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Handbook for stable isotope data interpretation in India

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Handbook for stable isotope data interpretation

Final report

Activity 4: Development of a handbook for stable isotope data interpretation

Advisory Service for the IEWP Priority Area 4 – Groundwater Use: Support to Assess
Groundwater Aquifers by Using Existing Isotope Data in India.

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Abbreviations

^1H	protium
^2H	deuterium
^3H	tritium
^{16}O	oxygen-16
^{17}O	oxygen-17
^{18}O	oxygen-18
α	fractionation factor
arcmin	arcminute, a minute of arc
ε	enrichment factor
δ	delta value in ‰
‰	permil
°C	degree Celsius
cP	centipoise (unit of dynamic viscosity)
DE	deuterium excess
GMWL	Global Meteoric Water Line
GNIP	Global Network of Isotopes in Precipitation
GNIR	Global Network of Isotopes in Rivers
H ₂ O	water molecule
IAEA	International Atomic Energy Agency
IRMS	Isotope Ratio Mass Spectrometer
LMWL	Local Meteoric Water Line
LAS	Laser Absorption Spectroscopy
MWL	Meteoric Water Line
NIST	National Institute of Standards and Technology
R	abundance ratio
RMWL	Regional Meteoric Water Line
Torr	unit of pressure
VSMOW	Vienna Standard Mean Ocean Water
WMO	World Meteorological Organization

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Summary

The water molecule is composed of lighter and heavier isotopes of oxygen and hydrogen. Oxygen-18 and deuterium are the two heavier stable isotopes which can be used as tracer in hydrological studies. Due to the fact that these isotopes are integral part of the water molecule, they are considered as an ideal tracer. Differences in the physical properties of water molecules containing these heavier isotope species and the resulting changes in isotopic composition based on phase changes of water can be used for applications within the water cycle and therefore they provide methods for hydrogeological applications. Typical applications in groundwater related studies are identification of source areas, identification of water pathways, estimation of groundwater recharge, and groundwater–surface water interactions. Finally these results can be used to improve the general system understanding and support decisions in water resource management.

The main reason for different isotope values within components of the water cycle is the fractionation between lighter and heavier isotope species during phase changes dependent on temperature conditions. This will lead to typical isotope values for water that has undergone for example an evaporation or condensation process. In case of condensation within a cloud the isotope fractionation will result in typical isotope values of precipitation at specific locations and seasons. The stable isotopes oxygen-18 and deuterium provide a characteristic isotopic signature to the hydrological system via the precipitation input. Generally isotope values of precipitation are lighter in colder areas and seasons and heavier in warmer regions or seasons. This signal or “fingerprint” can be followed in the soil water, groundwater and in surface waters to investigate hydrological processes and provide answers for hydrological and hydrogeological questions such as elevation of the recharge area, time of groundwater recharge, connectivity of aquifers, or mixing between different water sources.

By combining isotope values and hydro-chemical information such as electrical conductivity or chloride concentrations a better understanding of the groundwater recharge processes can be gained. Generally an increased electrical conductivity or chloride concentration in combination with enriched isotope values is linked to evaporative effects and both parameters show a positive correlation.

The handbook is divided in five main sections. In chapter 1 and 2 the theoretical principles of stable isotopes and isotopic effects are discussed. In chapter 3 some applications of stable isotopes in groundwater are presented, followed by chapter 4 with practical aspects of sampling and laboratory methods, and the fifth chapter is giving a step-by-step description of the methodology to interpret stable isotopes.

1. Theoretical principles of stable isotopes

Atoms are build up by a nucleus which is surrounded by electrons. The nucleus consist mainly of two type of particles of the same mass: protons and neutrons. The number of positively charged protons in the nucleus (Z), defining the atomic number, is equal to the number of negatively charged electrons surrounding it, and therefore the atom is neutral. Because of the small mass of the electrons compared to the masses of the particles in the nucleus, the sum of protons and neutrons (N) is defining the mass number of the atom.

The notation of a specific nuclide, elements characterized by the specific setup of the nucleus, is therefore defined as:

$$_Z^A X_N \quad (1)$$

With X = chemical element; A = sum of protons (Z) and neutrons (N) [mass number]; Z = number of protons [atomic number].

Examples: $_1^2 H_1$; $_6^{12} C_6$; $_7^{14} N_7$; $_8^{16} O_8$

Isotopes, from the Greek words isos ("ἴσος" "equal") and topos ("τόπος" "place") are atoms with the same amount of protons, but different amounts of neutrons in the nucleus. Isotopes have the same chemical characteristics, defined mainly by their amount of electrons, but different physical properties (see Figure 1). The different physical behaviour of specific isotopes of one chemical element is based on the mass differences. The mass and the ratio of protons to neutrons are important factors defining the characteristics of isotopes. Some of them are stable while others are radioactive and decay.

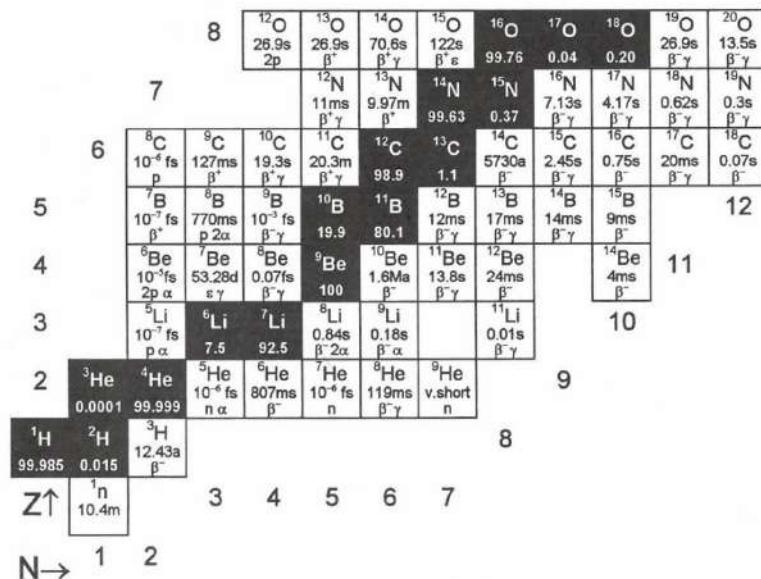


Figure 1: Lower part of the chart of nuclides showing light elements and their percent abundance (stable isotopes) and half-lives and radioactive decay type (radioisotopes); from Clark and Fritz (1997).

1.1. Stable isotopes of the water molecule

A water molecule (H_2O) can be composed of the lighter and more abundant isotopes oxygen-16 (^{16}O) and protium (^1H), or the heavier and less abundant isotopes oxygen-17 (^{17}O), oxygen-18 (^{18}O) and deuterium (^2H). For hydrogen the natural abundance of ^1H is 99.985% and of ^2H only 0.015%. In case of oxygen the abundances for ^{16}O , ^{17}O , and ^{18}O are 99.76%, 0.04%, and 0.2%, respectively.

The radioactive isotope of hydrogen, tritium (^3H), is not considered here. Possible combinations are consequently $^1\text{H}^1\text{H}^{16}\text{O}$, $^1\text{H}^2\text{H}^{16}\text{O}$, $^2\text{H}^2\text{H}^{16}\text{O}$, $^1\text{H}^1\text{H}^{17}\text{O}$, $^1\text{H}^2\text{H}^{17}\text{O}$, $^2\text{H}^2\text{H}^{17}\text{O}$, $^1\text{H}^1\text{H}^{18}\text{O}$, $^1\text{H}^2\text{H}^{18}\text{O}$, and $^2\text{H}^2\text{H}^{18}\text{O}$. However water molecules containing two deuterium isotopes are rather rarely found in natural waters, and for hydrological applications only the combinations $^1\text{H}^1\text{H}^{16}\text{O}$, $^1\text{H}^2\text{H}^{16}\text{O}$, and $^1\text{H}^1\text{H}^{18}\text{O}$ are of practical interest.

The natural abundance of water molecules containing an ^{18}O isotope ($^1\text{H}^1\text{H}^{18}\text{O}$) is 2040 molecules per 10^6 water molecules (ppm), for water molecules containing a ^2H isotope ($^1\text{H}^2\text{H}^{16}\text{O}$) it is 312 ppm.

The relative abundance of these isotopes in the hydrological cycle is very variable and is dependent on the origin and history of the water molecule. For example water molecules in the ocean have relatively more heavy isotopes (^{18}O and ^2H) in comparison to precipitation and terrestrial water, like e.g. surface water and groundwater.

The mass differences and therefore different physical behaviour (see Table 1) of heavier versus light isotopes lead to a change of the isotopic ratios of water after a phase change occurred. Phase changes are condensation, evaporation, freezing, melting and sublimation, that occur between the liquid, gaseous, and solid forms of water. This process of changed isotopic ratios is called isotope fractionation, and forms the principle of the application of stable water isotopes in the water cycle.

Table 1: Characteristic physical properties of different water molecules (from Hoefs, 2009).

Property	$^1\text{H}_2^{16}\text{O}$	$^2\text{H}_2^{16}\text{O}$	$^1\text{H}_2^{18}\text{O}$
Density @20°C [$\text{g}\cdot\text{cm}^{-3}$]	0.997	1.1051	1.1106
Temperature of maximum density [°C]	3.98	11.21	4.30
Melting point @760 Torr [°C]	0	3.81	0.28
Boiling point @760 Torr [°C]	100	101.42	100.14
Vapour pressure @100°C [Torr]	760.00	721.60	
Viscosity @20°C [cP]	1.002	1.247	1.056

1.2. Units and standards

Measurements of absolute isotope concentrations is very complicated and complex, instead the isotope ratio between the heavier and the lighter isotope of an element is determined. The abundance ratio (R) is defined as:

$$R = \frac{\text{abundance of heavy isotope}}{\text{abundance of light isotope}} \quad (2)$$

Examples: $^2R_{(\text{H}_2\text{O})} = \frac{[^2\text{H} \ ^1\text{H}\text{O}]}{[^1\text{H}_2\text{O}]}$ and $^{18}R_{(\text{H}_2\text{O})} = \frac{[^2\text{H} \ ^1\text{H}\text{O}]}{[^1\text{H}_2^{16}\text{O}]}$

The ratio is then compared to an international standard. Due to the fact that this deviation is rather small, the difference of the isotope ratio in a sample compared to the ratio in the standard is expressed as δ value in ‰. This is also called δ -notation. For stable water isotopes the international standard Vienna Standard Mean Ocean Water (VSMOW) is used:

$$\delta {}^2H = \frac{\left({}^{2H}/{}^{1H} \right)_{Sample}}{\left({}^{2H}/{}^{1H} \right)_{Standard}} - 1 \text{ [‰]} = \frac{({}^2R)_{Sample}}{({}^2R)_{Standard}} - 1 \text{ [‰]} \quad (3)$$

$$\delta {}^{18}O = \frac{\left({}^{18}O/{}^{16}O \right)_{Sample}}{\left({}^{18}O/{}^{16}O \right)_{Standard}} - 1 \text{ [‰]} = \frac{({}^{18}R)_{Sample}}{({}^{18}R)_{Standard}} - 1 \text{ [‰]} \quad (4)$$

The ratio of VSMOW is defined by the International Atomic Energy Agency (IAEA) and the National Institute of Standards and Technology (NIST) as:

$${}^2R_{Standard \ (VSMOW)} = \frac{[{}^2H]}{[{}^1H]} = 155.76 \cdot 10^{-6} \quad (5)$$

$${}^{18}R_{Standard \ (VSMOW)} = \frac{[{}^{18}O]}{[{}^{16}O]} = 2005.20 \cdot 10^{-6} \quad (6)$$

The δ value for the international standard VSMOW is therefore 0‰ for $\delta^{18}O$ and δ^2H , respectively. A sample showing a negative δ value is depleted in heavier isotopes, and a sample with a positive δ value is enriched in heavier isotopes in respect to the VSMOW.

Several terms are used to describe the difference between two isotope values:

- more/ less positive vs. more/less negative
- higher vs. lower values
- heavier vs. lighter values
- enriched vs. depleted isotope species

1.3. Isotope fractionation

Isotope fractionation is an alteration of the isotopic composition of water caused by the change from one phase to another phase, like e.g. liquid water to water vapour in case of an evaporation process or from solid water to liquid water in case of a melting process. The mass differences of the nuclei and therefore the differences of the physical properties (see Section 1.1) are responsible for this process. The main consequences are that heavier isotopes have (i) a lower mobility with a lower diffusion velocity, a smaller collision frequency, and a slower reaction, and (ii) a higher binding energy. For example a heavy water molecule ($^1\text{H}_2^{18}\text{O}$ or $^1\text{H}^2\text{H}^{16}\text{O}$) has a lower vapour pressure than a light water molecule ($^1\text{H}_2^{16}\text{O}$), and will therefore be less likely to be change the phase from liquid to gaseous in an evaporation process. On the other hand it will be more likely for a heavy molecule to change the phase from gaseous to liquid in a condensation process. This effect is called a mass-dependent isotope fractionation.

