irrespective of well depth, both inside and outside the PAU campus.

Hydro-chemical facies

Piper diagrams (Piper, 1944 and 1953) are used to understand the hydro-chemical patterns and water type, which help in hydro-geochemical classification (Back and Hanshaw, 1965). The piper diagrams for this study, obtained with the Geochemist Workbench software (Bethke and Yeakel, 2012) (Figure 3), is classified in to six hydro-chemical facies based on the dominance of different cations and anions, such as: facies 1: Na^+-Cl^- type (saline), facies 2: Ca^{2+}- HCO_3^- type (temporary hardness), facies 3: Na^+-Ca^{2+}- HCO_3^- type, facies 4: Ca^{2+}-Mg^{2+}- Cl^- type, facies 5: Ca^{2+}- Cl^- type (permanent hardness), and facies 6: Na^+-HCO_3^- type (alkali carbonate). In the study area, most of the samples are Ca-HCO_3 type where the alkaline earth elements ($Ca^{2+}$and Mg^{2+}) exceed the alkalis (Na^+ and K^+), and weak acids (CO_3^{2-} and HCO_3^-) exceed strong acids (Cl^- and SO_4^{2-}).

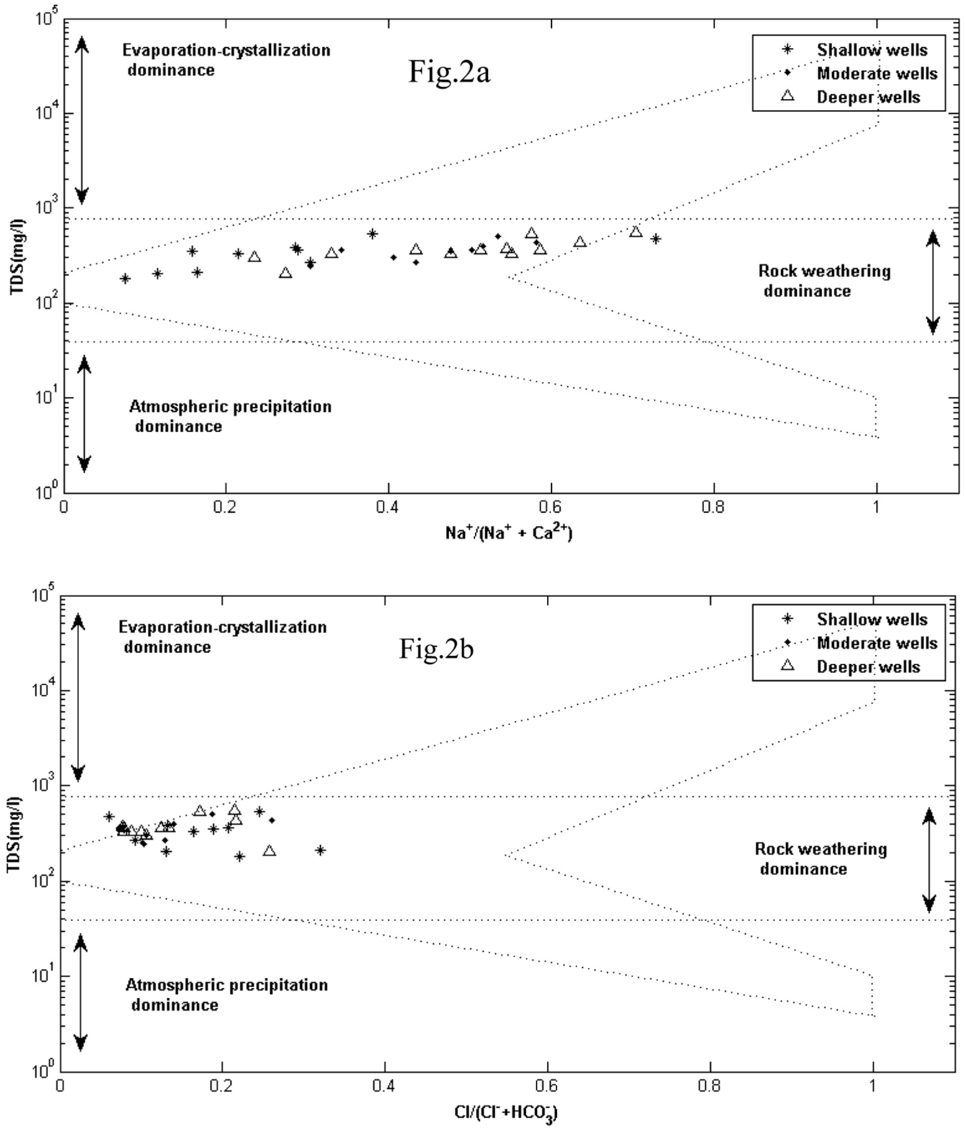

Figure 2. (a) Gibb's diagram1 and (b) Gibb's diagram 2.

Geochemical equilibrium and reactions

The groundwater chemistry of the study area is further investigated by adopting equilibrium thermodynamic approach. $Ca^{2+}$and Mg^{2+} in groundwater are most likely to be supplied by the dissolution of various minerals, such as dolomite, gypsum, calcite, or weathering of silicate minerals (Freeze and