Two types of isotope fractionation can be distinguished: equilibrium fractionation and kinetic fractionation. Equilibrium fractionation occurs in an equilibrium reaction, where the reactant and the product stay in close contact, are well mixed, and back reactions can occur. This reaction is described by the equilibrium fractionation factor α :

$$\alpha_{reactant \leftrightarrow product} = \frac{R_{reactant}}{R_{product}} \quad (7)$$

For a phase change between liquid water and water vapour in an evaporation process this will lead to a fractionation factor α :

$$\alpha^{18}\text{O}_{liquid \leftrightarrow vapour} = \frac{(^{18}\text{O}/^{16}\text{O})_{water}}{(^{18}\text{O}/^{16}\text{O})_{vapour}} = 1.0093 \quad @25^\circ\text{C} \quad (8)$$

For α values larger than 1 the isotopic ratio of the product will be smaller than the ratio of the reactant. In the case of an evaporation process the produced water vapour (product) will be lighter compared to the heavier liquid water (reactant).

$$^{18}\text{R}_{vapour} = \frac{^{18}\text{R}_{water}}{1.0093} \quad @25^\circ\text{C} \quad (9)$$

Isotope fractionation and therefore the fractionation factor α is strongly temperature dependent. The fractionation is much stronger at lower temperatures than at higher temperatures. The fractionation factor α for ^{18}O for a water/water vapour exchange in dependence of the temperature (T) is shown in Figure 2.

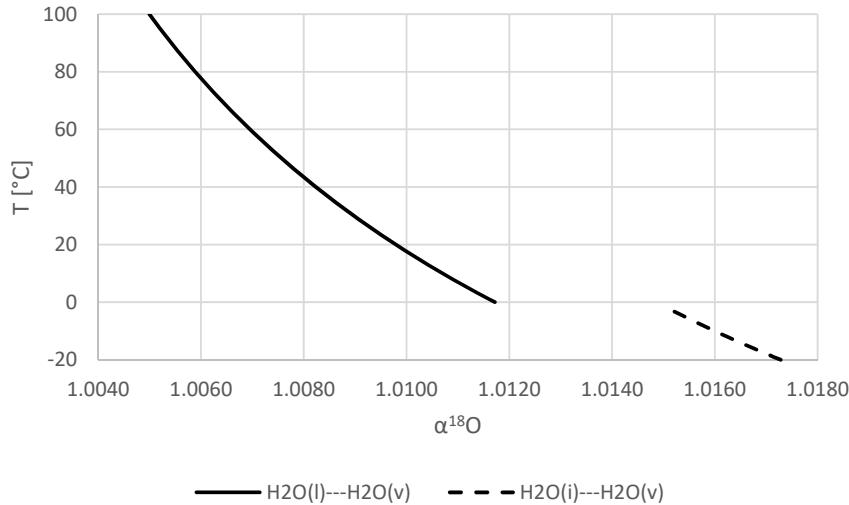


Figure 2: Temperature dependency of the fractionation process of ^{18}O for liquid-vapour (0-100°C) and ice-vapour (-20-0°C) (values from Majoube, 1971).

To describe the isotopic difference between the reactant and the product the enrichment factor ε [%] can be used:

$$\varepsilon^{18}\text{O}_{\text{liquid} \leftrightarrow \text{vapour}} = \left(\frac{(^{18}\text{O}/^{16}\text{O})_{\text{water}}}{(^{18}\text{O}/^{16}\text{O})_{\text{vapour}}} - 1 \right) \cdot 1000 \text{ ‰} = 9.3\text{ ‰} @ 25^\circ\text{C} \quad (10)$$

In the case of an evaporation process at 25°C the produced water vapour (product) will have a δ value which is 9.3 ‰ different from the liquid water (reactant).

Fractionation factors are commonly expressed as $10^3 \ln \alpha$, because this expression is an approximation to the equilibrium fractionation expressed in ‰:

$$\varepsilon^{18}\text{O}_{\text{liquid} \leftrightarrow \text{vapour}} \approx \delta^{18}\text{O}_{\text{liquid}} - \delta^{18}\text{O}_{\text{vapour}} \approx 1000 \cdot \ln \alpha^{18}\text{O}_{\text{liquid-vapour}} \quad (11)$$

However in most cases an isotopic equilibrium is not reached because of temperature changes or the removal of the produced water vapour, and kinetic fractionation has been considered. The kinetic fractionation is an irreversible process, where the product of the process is continuously removed.

In an evaporation process the effect is dependent on the relative humidity (h) condition of the atmosphere. The kinetic fractionation is described after Gonfiantini (1986) with the following relationships (Clark and Fritz, 1997):

$$\Delta\varepsilon^{18}O_{liquid \rightarrow vapour} = 14.2 \cdot (1 - h) \text{ ‰} \quad (12)$$

$$\Delta\varepsilon^2H_{liquid \rightarrow vapour} = 12.5 \cdot (1 - h) \text{ ‰} \quad (13)$$

One way to describe the change of isotopic composition during phase changes is the Rayleigh distillation equation. The equation describes the fractionation of isotopes in two reservoirs, whereas one reservoir decreases in size. During an evaporation process the remaining liquid water becomes more and more enriched with heavier isotopes. This effect can be described by:

$$R = R_0 \cdot f^{(\alpha-1)} \quad (14)$$

With R = resulting isotope ratio; R_0 = initial isotope ratio; f = fraction of water remaining; α = equilibrium fractionation factor.

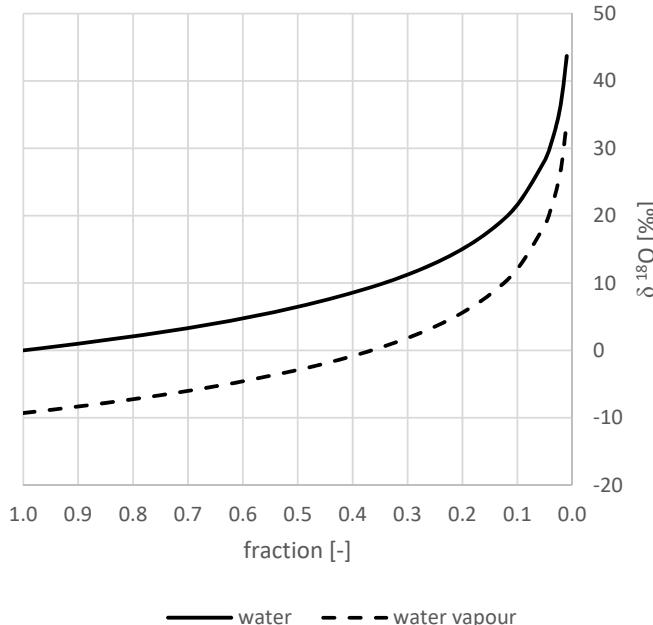


Figure 3: Enrichment of ^{18}O during an evaporation process of water at 25°C and 100% humidity conditions; solid line remaining water; dashed line produced water vapour.

The Rayleigh equation can be applied for open systems under a constant equilibrium fractionation factor, where the product is continuously removed (see Figure 3). However normally evaporation takes place under non-equilibrium conditions with humidity of the air being an important factor. If the humidity is lower than 100% a kinetic fractionation has to be included.

The total fractionation between liquid water and water vapour is the sum of the equilibrium fractionation ($\varepsilon_{\text{liquid} \leftrightarrow \text{vapour}}$) and the kinetic fractionation ($\Delta\varepsilon_{\text{liquid} \rightarrow \text{vapour}}$):

$$\delta^{18}\text{O}_{\text{liquid}} - \delta^{18}\text{O}_{\text{vapour}} = \varepsilon^{18}\text{O}_{\text{liquid} \leftrightarrow \text{vapour}} + \Delta\varepsilon^{18}\text{O}_{\text{liquid} \rightarrow \text{vapour}} \quad (15)$$

In case of progressive evaporation this will result in an increasing enrichment of heavier isotopes in the remaining liquid water phase. The smaller the humidity the higher the change in $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values. In a graph showing the $\delta^2\text{H}$ values in relationship to the $\delta^{18}\text{O}$ values of evaporated water the values follow a so called evaporation line (see Figure 4). The slope of this line is dependent on the temperature and humidity condition during the evaporation process, and values of the evaporation lines are ranging between 3.9 for $h=0\%$ and 6.8 for $h=95\%$. In case of groundwater, isotopic values which are deviating from the Global Meteoric Water Line (GMWL) or Local Meteoric Water Line (LMWL) and are following an evaporation line are often found under arid and semi-arid climates. Low slopes of evaporation lines of these groundwater samples are often linked to diffusive evaporation from soil water and fractionation already before the percolation takes place.

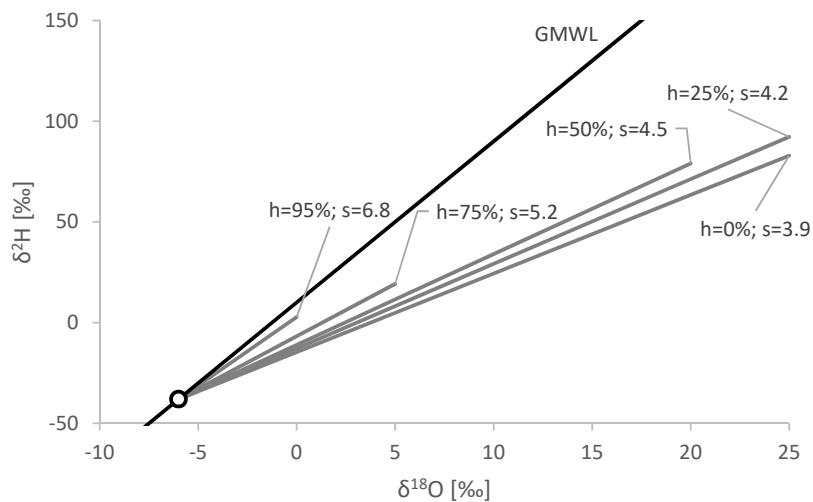


Figure 4: Example of evaporation lines and the effect of humidity. With h = relative humidity in % and s = slope (after Gonfiantini, 1986 from Clark and Fritz, 1997).

The slopes of the evaporation lines can also be used to determine the original isotopic composition of the initial water (precipitation water prior to evaporation). Geyh and Ploethner (1997) suggest a correction of the $\delta^{18}\text{O}$ value due to evaporative enrichment (Leibundgut et al., 2009):

$$\delta^{18}\text{O}_{\text{corrected}} = \frac{\delta^2\text{H}_{\text{measured}} - s \cdot \delta^{18}\text{O}_{\text{measured}} - DE}{8-s} \quad (16)$$

$$\delta^2\text{H}_{\text{corrected}} = 8 \cdot \delta^{18}\text{O}_{\text{corrected}} + 10 \quad (17)$$

Where $\delta^{18}\text{O}_{\text{corrected}}$ and $\delta^2\text{H}_{\text{corrected}}$ are representing the original isotope composition of the initial water. The measured isotope values of the sample are $\delta^{18}\text{O}_{\text{measured}}$ and $\delta^2\text{H}_{\text{measured}}$, s characterises the slope of the evaporation line, and DE is with 10‰ the deuterium excess value of the GMWL. This method can be used to identify the source of groundwater which is affected by evaporation (see Figure 5).

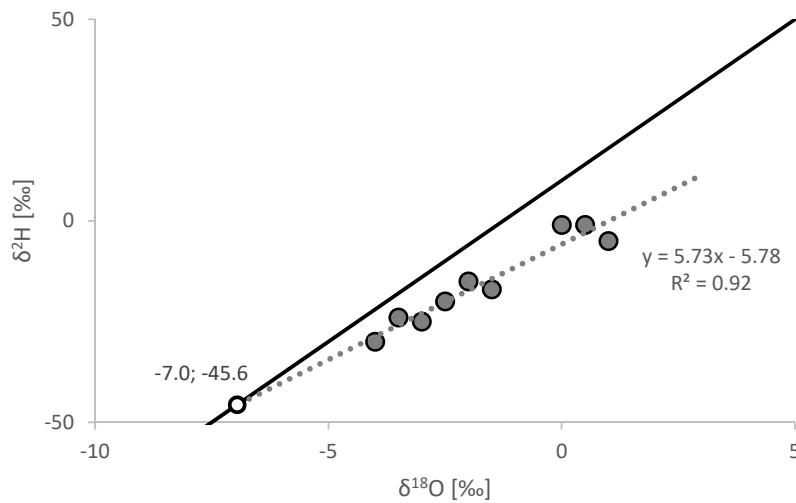


Figure 5: Example of evaporation line (slope = 5.73, intercept = -5.78) for groundwater samples and interception with GMWL indicating the original isotope composition of precipitation prior to evaporation ($\delta^{18}\text{O} = -7\text{\%}$ and $\delta^2\text{H} = -45.6\text{\%}$).

In case of condensation, the phase change from water vapour to liquid water, the resulting precipitation is enriched with heavy isotopes in comparison to the remaining water vapour in the atmosphere. Also this process can be described by a Rayleigh distillation equation similar to that one of an evaporation process.

2. Isotope effects

In the hydrological cycle water is undergoing different evaporation and condensation processes with phase changes and therefore corresponding isotope fractionation. This fractionation leads to several large scale isotope effects in precipitation. These effects are the foundation of isotope value interpretations in the course of hydrological cycle.

2.1. Meteoric water lines

2.1.1. Global meteoric water line

Values of δ^2H and corresponding $\delta^{18}O$ in precipitation are correlated and follow a linear relationship on a global scale. This relationship is defined by Craig, 1961 as “Global Meteoric Water Line” (GMWL) with a slope of 8 and an intercept of 10:

$$\delta^2H = 8 \cdot \delta^{18}O + 10 \text{ ‰} \quad (18)$$

Dansgaard (1964) introduced the deuterium excess (DE), as the intercept of the GMWL, which is defined as:

$$DE = \delta^2H - 8 \cdot \delta^{18}O \text{ ‰} \quad (19)$$

The deuterium excess value of the GMWL is therefore 10, and typical values of DE range from 0 to 20, depending on the specific humidity conditions during the evaporation process at the water source area. The DE value of 10 for the GMWL is based on the kinetic enrichment of vapour evaporating from the ocean at an average humidity of 85%.

Since the slope and deuterium excess are not numerical coefficients and are not constants, real values are slightly different and depend on climatic factors. Rozanski et al. (1993) determined, based on 206 global precipitation stations from the IAEA network, the following relationship:

$$\delta^2H = 8.17 \pm 0.06 \cdot \delta^{18}O + 10.35 \pm 0.65 \text{ ‰} \quad (20)$$

Figure 6 shows the GMWL's using slopes and intercepts of Craig (1961) and Rozanski et al. (1993).

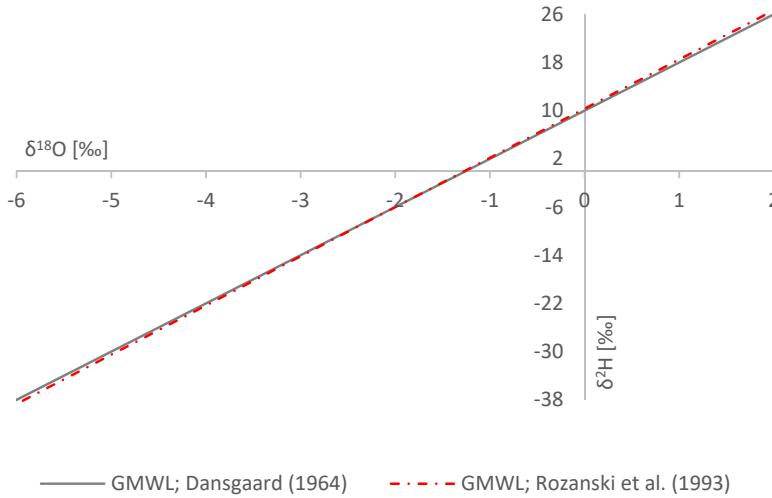


Figure 6: Global Meteoric Water lines (Dansgaard, 1964 and Rozanski et al., 1993).

2.1.2. Local meteoric water line

For regional and local investigations Regional Meteoric Water Lines (RMWL) or Local Meteoric Water Lines (LMWL) as references should be determined from local precipitation station values. The LMWL's could be quite different from the general global equations because of differences in slope and deuterium excess. The slope is defined by equilibrium conditions during condensation of precipitation within clouds, whereas the deuterium excess is influenced by the relative humidity condition during the evaporation process of the source water.

For India LMWL for 31 stations from the Global Network of Isotopes in Precipitation (GNIP) database from IAEA/WMO (2019) were analysed. Values for the slopes are ranging between 6.95 and 8.82 and for the intercept between 2.76 and 17.2. Tabled values for all stations can be found in the Appendix.

Kumar et al., 2010 report a Meteoric Water Line (MWL) for India and several regional water lines (RMWLs) for northern India, southern India, and the western Himalayas. The differences of the slopes and intercepts of these lines are attributed to differences in geographical and meteorological conditions, such as different vapour source during the monsoon seasons (see Figure 7).

Meteoric Water Line for India (MWL_I):

$$\delta^2H = 7.93 \pm 0.06 \cdot \delta^{18}O + 9.94 \pm 0.51 \text{‰} \quad (n = 272; r^2 = 0.98) \quad (21)$$

Regional Meteoric Water Line for northern India:

$$\delta^2H = 8.15 \pm 0.12 \cdot \delta^{18}O + 9.55 \pm 0.80 \text{‰} \quad (n = 65; r^2 = 0.99) \quad (22)$$

Regional Meteoric Water Line for southern India:

$$\delta^2H = 7.82 \pm 0.17 \cdot \delta^{18}O + 10.23 \pm 0.85 \text{‰} \quad (n = 62; r^2 = 0.97) \quad (23)$$

Regional Meteoric Water Line for the western Himalayas:

$$\delta^2H = 7.95 \pm 0.09 \cdot \delta^{18}O + 11.51 \pm 0.89 \text{‰} \quad (n = 123; r^2 = 0.99) \quad (24)$$

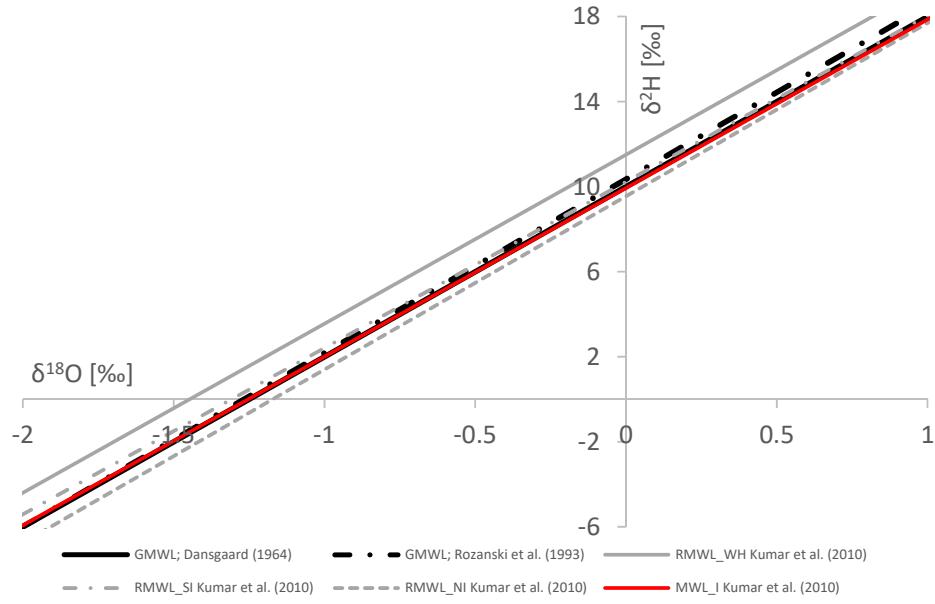


Figure 7: Indian Meteoric Water Lines; MWL_I = Meteoric Water Line for India; RMWL = Regional Meteoric Water Line; WH = Western Himalayas; SI = Southern India; NI = Northern India.

2.2. Isotope effect in precipitation

Two major factors are influencing the stable isotope composition of precipitation: the temperature (fractionation factor) and the proportion of water still available in the air package that is undergoing condensation and precipitation (Rayleigh distillation). Based on these two controlling factors several effects can be observed on a local and temporal scale. Below the most relevant ones are discussed.

2.2.1. Temperature and seasonal effect

Temperature during the condensation process is an important factor which is influencing the isotopic composition of precipitation. The temperature dependent fractionation factor α (see Section 1.3) is responsible for a more pronounced fractionation at lower temperatures compared to higher ones. This results in isotopically depleted precipitation in cold environments and isotopically enriched precipitation in warmer climates.

Dansgaard (1964) derived temperature effects of precipitation which can be expressed by a relationship with the mean annual air temperature T_a :

$$\delta^{18}\text{O} = -0.69 \cdot T_a - 13.6 \text{ ‰} \quad (25)$$

The equation shows for relationship between $\delta^{18}\text{O}$ and the mean annual air temperature with a decrease of $0.69\text{‰}/^\circ\text{C}$, which is even higher for temperatures below 0°C . In Figure 8 the relationship between the mean annual and mean monthly temperatures and the $\delta^{18}\text{O}$ values of the annual and monthly precipitation is shown for stations in India and in neighbouring countries. The relationship for annual values within the region is slightly less strong with a decrease of only $0.4\text{‰}/^\circ\text{C}$.

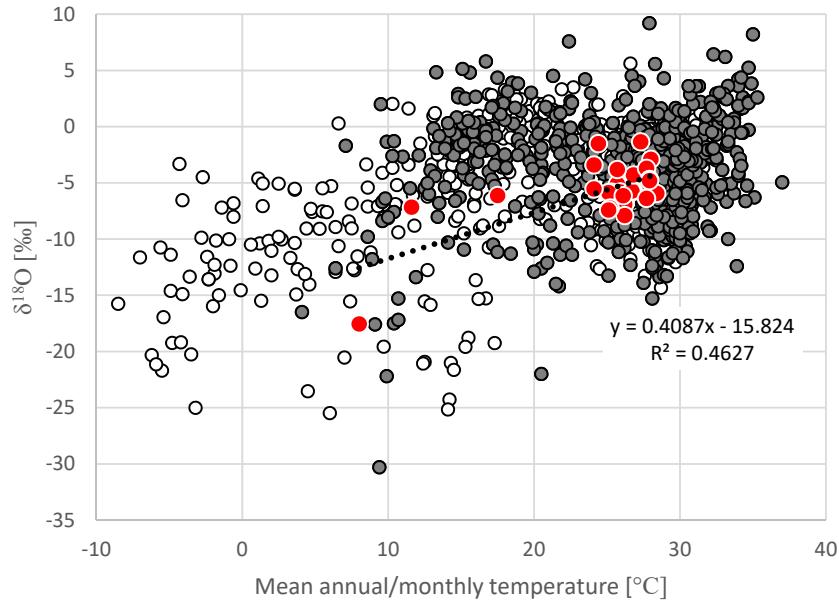


Figure 8: Relationship between mean annual/monthly temperature ($T_{\bar{o}}$) and annual/monthly $\delta^{18}\text{O}$ values of precipitation; GNIP data: filled grey circles = Stations in India (monthly values), open circles = Stations in surrounding countries (monthly values); filled red circles = Stations in India and surrounding countries (annual values).

In regions where the air temperature is changing during the seasons this effect is visible also in the isotope composition of precipitation, and can be used as an input function in the system for further investigations in soil- and groundwater. This effect is also called seasonal effect, with depleted isotope values during the colder months and enriched isotope values during the warmer periods of the year. This temperature driven seasonal effect can be overlain and modified by different trajectories of air masses and different fractionation processes in its source areas. This is also the case in many locations in India, where seasonal variations in the composition of the isotopes in precipitation is controlled by different source areas during the monsoon periods. Kumar et al. (2010) explain the annual variation in different regions of India by the source area of the northeast monsoon being the Bay of Bengal, whereas the southwest monsoon air masses originate from the Arabian Sea.

In general the seasonal effect can be used as an input function in the hydrological system by combining the isotope values and the precipitation amounts into a precipitation weighted mean value. If this “fingerprint” of the precipitation input is known, it can be detected in time series of rivers, soil water, and groundwater, and can be used to estimate travel times and mean residence times. The annual precipitation weighted mean value can also be used to characterise the mean isotope composition of the groundwater recharge.

2.2.2. Elevation effect

The elevation effect or altitude effect is based on orographic precipitation that occurs as air masses are rising at obstacles like mountains. If an air mass is rising it cools adiabatically with increasing elevation, saturation will occur, water vapour will condense, and finally precipitation is happening. During this process the heavy isotopes will condense first and enriched precipitation is the result. The remaining water vapour is depleted in heavy isotopes and the successive precipitation will be isotopically lighter. Additionally to this repeated rainout with increasing elevation the equilibrium enrichment is stronger at lower temperatures. The relationship is almost linear with a decrease of $\delta^{18}\text{O}$ values of -0.15 to $-0.5\text{\textperthousand}$ per 100 metres elevation increase. For $\delta^2\text{H}$ the elevation effect is between -1 and $-4\text{\textperthousand}/100\text{m}$.

In Figure 9 the relationship between the elevation and the $\delta^{18}\text{O}$ values of the annual and monthly precipitation is shown for stations in India and in neighbouring countries. The relationship for annual values within the region shows a slope of $-0.23\text{\textperthousand}/100\text{m}$.