Cherry, 1979). Also, if certain minerals, e.g., calcite and dolomite are in equilibrium with groundwater, it is assumed that these minerals can control the groundwater chemical composition (Rajmohan and Elango, 2004; Sonkamble et al., 2013). In this study, Saturation Indices (SI) of calcite, dolomite, and halite were calculated with the help of the GWB software, using the default thermodynamic database to determine the chemical equilibrium in the mineral-water system. The SIs are approximate indicators of equilibrium because of uncertainty in the analytical measurements and the thermodynamic constants used to calculate the equilibrium constants. Deutsch et al., (1982) suggested an SI of ± 5% of the logarithm of the solubility product (log K) of the solid for the probable range of saturation; while, Paces (1972) suggested a broad range of SI of ± 0.5 units from zero for equilibrium or for saturation. With the exception of few samples, all groundwater samples inside and outside campus, irrespective of depth, are super saturated with respect to both calcite and dolomite, and all the samples are under saturated with respect to halite (Table 3). These findings suggest that the carbonate mineral phases are extensively present in the corresponding host rock and the incongruent dissolution of these carbonate minerals

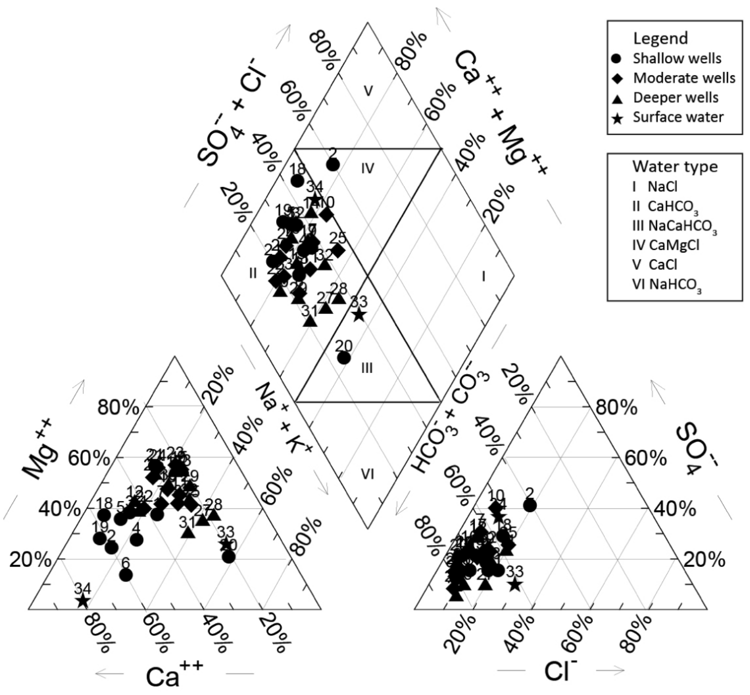

Figure 3. Piper diagram showing water types for samples in the study area.

is among the major controlling process of groundwater chemical constituents in the study area. In addition, because, Ca^{2+} and Mg^{2+} are the dominant cations in the groundwater, this can be explained by the weathering of calcite and dolomite, as expressed by the following reactions:

Calcite : $CaCO_3 + H_2O + CO_2 \leftrightarrow Ca^{2+} + 2\ HCO_3^-$ (1)

Dolomite : $CaMg(CO_3)_2 + 2H_2O + 2\ CO_2 \leftrightarrow Ca^{2+} + Mg^{2+} + 4\ HCO_3^-$ (2)

The relationship between Ca^{2+} and HCO_3^- concentrations is shown in Figure 4. Most of the data points are distributed around the line of calcite and dolomite weathering, which suggests that the weathering reactions for calcite and dolomite mainly account for the Ca^{2+} concentration of the groundwater in the study area.

Ion Exchange

Another significant factor that affects the groundwater chemical constituents is ion exchange (Appelo and Postma 2005). The chloro-alkaline indices CAI-I and CAI-II (hereafter referred as Schoeller indices), can be used to study ion exchange processes (Schoeller 1965, 1967). When there is an exchange of Ca^{2+} or Mg^{2+} in groundwater with Na^+or K^+ in aquifer matrix, both CAI-I and CAI-II are negative, and if there is a reverse ion exchange, both indices are positive. The Schoeller indices are calculated as:

$$CAI - I = \frac{Cl^- - (Na^+ + K^+)}{Cl^-} \quad (3)$$

$$CAI - II = \frac{Cl^- - (Na^+ + K^+)}{HCO_3^{\ -} + SO_4^{\ 2-} + CO_3^{\ 2-} + NO_3^{\ -}} \quad (4)$$

where all ions are expressed in meq/l.

The calculated values of CAI-I and CAI-II for groundwater samples are presented in Table 3. The results show that all the samples, except two shallow wells (BW2 inside the campus and HP3 outside the campus) have negative Schoeller index values suggesting the possibility of ion exchange of Ca^{2+} or Mg^{2+} in groundwater with Na^+ or K^+ in the aquifer matrix. The calculated Schoeller indices strongly suggest the occurrence of ion exchange process and potentially explain Na^+ and K^+ concentration in the groundwater of the study area.

Groundwater quality evaluation for drinking

The water quality standard for drinking has been specified by WHO and BIS, based on the dissolved ions and toxic trace elements. The behavior of major ions and important physico-chemical parameters and the suitability of groundwater for drinking in the study area are discussed below.

Groundwater of all wells with different depths in our study area showed alkaline nature and could be classified as fresh water as per TDS measurement (TDS <1,000; Freeze and Cherry (1979)) (Table 4). Considering total hardness, groundwater samples are within the safe limit of usage (Table 4).

Table 2. Summary statistics of groundwater and surface water chemical constituents. The WHO (WHO, 1996, 2011) standards for drinking with maximum permissible limit (MPL), and BIS (BIS, 2003) standard for Desirable limit (DL) and MPL are also shown.