This effect can be used to determine the average elevation of the groundwater recharge. The elevation effect can be used in hydrological studies to determine the mean recharge elevation of a spring or an aquifer.

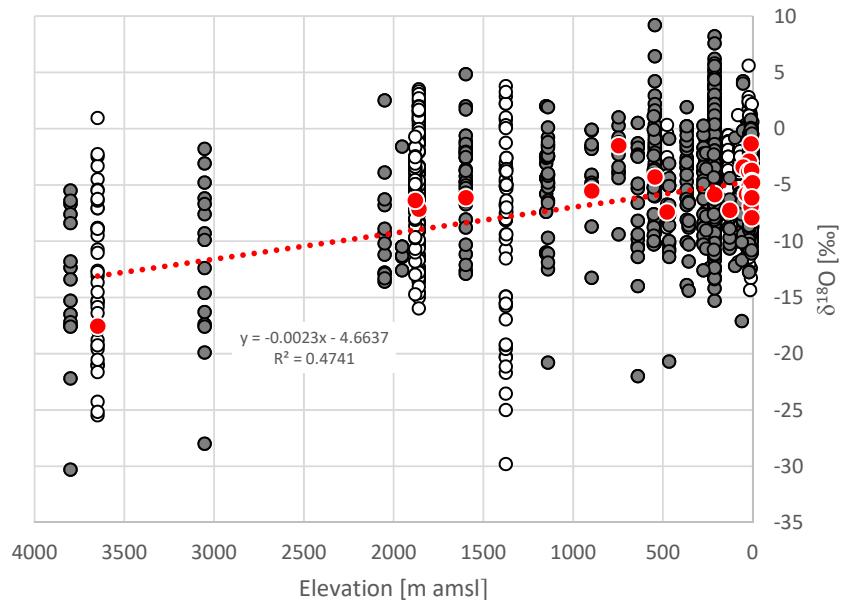


Figure 9: Relationship between elevation and annual/monthly $\delta^{18}\text{O}$ values of precipitation; GNIP data: filled grey circles = Stations in India (monthly values), open circles = Stations in surrounding countries (monthly values); filled red circles = Stations in India and surrounding countries (annual values).

2.2.3. Amount effect

The amount effect is caused by the depletion of heavy isotopes with increasing precipitation amounts. This effect can result in slopes of the MWL's which are less than 8 due to evaporation that occurs after condensation of precipitation. Falling raindrops can experience a kinetic fractionation while falling to the ground through dry air masses, therefore it is also called secondary evaporation. This effect is expected to be more pronounced in warm and hot climates, and decreases with increasing precipitation amounts.

The influence of the amount effect can be also observed for stations in India (Clark and Fritz, 1997). In Figure 11 the seasonal variations of precipitation amount, $\delta^{18}\text{O}$ of precipitation, air temperature, and the correlation between temperature and isotopic composition is shown for the GNIP station New Delhi. During the dry and colder months the $\delta^{18}\text{O}$ values are enriched compared to the lighter precipitations during the monsoon season. Also the LMWL for New Delhi, with a slope of 7.18, indicates an amount effect.

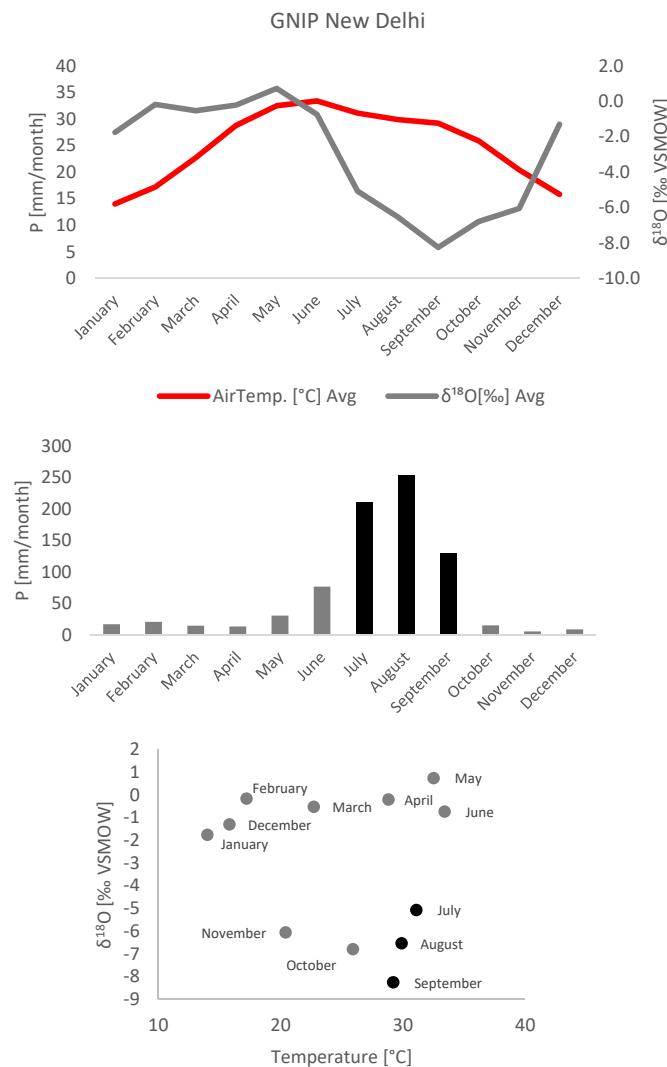


Figure 10: Seasonal variations of precipitation amount, temperature and $\delta^{18}\text{O}$ for New Delhi. (Data: IAEA/WMO, 2019).

2.2.4. Continental effect

The continental effect describes the increase of depleted precipitation with an increase of distance from the source area. During the course of an air package from the ocean towards more inland areas of the continents air masses are losing water and the heavy isotopes are more likely to precipitate first. This results in depleted remaining air masses, and the following precipitation event from this air mass will be isotopically lighter. The continental effect is more relevant for large scale investigations and can be masked by the seasonal and elevation effect or by involvement of re-evaporated water on the continents. Continental effects for $\delta^2\text{H}$ can range between 2 to 45‰/100km.

2.3. Regionalization of isotopes in precipitation

Regionalization of isotopic values measured as point values at stations is a useful tool to estimate the input function on a temporal and spatial scale, especially if investigations cover a larger area. Spatial data and maps of the distribution of isotopic values can assist in characterizing the input function of precipitation in the hydrological cycle. Based on the above described effects linear regressions can be formulated using precipitation amount, latitude, longitude, elevation, and air temperature into account.

Terzer et al. (2013) developed a regionalized cluster-based water isotope prediction (RCWIP) approach, based on the Global Network of Isotopes in Precipitation (GNIP) to predict global patterns of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in precipitation. In contrast to the classical linear regression approaches this attempt uses predefined climatic cluster. In Figure 11 results of the RCWIP isotope predictions are shown for India for the mean annual $\delta^{18}\text{O}$ values of precipitation and the error of modelled $\delta^{18}\text{O}$ values. Regionalized monthly values can be found in the Appendix.

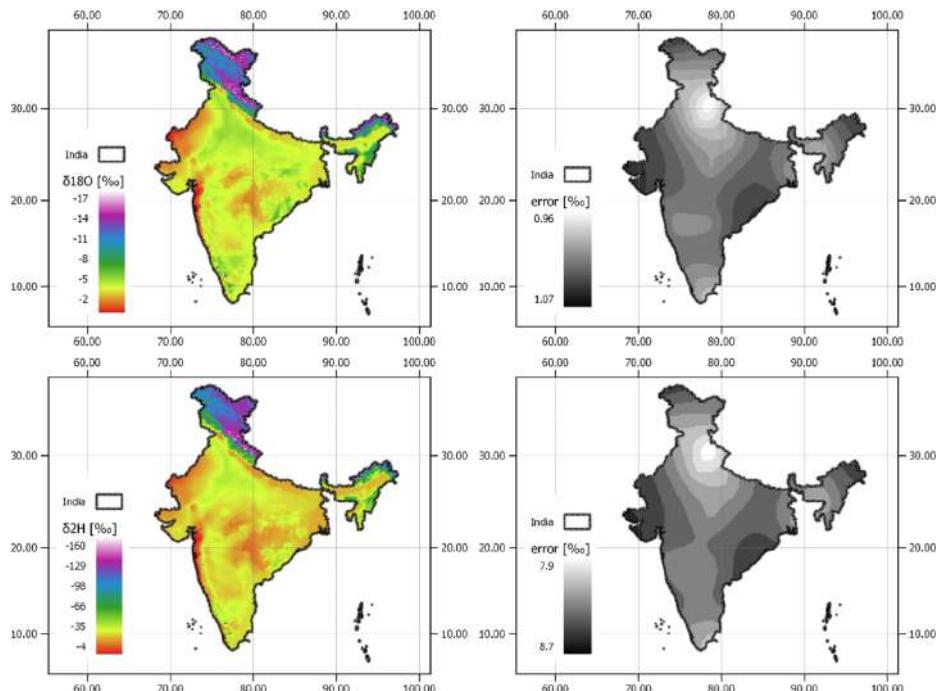


Figure 11: Maps of the mean annual $\delta^{18}\text{O}$ (upper) and $\delta^2\text{H}$ (lower) values of precipitation over India (left) and error of modelled values (right); (RCWIP model output; IAEA, 2019).

3. Application of stable isotopes in groundwater

In this chapter some examples of the application of stable water isotopes in the groundwater context are presented. For many applications detailed analysis of soil water isotopes, time series of surface water and groundwater, hydro-chemical information or additional tracers are needed.

Therefore here only applications are discussed in the context of spatial investigations with a limited isotopic data set.

As already mentioned earlier in this document the information contained in the stable isotope data can contribute to a better understanding of e.g. the groundwater recharge process, the estimation of evaporative effects, the characterization of the catchment area, surface water-groundwater connections, and groundwater mixing processes. This knowledge and understanding is often crucial for an improved groundwater management.

In order to estimate the recharge area of an aquifer system it is important to know the extent and the characteristics of the contributing catchment. Also to protect an aquifer system it is indispensable to spatially identify the contributing catchment and its recharge zones.

Mean catchment elevation

Especially in mountainous areas the elevation effect (see Section 2.2.2) can be used to estimate the mean elevation of the contributing catchment. Therefore the average isotopic composition of the groundwater or spring water is compared to the locally derived relationship between the elevation and the stable isotope values of the precipitation input. The elevation effect can be additionally influenced and superimposed by evaporative enrichment of precipitation prior to infiltration and recharge, by recharge during a different climatic period, or by mixing of different water sources and therefore influence the analysis.

In Figure 12 an example for the estimation of the mean catchment elevation of two springs is given. Spring 1 is located at 530 m amsl and spring 2 at 655 m amsl. By comparing the isotopic values of the spring waters with the corresponding elevation of this isotope value on the relationship for precipitation lead to considerable higher mean recharge s of the corresponding catchments. In the given example spring 1 has a mean catchment elevation of 807 m amsl and spring 2 of 867 m amsl.

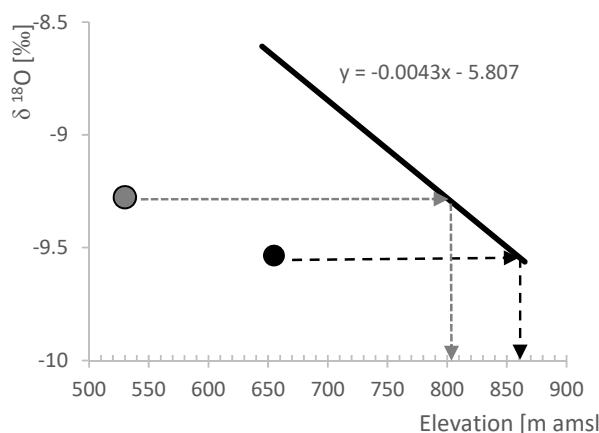


Figure 12: Example for the estimation of the mean catchment elevation for two springs. The black line represents the relationship between the elevation and the stable isotope values of the local precipitation input.

Unsaturated zone

In order to interpret spatial distributions of stable isotope values in groundwater correctly the temporal variability of the isotope data in different compartments of the hydrological cycle must be investigated and understood. Only if the isotope values in groundwater are stable or seasonal fluctuations are small or negligible a proper spatial interpretation can be carried out. In general isotope values in precipitation show a broad range of values throughout the year. This isotopic variation is attenuated and damped while passing through the unsaturated zone during infiltration and percolation before finally recharging the aquifer.

Groundwater recharge via the unsaturated zone is depending on the climate conditions. In temperate climates around 5 to 25% of the annual precipitation amounts infiltrates and is percolating to the groundwater. In arid environments this amount can be much lower (even below 1% of the annual precipitation amount) and also the isotopic composition of the percolation water can be modified and differ from that of the local precipitation. In arid regions the percolation water is generally more effected by evaporative enrichment compared temperate regions, because fractionating soil evaporation is the dominant process. In contrast transpiration fluxes (extraction of soil water from the unsaturated zone by the roots of plants), is a no fractionating process and is not changing the isotopic composition of the soil water.