Parameter	Groundwater Range	*Mean	Surface water Canal	Pond	WHO MPL	DL	BIS MPL
pH	7.2-8.1	7.7±0.1	7.5	7.4	9.2	6.5-8.5	9.2
Ec (μS/cm)	284-863	550.3±151.7	246	1400	1400	500	1000
TDS (mg/l)	182-552	352.2±97	157	896	1000	-	-
Na^+ (mg/l)	3-98	31.3±21.9	8	116	200	-	-
K^+ (mg/l)	3-9	4.5±1.4	3	105	-	-	-
Ca^{2+} (mg/l)	24-72	35.1±11.8	40	56	200	75	200
Mg^{2+} (mg/l)	10-53	28.1±10.5	1	44	150	30	100
HCO_3^- (mg/l)	73-270	187.6±51.5	70	426	-	-	-
Cl^- (mg/l)	10-50	18.7±11.1	8	120	600	250	1000
SO_4^{2-} (mg/l)	11-75	43.2±16.6	38	54	400	200	400
F^- (mg/l)	0.03-0.94	0.3±0.1	0.12	0.45	1.5	1.0	1.5
NO_3^- (mg/l)	0-17.5	3.7±4.4	0.3	11.5	45	45	45
Cu (mg/l)	0.003-0.017	0.02±0.04	0.004	0.02	2.0	0.05	1.5
Fe (mg/l)	0.07-0.7	0.22±0.16	0.1	0.3	0.3	0.3	1.0
Mn (mg/l)	0-0.1	0.01±0.02	0.01	0.2	0.4	0.1	0.3
Se (mg/l)	0-0.025	0.006±0.006	0	0.004	0.01	0.01	0.01
As (mg/l)	0.001-0.01	0.002±0.002	0.002	0.004	0.01	0.05	0.05
Zn (mg/l)	0.005-1.0	0.12±0.25	0.01	0.03	3	5	15
Cr (mg/l)	0.001-0.007	0.004±0.001	0.002	0.01	0.05	0.05	0.05
Hardness (mg/l $CaCO_3$)	132-320	204±44.5	104	320	500	300	600

*Mean values with standard deviation

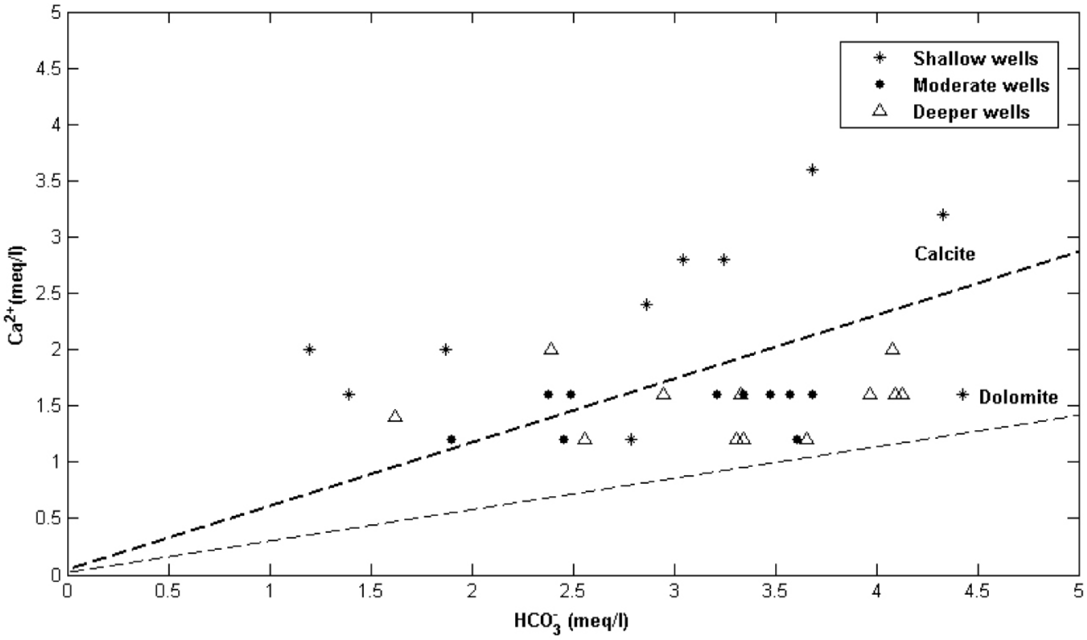

Figure 4. The Ca^{2+} versus HCO_3^- concentration of groundwater for all samples inside and outside campus.

Table 3. Saturation indices of minerals and Schoeller indices for groundwater samples from inside and outside campus.

Mineral	Range of Saturation Indices
Calcite	-0.319 – 0.393
Dolomite	-0.1 – 2.1
Aragonite	-0.48 – 1.5
Halite	-8.4 – -7.0
Schoeller indices	
CAI-I	-14.4 – 0.4
CAI-II	-0.7 – 0.08

Table 4. Suitability of groundwater for drinking based on Total hardness (TH) and dissolved solids (TDS).

Parameter	Remarks	% of groundwater samples
Total hardness (mg/l) as $CaCO_3$ (Sawyer and McCarty 1967)		
< 75	Soft	0
75-150	Moderately Hard	18
150-300	Hard	75
>300	Very Hard	7
TDS (mg/l)		
< 200	Excellent	4
200-500	Good	84
500-1500	Fair	12
>1500	Unsuitable	0

Considering major ions, the dominant ions in the groundwater of the study area are in the order of Ca^{2+}, $Mg^{2+} > Na^{+} > K^{+}$ for cations and $HCO_3^{-} > SO_4^{2-} > Cl^{-}$ for anions. All the samples are well within the drinking water limits considering major ions, except for the well near the dairy farm (TWDF), where the Mg^{2+} was higher than that of the safe drinking water limit.

Nitrate (NO_3^-) and Fluoride (F^-)

While NO_3^- is a common nitrogenous compound due to natural processes of the nitrogen cycle, anthropogenic sources have greatly increased the nitrate concentration, particularly in groundwater. Nitrate concentration of groundwater in the study area falls within the safe drinking water range. The highest NO_3^- concentration inside campus is found to be 15.5 mg/l for the well near the dairy farm (well no. 9, Table 1 and Figure 1b), which could be due to anthropogenic input from the dairy farm. Our results are consistent with that of Thind and Kansal (2002), who also reported NO_3^- concentration in groundwater to be the maximum near the dairy farm inside the campus and minimum near the canal owing to seepage from the canal. Thind and Kansal, (2002) also reported NO_3^- concentrations of the deeper wells inside the campus to be less as compared to the shallow wells. However, in this study, no clear distribution of NO_3^- is observed for shallow and deeper wells.

All the water samples in the study area exhibit F^- within the safe drinking water limit (Table 2).

Trace elements

Bhalla et al., (2011) reported high concentration of trace elements including Cr, Fe and Se in groundwater of Punjab. Also, Singh (1994) reported Cr and CN concentrations exceeding the permissible limit in groundwater of Ludhiana. However, from the present study all the groundwater samples from inside and outside campus are found to be within the safe limit of BIS (2003) with respect to Cu, Fe, Mn, Se, As, Zn and Cr.

Water quality evaluation for irrigation

Quality of irrigation water is an important factor for crop production. Irrespective of the sources of irrigation water, soluble salts are always present, which are mostly Na^+, Ca^{2+}, $Mg^{2+}$and sometimes K^+ as cations, and Cl^-, F^-, CO_3^{2-}, HCO_3^-, and NO_3^- as anions. The suitability of ground water for irrigation is generally assessed from its chemical composition along with other factors such

Table 5. Summary statistics of groundwater and surface water for irrigation quality parameters.

Parameter	Groundwater		Surface water	
	Range	*Mean	Canal	Pond
SAR	0.1-3.3	0.94±0.67	0.3	2.8
%Na	7.2-58.0	25.8±11.6	13.9	35.6
KR	0.04-1.34	0.33±0.2	0.1	0.8
SSP (%)	4.6-57.4	22.9.1±11.0	14.3	44.0
PI (%)	42.8-85.7	56.1±8.9	58.4	67.0
RSC (meq/l)	-2.2-1.26	-0.99±0.67	-0.9	0.5
MH	3.9-73.2	55.8±14.0	3.9	56.6
Ca^{2+}/Mg^{2+}	0.3-4.3	0.97±0.8	24.2	0.8

*Mean values with standard deviation

as: type of soil, type of crop, climate and drainage type. The various hazardous categories used for irrigation water quality evaluation in this study are: salinity hazard, sodicity (alkali) hazard and bi-carbonate hazard. KR and MH are also used as criteria to evaluate irrigation water quality. The range with mean and standard deviation calculated for these parameters are presented in Table 5.