Groundwater recharge is depending on seasonal precipitation inputs as well as on soil moisture conditions, and recharge is generally highest during the wet season. However often groundwater isotope values are found which are very close to the weighted average annual precipitation value. This is caused by the attenuation of the seasonal varying precipitation input values and a mixing of different precipitation sources during the passage through the unsaturated zone. The attenuation of the precipitation signal is ruled by the characteristics of the soil water movement and therefore by the geometry of the unsaturated zone with slow (porous soil matrix) and fast (macro pores and fissures) flow lines.

A critical depth can be found where the variation of the seasonal precipitation input is reduced to 2σ of the isotope analysis (see Figure 13). In case the groundwater table is deeper than the critical depth no seasonal fluctuations in the groundwater isotope values are observed, in case a shallow groundwater table is present, damped and phase shifted variations are observed (see Figure 14). In fine grained soils with slow flow pathways the critical depth in the order of meters, in fractured rocks the critical depth can be several tens of meters. If the groundwater table is shallow it might be necessary to take time series of samples, otherwise the information might not be representative due to the seasonal variability.

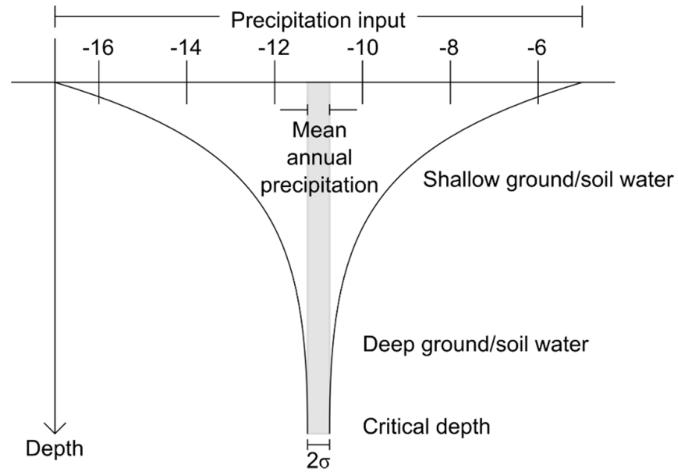


Figure 13: Attenuation of the seasonal isotope variations in precipitation in soil water and groundwater (modified after Clark and Fritz, 1997).

If seasonal variations are found in soil water or groundwater the amplitude and shift in time of the isotope signal can be used to calculate residence times. Maloszewski et al. (1983) developed a formula to calculate the residence time (T) based on the amplitudes of stable isotope time series:

$$T = \frac{\sqrt{\left[\frac{A_{\text{input}}}{A_{\text{output}}} \right]^2 - 1}}{\omega} \quad (26)$$

with A_{input} =amplitude in input e.g. precipitation, A_{output} =amplitude in output e.g. soil water or groundwater, ω =time shift (2π for 1 year).

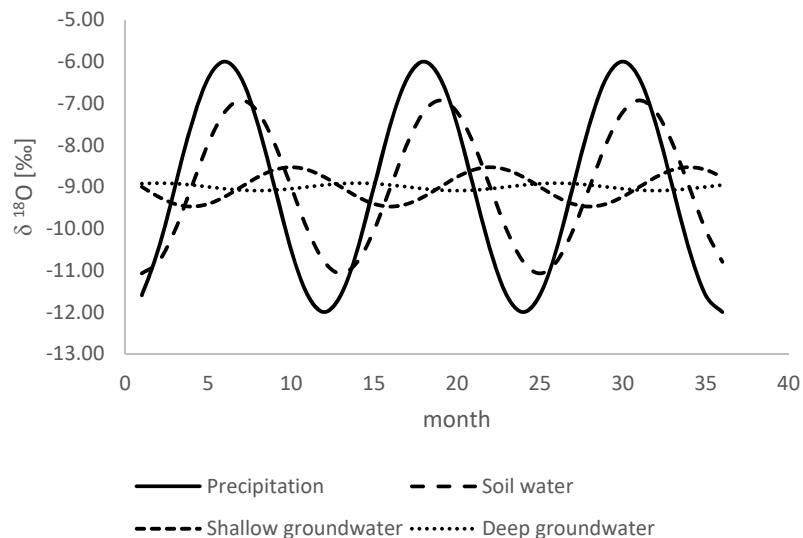


Figure 14: Idealized seasonal variation of isotope values in precipitation, soil water, and shallow and deep groundwater.

Application of formula 26 on data of Figure 14 lead to transit times for soil water, shallow groundwater, and deep groundwater of two, three, and eight months, respectively (see Table 2).

Table 2: Transit time calculation for soil water and groundwater using amplitude attenuation.

	Precipitation	Soil water	Shallow groundwater	Deep groundwater
Mean value [‰]	-9.00	-9.00	-9.00	-9.00
Amplitude [‰]	3.00	2.07	0.47	0.09
ω [-]	0	0.52	2.09	4.19
Transit time [month]	-	2	3	8

Under special circumstances the average composition of stable isotopes in groundwater can be different from the average precipitation input values due to an unbalanced seasonal recharge with higher recharge rates during specific time periods. If recharge rates are greater in a certain period of the year than isotope values of groundwater will have a tendency towards these values of precipitation. By using this bias the seasonality of groundwater recharge can be interpreted.

On the other hand a bias between values of stable isotopes of actual precipitation and the groundwater can also be caused by groundwater recharge that happened in the past under different climatic conditions with a different isotopic signature. In this case groundwater is not recharged recently, but groundwater is characterized by fossil water or paleo-water (see Figure 15).

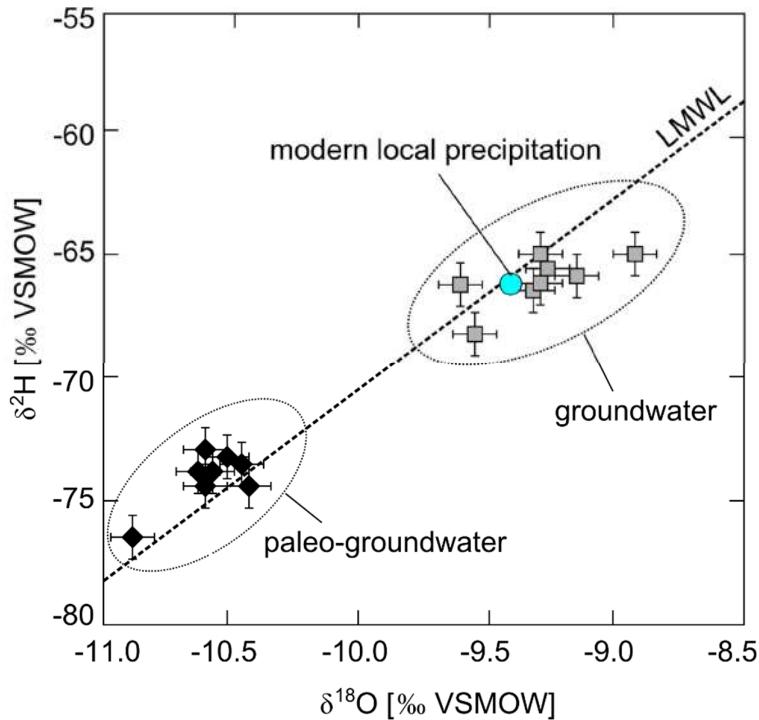


Figure 15: Stable isotope values of groundwater and paleo-groundwater compared with LMWL and weighted average of modern local precipitation (modified after Geldern et al. 2014).

Surface water-groundwater connection

Interdependencies between surface water bodies and groundwater aquifers are normally investigated by using artificial tracers or hydro-chemical or hydrodynamic data. Stable isotope data can be used in case the isotopic signature of surface- and groundwater are significantly different from each other. If groundwater is only recharge via local precipitation the groundwater isotope values should be very close to the weighted annual average of precipitation. In case there is an interaction with surface water bodies the value of groundwater can deviate.

In general surface water bodies, and especially lakes and reservoirs, are often enriched with heavier isotopes in comparison to groundwater due to evaporative processes. In case of rivers also the contributing catchment and the elevation of this is important and isotope values can differ considerably due to the elevation effect. Stable isotopes are a suitable tool to identify loosing river reaches and therefore infiltration of river water. Especially in alluvial aquifer systems this can be an important component of groundwater recharge. For groundwater management the knowledge of a potential contamination from surface water bodies could be of interest as well as the potential of water purification of infiltrated river water for drinking water supply.

For a qualitative assessment of surface water groundwater connections a comparison of the isotope values of the different source waters and the groundwater is useful. Figure 16 shows $\delta^2\text{H}$, $\delta^{18}\text{O}$ and tritium (${}^3\text{H}$) values of precipitation, surface water, and different groundwater wells in the Rhine valley, Germany. From the $\delta^2\text{H}$ - $\delta^{18}\text{O}$ graph (Figure 16 left side) it can be seen that groundwater is a mixture of local precipitation, lateral groundwater flow components, deep groundwater, and surface water in different proportions. However only by using the information from the tritium analysis revealed a clearer picture about the different recharge sources. For example is groundwater group A clearly influenced by surface water infiltration, group A+B a mixture between surface water and lateral groundwater inflow, and group B+C a mixture between lateral groundwater inflow and deep groundwater.

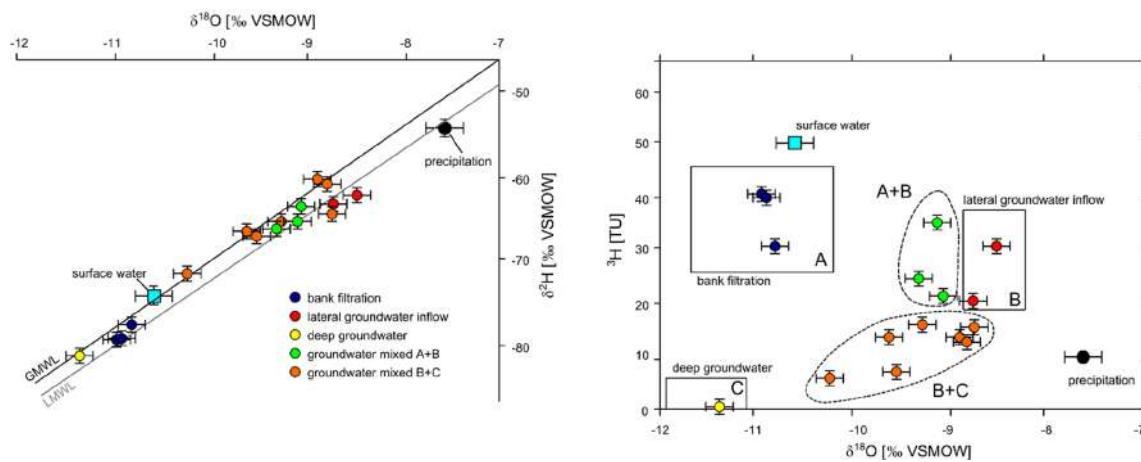


Figure 16: Relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ (left) and ${}^3\text{H}$ and $\delta^{18}\text{O}$ (right) for local precipitation surface water and groundwater in the Rhine valley, Germany (modified after Wenninger, 2007).

Groundwater mixing

Stable water isotopes are conservative tracers, unlike most hydro-chemical components, and can therefore be used of a linear mixing analysis. The basic assumption behind this method is that the involved water sources have a distinct different isotope composition. In case they are too similar (see Figure 16) often additional tracer like tritium or carbon-14 are used in the analysis.

For a quantitative assessment of water mixing, e.g. surface water groundwater interaction, mixing of different recharge origins or connection between aquifers a simple mass balance can be used to determine the contributions of two different sources according to:

$$\delta^{18}\text{O}_{\text{sample}} = x \cdot \delta^{18}\text{O}_{\text{component A}} + (1 - x) \cdot \delta^{18}\text{O}_{\text{component B}} \quad (27)$$

$$\delta^2\text{H}_{\text{sample}} = x \cdot \delta^2\text{H}_{\text{component A}} + (1 - x) \cdot \delta^2\text{H}_{\text{component B}} \quad (28)$$

with $\delta^{18}\text{O}_{\text{sample}}$ and $\delta^2\text{H}_{\text{sample}}$ = stable isotope values of the e.g. well water sample, component A and B = values of the two mixing components e.g. groundwater and surface water, x = fraction between 0 and 1.

Figure 17 shows the mixing between two water types (component A and B) in different fractions using formula 27 and 28 ranging from 0-100%.