Salinity Hazard

Salinity hazard is associated with high soluble salts in water and is measured in terms of TDS or EC. Based on TDS, all the groundwater samples and samples from surface water bodies are suitable for irrigation (TDS < 1500 mg/l)..

Sodicity (alkali) hazard

Irrigation water containing large amounts of Na^+ is of special concern, because increase of Na^+ concentration in irrigation water deteriorates soil quality norms by reducing permeability (Kelley 1951). Sodium hazard is usually expressed in terms of sodium adsorption ratio (SAR), % Na^+ and soluble sodium percent (SSP).

Sodium adsorption ratio (SAR)

The average SAR calculated for the groundwater samples of the study area is 0.9 (Table 5), and it evaluates the sodium hazard in relation to Ca^{2+} and Mg^{2+} concentrations. Water quality is described as excellent for irrigation when the SAR value is less than 10 and termed as unsuitable with a SAR value greater than 26. Accordingly, all the samples including the surface waters are classified as suitable for irrigation.

The United States of Salinity diagram (USSL 1954) can be used for a detailed analysis for suitability of water for irrigation, which uses EC as salinity hazard and SAR as alkalinity hazard. The USSL diagram (Richards 1954) for water samples is presented in Figure 5, which shows that all samples fall in the C2S1 and C3S1 categories. This indicates that all the groundwater and surface water samples are of medium salinity and low sodium. As such, both ground and surface waters can be used in all types of soil for irrigation without the risk of exchangeable Na^+. Thus, the USSL diagram classifies the groundwater and surface water in the study area as good quality for irrigation.

Percent Sodium (% Na^+)

Sodium in irrigation water is generally expressed as % Na^+ and is calculated with respect to the relative proportion of cations present in water as:

$$\%\,Na^+ = \frac{Na^+ + K^+}{Ca^{2+} + Mg^{2+} + Na^+ + K^+} \times 100 \tag{5}$$

where the quantities of all cations are expressed in meq/l. According to BIS (2003), the maximum Na^+ recommended in irrigation water is 60%. In reference to % Na^+, 37% of groundwater samples are of excellent quality; 53% are of good quality for irrigation, and 10% of groundwater samples are of fair quality. The canal water is also of excellent quality for irrigation based on % Na^+ calculation.

Wilcox (1955) classified groundwater based on % Na^+ and EC for irrigation use. The Wilcox diagram for all the samples is shown in Figure 6. Following the Wilcox diagram, all the water samples are classified as good for irrigation.

Soluble sodium percent (SSP)

SSP is another parameter used to assess suitability of water for irrigation. SSP can be expressed as:

$$SSP = \frac{Na^+}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \tag{6}$$

where the quantities of all cations are expressed in meq/l. Water with a SSP greater than 50% is unsafe for irrigation (USDA 1954); which may result in sodium accumulation that will cause a breakdown in the soil's physical properties. Based on SSP, all the samples are good quality waters for irrigation, except one shallow groundwater sample from outside campus (well no. 20), which is found to have a SSP of 57%.

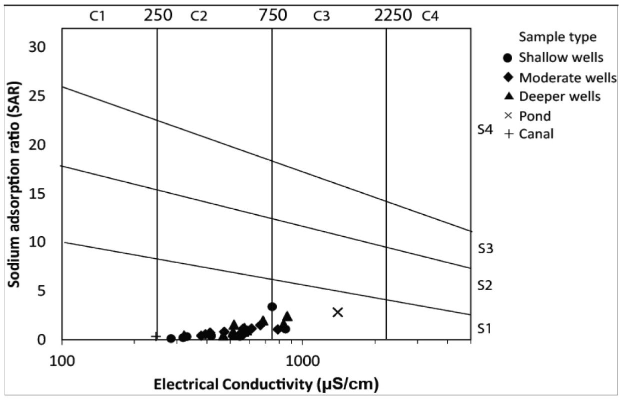

Figure 5. Water classification based on USSL diagram.

Bi-carbonate hazard

Water having excess carbonate and bicarbonate over the alkaline earths, mainly calcium and magnesium, affects agriculture unfavorably (Eaton 1950; Richards 1954). RSC is an indirect expression for CO_3^{2-} and HCO_3^- of Na^+ in groundwater, which can be expressed as:

$$RSC=\left(HCO_3^{-}+CO_3^{2-}\right)-\left(Ca^{2+}+Mg^{2+}\right) \qquad (7)$$

where the quantities of all cations and anions are expressed in meq/l.

Water with RSC <1.25 are considered to be safe for irrigation, whereas water with RSC >2.5 are considered unsuitable for irrigation. The negative RSC values (Table 5) indicate that the alkaline earths (Ca^{2+} and Mg^{2+}) are in excess and Na^+ buildup in the soil is unlikely, if irrigated with this water. RSC values for all the water samples studied are less than 1.25, which suggests that water in the entire study area is safe for irrigation.

Permeability Index (PI)

The permeability of soil is affected by the long term use of irrigation water as it is influenced by Na^+, Ca^{2+}, Mg^{2+} and HCO_3^- content of the soil (Ramesh and Elango 2012). Doneen (1966) proposed a criterion for evaluating the suitability of groundwater based on permeability index (PI), which can be evaluated as (Ragunath 1987):

$$PI=\frac{Na^{+}+\sqrt{HCO_3^{-}}}{Ca^{2+}+Mg^{2+}+Na^{+}}\times 100 \qquad (8)$$

where the quantities of all cations and anions are expressed in meq/l.

Based on PI, water is classified as excellent (PI >75%), good (PI in the range of 25-75%) and unsuitable (PI <25%) for irrigation. In the study area, all the samples, except well no. 20 fall in the class II category (PI value of 25-75%) in the Doneen chart (Domenico and Schwartz 1990), which suggests the suitability of groundwater and canal water for irrigation.

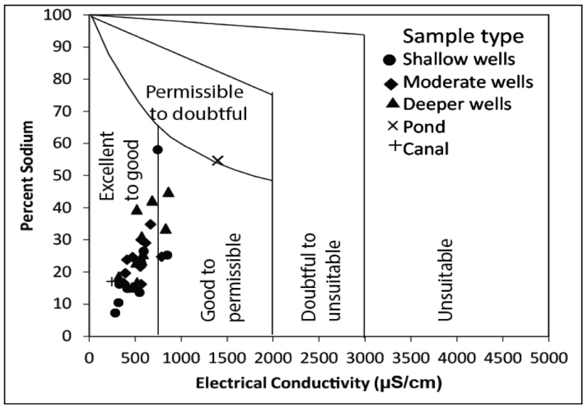

Figure 6. Suitability of groundwater and surface water for irrigation as per the Wilcox diagram.

Kelley's Ratio (KR)

The sodium problem in water for irrigation can be expressed in terms of KR, which can be calculated as (Kelley 1940; Paliwal 1967):

$$KR=\frac{Na^{+}}{Ca^{2+}+Mg^{2+}} \qquad (9)$$

where the cations are in meq/l.

KR values of less than 1 are found to be suitable for irrigation, whereas, KR of more than 1 indicates an excess of Na^+ in water, and hence are unsuitable for irrigation. In the study area, all the samples, except well no. 20, are safe for irrigation according to the values of KR.