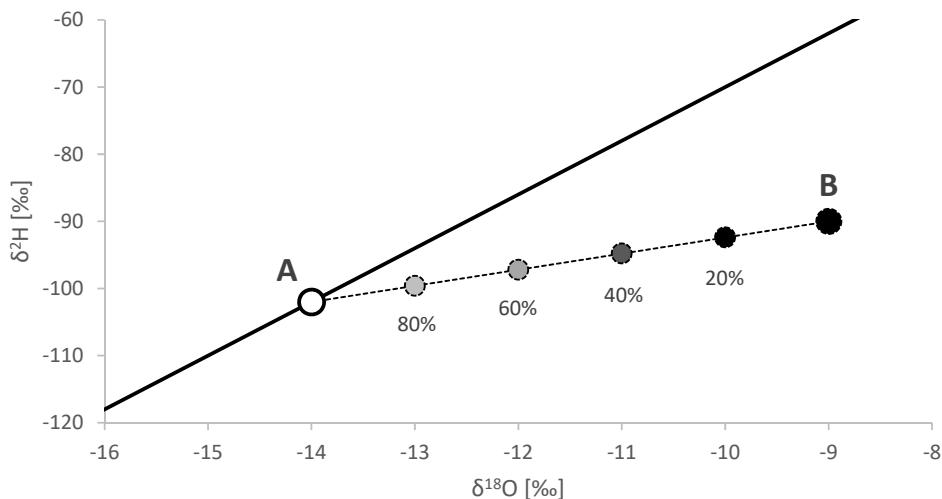


Figure 17: Fractional mixing of two groundwater aquifers (A and B) based on stable isotope values (modified after Clark and Fritz, 1997).

Salinity issues in groundwater

A common problem in groundwater management is groundwater salinization which can have negative effects on the use of groundwater for drinking water purposes. Several processes can be responsible for high salinization of groundwater like natural effects (infiltration of brines, evaporation, and dissolution of salt minerals) and human activities (irrigation, contamination of brines, and over-exploitation in coastal areas). Typically Total Dissolved Solid (TDS) and Chloride (Cl) or electrical conductivity (EC) are parameters linked to salinization. Concentrations of >1000 mg/L for TDS and >250 mg/L for chloride are not suitable for drinking water (WHO 2017).

Hydro-chemical analysis in combination with isotope data can be used to identify the causes of an increased salinization. In case evaporative processes play a role in the salinization the relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ follow an evaporation line and the correlation between the isotopes and e.g. Cl or EC are positive. On the other hand if dissolution of salt minerals are the cause for salinization the isotopic signature remains unchanged and there is no correlation between isotopes and dissolved substances. In Figure 18 groundwater samples effected by both described processes are shown by plotting the relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ as well as chloride values against $\delta^{18}\text{O}$.

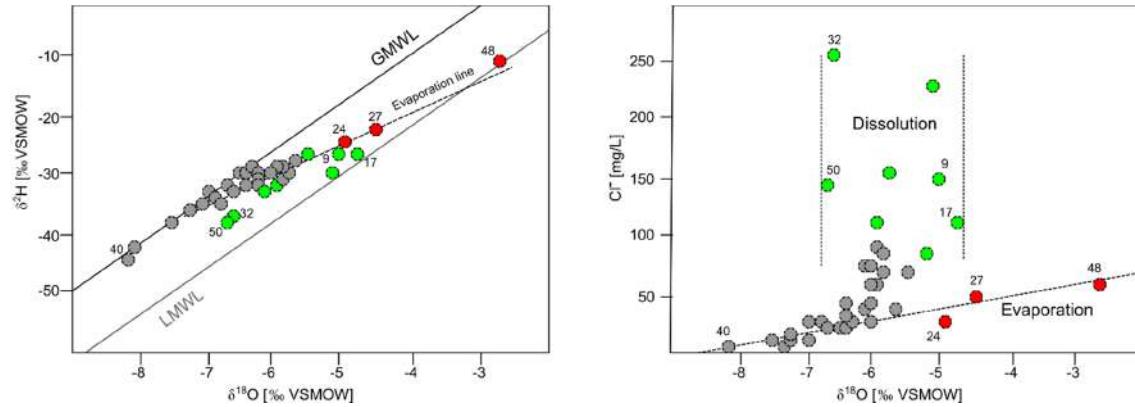


Figure 18: Relationship between $\delta^2\text{H}$ and $\delta^{18}\text{O}$ (left) and Cl and $\delta^{18}\text{O}$ (right) for groundwater samples (modified after Kattan, 1996).

4. Practical aspects

4.1. Sampling of stable water isotopes

A good sampling procedure is important for high quality results and reliable interpretation of stable isotope values. This includes next to the isotopic values themselves other metadata like e.g. location, elevation, water table depths and basic physicochemical information like electrical conductivity, water temperature, pH, dissolved oxygen and alkalinity.

The sampling for stable water isotopes is rather straightforward, because no filtration or preservation is needed. The only important aspect of sampling is that evaporation from the sampling bottles is avoided. A well-sealed and dry glass or polyethylene bottle is sufficient. Normally an amount of 50 mL is sufficient for the analysis of oxygen-18 and deuterium.

Groundwater sampling

Before groundwater samples are collected the static water level of the well should be measured relative to a defined reference point. After the water level has been measured the well should be purged with a pump. Generally three well volumes should be removed before groundwater samples are collected. An example for a field Information template and sample list template for isotope and/or chemical analysis from IAEA is attached in the Appendix.

Precipitation sampling

The main consideration for precipitation water sampling is to avoid evaporation from the collection bottle. The exposure of sampled water to the atmosphere will change the isotopic composition of the sample. A precipitation water samples represents an integral sample of the whole sampling period, which could be on an event, daily, or monthly basis. Therefore it is important to avoid losses or spill over from the collection device. In case precipitation samples cannot be collected manually for the timing of the designated sampling period precipitation totalizers, which are protected against evaporation, can be used. Details of the different methods can be found in IAEA/GNIP (2014).

4.2. Measurements of $\delta^2\text{H}$ and $\delta^{18}\text{O}$

Measurements of the absolute isotope concentrations are very complicated and not necessary for the application of stable water isotopes in hydrology. It is sufficient to determine the isotope ratio between the heavier and the lighter isotope of an element. The classical approach to determine isotope ratios is by using an Isotope Ratio Mass Spectrometer (IRMS). The measurement principle is based on the separation of atoms and molecules with different masses during their movement in a magnetic field. In a preparation step water samples to be analysed for their isotopic composition are transferred into a gas. In case of ^{18}O this is done by an equilibration unit with CO_2 reference gas ($\text{CO}_2\text{-H}_2\text{O}$ equilibration), and for ^2H either by an equilibrium unit with H_2 reference gas ($\text{H}_2\text{-H}_2\text{O}$ equilibration) or by a reduction within a reduction oven using e.g. Chromium. Samples are always analysed together with laboratory standards of known isotope ratios so that the results can be translated to the δ -notation based on the VSMOW. Via an inlet system the sample gases are brought into the IRMS, ionised by electron bombardment, and the ions are accelerated and sent through a magnetic field. Based on the different masses lighter ions are deflected more than heavier on their passage. At the detector unit the separated ions are captured separately and the impulses are counted. More details about the IRMS can be found in Hoefs (2009) and Clark and Fritz (1997).

Isotope Ratio Mass Spectrometers were used in the past decades as the standard instrument to measure stable water isotopes. Currently the new developed Laser Absorption Spectroscopy (LAS)

technique offers an optical, fast, precise, and cost effective alternative. The principle of a LAS is a single absorption line in the absorption spectrum of the laser by an isotope species. After converting the liquid water sample to water vapour in an oven the gas sample is transferred into a cavity and exposed to a laser source. The transmitted laser intensity is related to the concentration of the species in the cavity based on the Beer-Lambert law. The measured intensity, detected by a photodiode, is then used to determine the isotope ratios. More details about the LAS technique can be found e.g. in IAEA (2009), Lis et al. (2008) and Crosson (2008).

Depending on the used technique and instrument the measurement errors for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are typically in the range of $\pm 0.3\text{\textperthousand}$ and $\pm 1.0\text{\textperthousand}$, respectively.

4.3. Sources of information

Reference time series of stable isotope values in precipitation are needed to carry out applications of stable isotopes in groundwater studies. Often snap samples of groundwater are taken that need to be interpreted in relation to the long term spatial and seasonal isotopic characteristics of the precipitation and therefore groundwater recharge. For this purpose national or international reference stations can be used and compared with the groundwater sample values. In addition to this in case of surface water-groundwater interactions there is a need for isotopic values of rivers or other surface water bodies. Also a comparison with physical and chemical parameters help to interpret the hydrological relationships which would, only based on isolated individual isotopic information, be difficult.

International monitoring networks

In 1961 the International Atomic Energy Agency (IAEA) and the World Meteorological Organization (WMO) established an international monitoring network for the stable water isotopes 18-O and 2-H , and the radioactive isotope tritium in precipitation. The Global Network of Isotopes in Precipitation (GNIP) contains monthly precipitation samples of over 1000 meteorological stations in more than 125 countries and territories (IAEA, 2015). In 2002 the Global Network of Isotopes in Rivers (GNIR) was initiated to complement the GNIP database with isotopic information of surface water bodies (IAEA, 2013). Both databases can be accessed via the WISER platform hosted within the IAEA's repository for technical resources (http://www-naweb.iaea.org/napc/ih/IHS_resources_isohis.html)

In the case of India the GNIP database contains actually stable isotope values in precipitation of 36 stations with monthly data, three stations with daily data, and one station with isotope values of water vapour. The GNIR database does not have any station within India. Sample numbers and slopes and intercepts of the LMWLs for the Indian stations can be found in the Appendix.

Gridded global datasets

An alternative for using information of point data for the GNIP stations is the dataset from the Regionalized Cluster-Based Water Isotope Prediction (RCWIP) approach, developed by Terzer et al. (2013). Based on the GNIP data global patterns of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in precipitation are predicted. Average monthly $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of precipitation are available in a resolution of 10 arcmin. The dataset can be also accessed and downloaded from the IAEA website (http://www-naweb.iaea.org/napc/ih/IHS_resources_rcwip.html). Monthly regionalized values for India can be found in the Appendix.

5. Description of used methodology

In this chapter a step by step description of the used methodology is given. This includes necessary spatial data sets for the analysis, isotope and hydro-chemical data, basic statistical analysis and calculations, and maps and graphs that are used for the interpretation of isotope data.

Data and information collection

In a first step general background information about the study area is collected. This includes a literature study about scientific publications and official reports of relevant topics. This information is needed to gain a first overview of the geographic setup of the area. Useful information includes details about the topographic, hydrologic, geologic, and hydrogeological setting, as well as information regarding soils and land cover/land use in the area.

In a second step the available isotopic and water quality data of groundwater samples are collected. This data ideally includes next to the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values, in-situ water sample parameters like temperature, EC and pH values, and hydro-chemical information of basic anions and cations, also water sample relevant meta-information of e.g. sampling point location, elevation, and information of the groundwater well settings.

In a third step hydro-meteorological information and isotope values of precipitation and if available surface water bodies are collected. Therefor the datasets (described in Section 4.3) of international monitoring networks like the Global Network of Isotopes in Precipitation (GNIP) or Global Network of Isotopes in Rivers (GNIR) can be used. In case of larger areas, or areas where no GNIP stations in the vicinity are available it is useful to utilize regionalized gridded global datasets like the Regionalized Cluster-Based Water Isotope Prediction (RCWIP).

In the fourth step all relevant geospatial data sets are collected. These include, but are not limited to raster or shapefiles of e.g. administrative boundaries, location of city and villages, elevation, rivers, lakes, reservoirs, catchment boundaries, geology, geomorphology, hydrogeology, soils, land cover land use. Also spatial information of groundwater relevant information like groundwater levels could be useful.

In Table 3 an overview of the relevant data sets and their typical units and file formats is given. Examples of data used for the case studies can be found in Appendix A on page 26 for the Haryana pilot area, and Appendix A on page 27 for the Karnataka pilot area.

Table 3: Required typical background information, data sets, and geospatial data used in spatial isotope data interpretations.

Background information	Topography Hydrology Geology Hydrogeology Soils Land cover/ land use General other relevant information	Information from literature study scientific publications and official reports overview of study area and geographic setup
------------------------	--	--

		Parameter	Units
Groundwater sample data	Metadata	Location (Lat/Lon) Elevation (ELEV)	Geographic coordinates m amsl
	Groundwater well	Total well depth Filter depth Static water table	m amsl m amsl m amsl
	Isotopes	Oxygen-18 (^{18}O) Deuterium (^2H)	δ VSMOW ‰ δ VSMOW ‰
	Water Quality	Electrical conductivity (EC) Water Temperature (Tw) pH value (pH) Total dissolved solids (TDS) Salinity Major anions and cations	$\mu\text{S}/\text{cm}$ °C - mg/L PSU, ppt, g/kg mg/l
Hydro-meteorological data	Meteorology	Monthly Air Temperature (Ta) Monthly Precipitation (P) Oxygen-18 (^{18}O) Deuterium (^2H)	°C mm/month δ VSMOW ‰ δ VSMOW ‰
	Hydrology	Location of rivers, lakes, reservoirs Discharge (Q) or Volumes (V) Oxygen-18 (^{18}O) Deuterium (^2H)	Geographic coordinates m³/s or m³ δ VSMOW ‰ δ VSMOW ‰

Geospatial information	Administration	Administrative units and boundaries of states, districts, locations; shape files
	Places	Location of cities and villages; shape files
	Topography	Digital Elevation Model (DEM); raster file
	Hydrology	Rivers, lakes, reservoirs, catchments; shape files
	Geology	Geological map; shape file
	Geomorphology	Geomorphological map; shape file
	Hydrogeology	Hydrogeological map; shape file
	Soils	Soil map; shape file
	Land use/ Land cover	Land use/ Land cover map; shape or raster file
	Groundwater	Water level data; shape file
	Other information	All other relevant background maps available

Data organization and data quality check

After collecting the necessary background information, water sample data, and geospatial data sets the data needs to be organized and a preliminary quality check carried out. Under normal circumstances it is enough to organize the water sample and precipitation data in a spreadsheet for further analysis. The geospatial information can be organized and stored within a GIS environment. For the two case studies presented in the Appendix QGIS version: 3.8.2 – Zanzibar (<https://qgis.org>) was used.

Data quality control was preliminary carried out using a visual data quality check approach.

Therefore data sets can be plotted using common spreadsheet, data visualization and analysis tools like e.g. Microsoft Excel, R Programming, Python, or SPSS.

Examples of organized data sets used for the case studies can be found in Appendix B on page 27-30 for the Haryana pilot area, and Appendix B on page 29-32 for the Karnataka pilot area. Typically the data is organized for further analysis in a well-structured way containing all relevant information (see Table 4) like e.g. sample number, location, administrative location, sample meta data, isotope values, hydro-chemistry data, and information that could be later used for grouping of samples like underlying geology, soil type or land use/land cover classes.

Table 4: Example of table structure for data organization

NO	...	STATE	DISTRICT	...	SAMPLE TYPE	DEPTH	LAT	LONG	ALT	EC	...	$\delta^{18}\text{O}$	δD	...	AQUIFER	ZONE TAPPED	...
[<i>-</i>]	...	[<i>-</i>]	[<i>-</i>]	...	[<i>-</i>]	[m]	[DDEG]	[DDEG]	[m amsl]	[$\mu\text{s}/\text{cm}$]	...	[‰]	[‰]	...	[no. 1,2,3]	[<i>-</i>]	...
16	...	Haryana	Kaithal	...	GW	100	29.650478	76.368083	237	11590	...	-6.96	-46	...	1	58.5	...
17	...	Haryana	Kaithal	...	GW	200	29.650478	76.368083	238	3910	...	-6.73	-41	...	2	172	...
...

Data grouping and analysis

The first step of the data analysis is the determination of the input signal from precipitation.

Therefore locally measured isotope values in precipitation can be used and site specific Meteoric Water Lines (MWL) be determined by defining a regression between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values of precipitation. In case these values are not available the Local (LMWL) or Regional (RMWL) Meteoric Water Lines can be used as presented in Section 2.1. For a better comparison usually also the Global Meteoric Water Line (GMWL) is used. To assess the monthly or seasonal input variability of precipitation it is also recommended to investigate average monthly or weighted seasonal values like e.g. in Figure 6 and 7 for the Haryana pilot area and Figure 7 and 8 for the Karnataka pilot area.

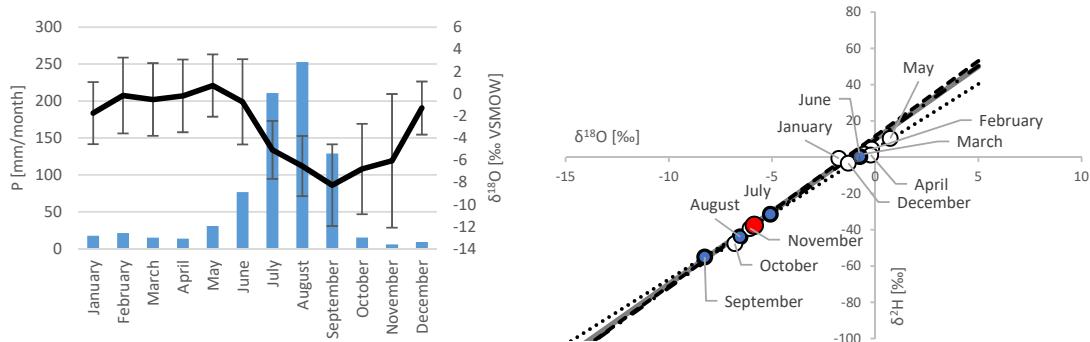


Figure 19: Example for variability of isotope values in precipitation; monthly variability (left) and $\delta^{18}\text{O}-\delta^2\text{H}$ graph (right).

In the second analysis step the groundwater isotope values are compared to the input signal of precipitation (see Figure 19). This analysis gives a first overview and can be used to identify differences between sample groups. Also grouping the data according to aquifer groups, geological units, soil types, or hydrological catchments helps with the later interpretation of the data. In Figure 20 two examples of groundwater sample data comparisons with precipitation values are given.

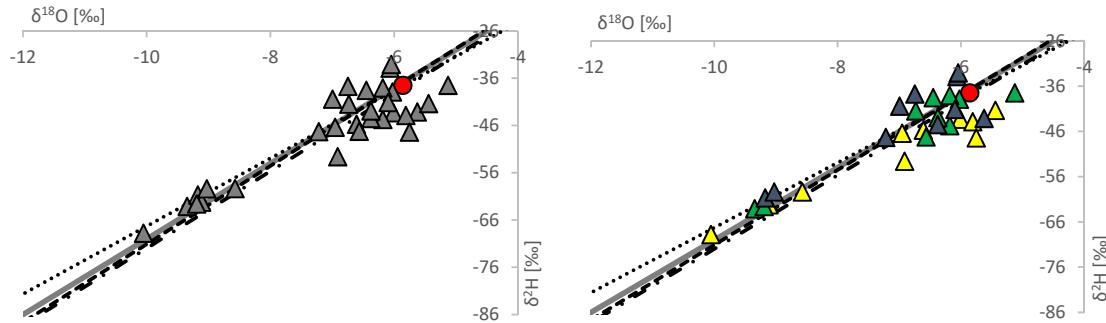


Figure 20: Examples for a comparison between isotope values of groundwater samples and precipitation inputs, all data ungrouped (left) and data grouped based on aquifer groups (right).

The third step of the analysis includes the calculation of the deuterium excess value (DE). In order to determine the DE value formula 19 in Section 2.1.1 can be used. This value assists in identifying samples which are influenced by evaporative effects. Figure 21 shows an example of the Karnataka pilot area with negative deuterium excess values and samples that are influenced by evaporative enrichment.

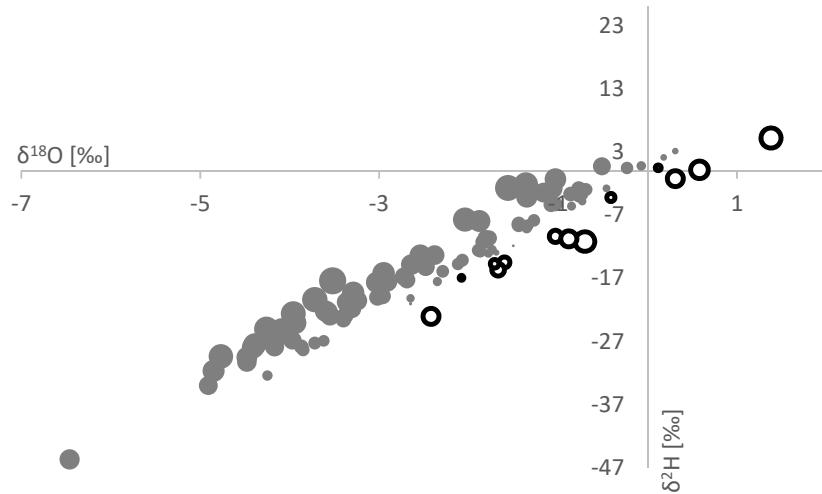


Figure 21: Example of groundwater samples influenced by evaporation indicated by negative DE values (open circles).

Maps and graphs interpretation

In the final step of the analysis maps and graphs are created which can be used for the interpretation of the stable water isotope values of groundwater.

Maps showing combined information of isotope values and geospatial information like elevation, geological layers or soil information help to interpret the spatial occurrence of isotope values and their spatial distribution.

Figure 22 shows an example of the combination of geological information with isotope values in groundwater for the Karnataka pilot area. The geological data used in this map was also used to group the isotope values of groundwater based on the geological layers.

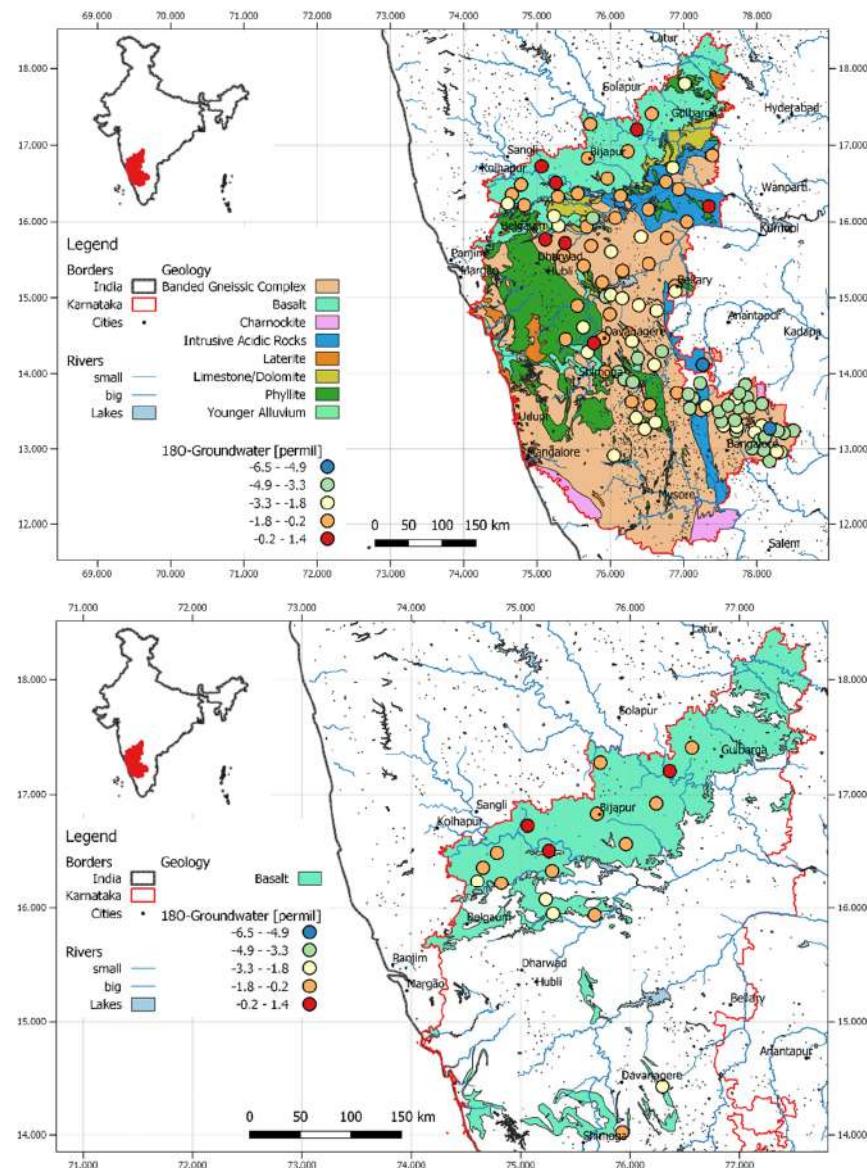


Figure 22: Example maps of isotope values in groundwater with underlying geology within the Karnataka pilot area; all samples (upper maps) and basalt area only (lower map).

By using graphs with combined information of isotopes or deuterium excess values together with e.g. groundwater table depth, elevation, or water quality parameters information about evaporation effects, recharge elevation or recharge mechanisms can be gathered.