Magnesium Hazard (MH)

Excess of magnesium affects the quality of soil, which is the cause for poor yield of crops. MH value for irrigation water can be expressed as (Szabolcs and Darab1964):

$$MH=\frac{Mg^{2+}}{\left(Ca^{2+}+Mg^{2+}\right)}\times 100 \qquad (10)$$

where all the cations are in meq/l.

Water with MH values > 50% are unsuitable for irrigation. In the study area, MH for the groundwater samples ranges from 3.9 to 73.2 with an average of 55.8 (Table 5). 37% of groundwater samples and the canal water in the study area are found to be safe for irrigation (MH < 50); whereas, 63% of groundwater samples and the pond water are unsuitable for irrigation (MH >50). Groundwater samples with MH >50% are mostly from moderate to deeper level (Tables 1 and 5). Irrigating with water having MH > 50% may cause adverse effect on the agricultural yield. However, with an average MH of nearly 50% may indicate moderate quality water for irrigation. High magnesium concentration observed in the study area could be from anthropogenic sources.

In order to further evaluate the magnesium hazard for irrigation water, the ratio of Ca^{2+}/Mg^{2+} can be considered as a criterion (Ayers and Westcot, 1985). When the ratio Ca^{2+}/Mg^{2+} is < 1 in the irrigation water, the potential effect of Na^+ may be slightly increased. The suitability of groundwater and surface water in the study area based on Ca^{2+}/Mg^{2+} ratio exhibits the same behavior as that of MH (Table 5).

CONCLUSION

The suitability of groundwater for domestic and agricultural uses is evaluated inside the PAU campus and surrounding area, based on the physico-chemical properties of groundwater. Concentration of major ions, both inside and outside the PAU campus are in the order of Ca^{2+}, $Mg^{2+} > Na^+ > K^+$ for cations and $HCO_3^- > SO_4^{2-} > Cl^-$ for anions. Water rock interaction is the dominant mechanism controlling the groundwater chemistry. Calcite and dolomite are found to be saturated in groundwater, whereas halite and gypsum are unsaturated. Mineral weathering along with ion exchange, control the groundwater chemistry of the study area. Based on major ion and trace element concentrations, groundwater samples fall within the permissible limit of WHO and BIS, and are found to be safe for drinking and domestic applications. In terms of irrigation water quality parameters, such as dissolved solids, SAR, % Na^+, RSC, PI, and KR, all the groundwater samples except one shallow well (well no. 20), are found suitable for irrigation for most of the soil types. Considering magnesium hazard, however, 63% of the groundwater samples have a MH value of >50%, which may restrict the use of this water for irrigation. The canal water is found to be of excellent quality for irrigation based on all the irrigation quality parameters.

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*"I didn't like to stop playing for a second to bother with eating or going to the bathroom. I was a really skinny kid, and I remember my mother always telling people, 'I don't know how she's alive. I think she gets all of her nutrients from air pollution."- Tig Notaro -An American Actress

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*"Carpooling is important for urban density, air pollution and other reasons, but carpooling is not the kind of thing that actually changes the energy equation."- Clay Shirky - American writer, consultant and teacher

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* "The Chinese have figured out that they have a giant environmental problem. Folks in Beijing, some days, literally can't breathe. Over a million Chinese die prematurely every year because of air pollution".- Joe Biden- 47th Vice President of the United States

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*"Sooner or later, we will have to recognise that the Earth has rights, too, to live without pollution. What mankind must know is that human beings cannot live without Mother Earth, but the planet can live without humans." - Evo Morales - Bolivian politician and 80th President of Bolivia

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*"I'd never felt afraid of pollution before and never wore a mask no matter where. But when you carry a life in you, what she breathes eats and drinks are all your responsibility; then you feel the fear." - Chai Jing - Chinese journalist and environmental activist.

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*"We already have the statistics for the future: the growth percentages of pollution, overpopulation, desertification. The future is already in place."- Gunter Grass- German novelist and recipient of the 1999 Nobel Prize in Literature