The graphs in Figure 23 show examples of the combination between isotope data and other data. Typical features used in isotope comparisons are:

- Different water sources
- Elevation of sampling point
- Tapped aquifer zone
- Groundwater table
- In-situ parameters
- Hydro-chemical parameters

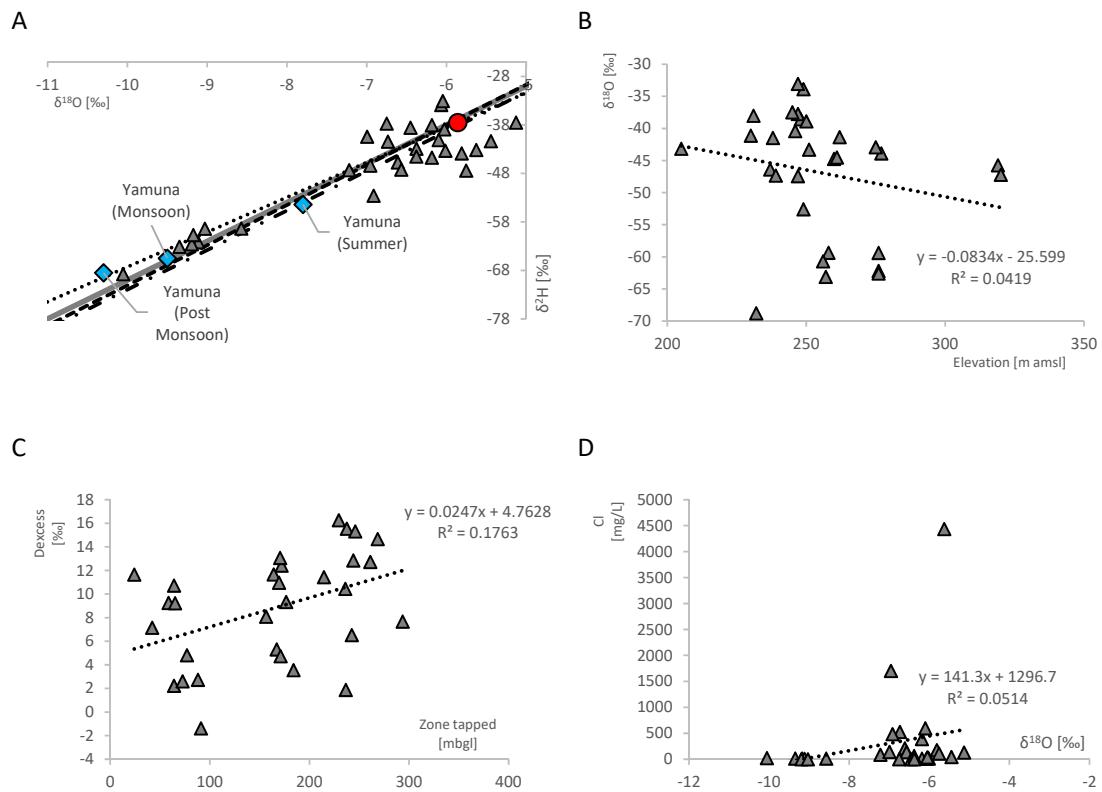


Figure 23: Example plots combining isotopic information and other relevant data; (A) precipitation and surface water sources, (B) $\delta^{18}\text{O}$ -elevation, (C) Deuterium excess-tapped zone, (D) Chloride- $\delta^{18}\text{O}$.

Finally the combination of spatial maps and graphical displays of the data enables the interpretation of the groundwater data. Figure 24 illustrates the schematic flowchart of the used methodology, including the four main steps of the methodology.

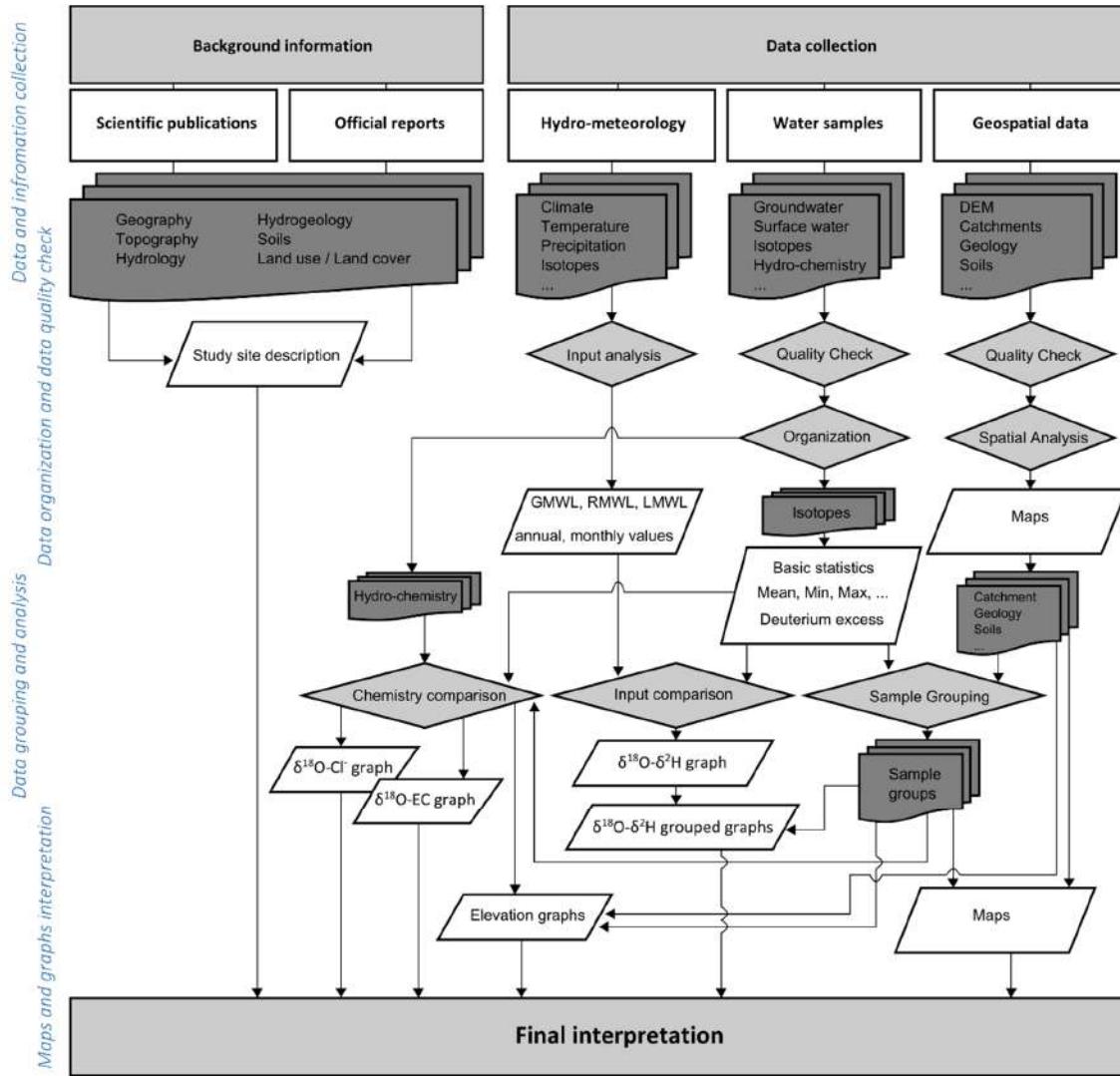


Figure 24: Flowchart of the methodology for spatial isotope analysis.

Conclusions and recommendations

Stable water isotopes can provide a useful contribution in the solution of hydrogeological problems and questions. They provide a suitable tool in groundwater investigations especially if they are used and interpreted in combination with other information like geology, hydrogeology, and hydrochemistry.

Probably the most important advantage of stable water isotopes for hydrogeological studies is their occurrence as natural tracers and their spatially distributed input in the hydrological system by precipitation. Therefore they can be used to determine origin and timing of groundwater recharge, characteristics of the contributing hydrological catchment, residence times, flow pathways, and surface water-groundwater interactions.

Stable water isotopes are widely used in scientific research applications which are unfortunately not always easily transferable in a standardized way to the practical aspects of hydrogeology and questions of groundwater management. In this context a good knowledge of the spatial characteristics of precipitation input and values of interacting surface water bodies is needed next to an adequate sampling strategy in a spatial and temporal aspect. For the long-term precipitation input reference values of the Global Network of Isotopes in Precipitation (GNIP) or the regionalized cluster-based water isotope predictions (RCWIP) can be useful to characterize the temporal pattern of groundwater recharge. For the spatial interpretation of isotope data of groundwater it is important to establish a monitoring network of sampling points which are observed on a regular basis. Good examples of such networks can be found in e.g. Austria (UBA, 2015) and Switzerland (Schotterer, 2010).

The two pilot site application in Haryana (alluvial system) and Karnataka (hard rock system), presented in the Appendix, also identified several shortcomings and limitations. For the Haryana pilot site the biggest limitation is the small sample number. Therefore it is recommended to increase the sample number to better characterize the spatial distribution of isotope values in this area. Also a better understanding of and estimation of isotope values of surface water bodies, like rivers and canals is needed to determine these important sources of groundwater recharge. The Karnataka pilot study revealed the importance of hydro-chemical information. In this study missing basic water quality parameters like e.g. chloride or nitrate concentrations limited the interpretation.

As an additional investigation method it is recommended to determine groundwater ages using radioactive isotopes like tritium or carbon-14. This could be helpful for the differentiation between recently recharged groundwater and old groundwater which has been recharged under different climate conditions.

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Appendix A

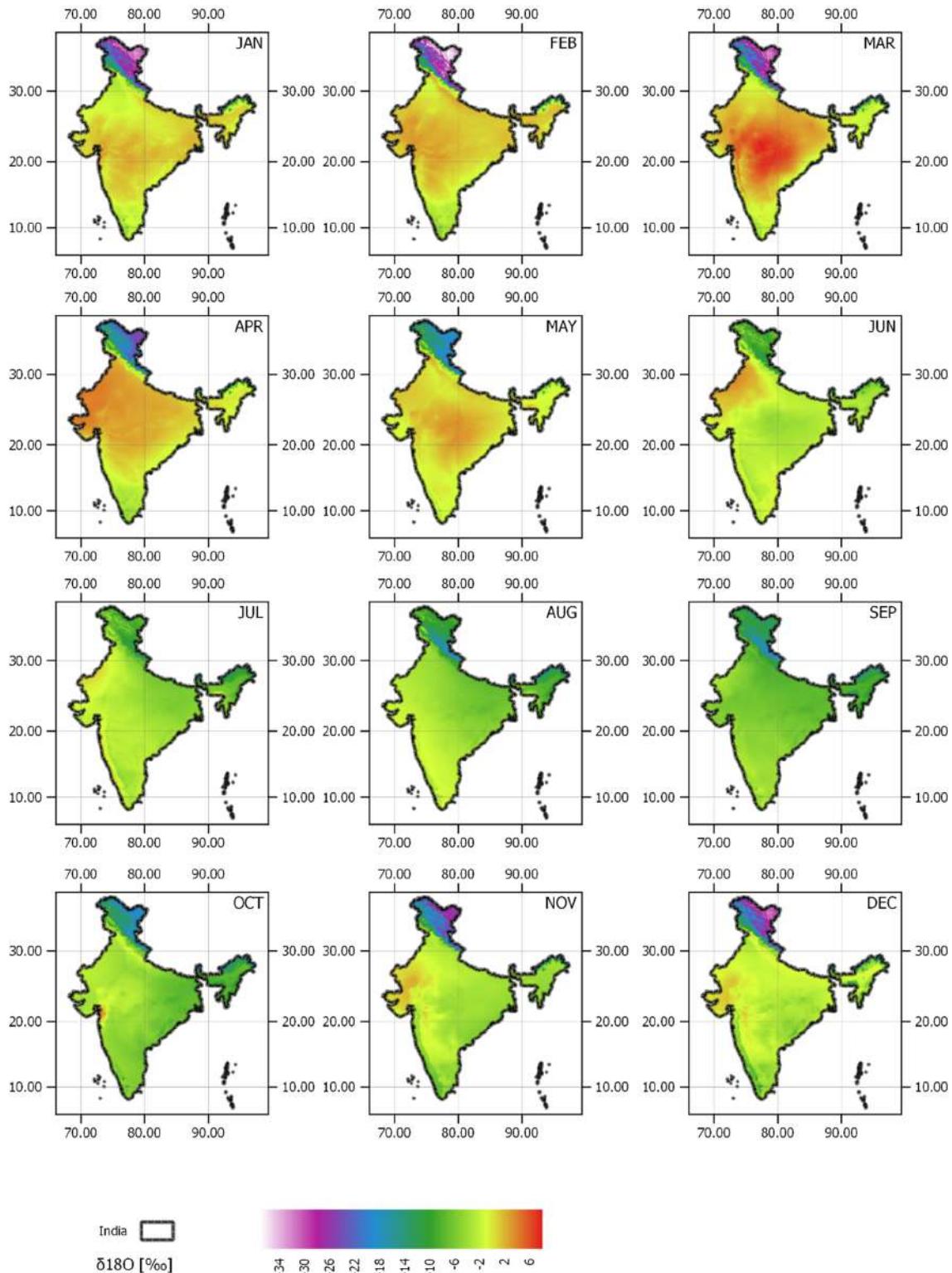
LMWLs for India

Slopes (a) and intercepts (b) of GNIP stations in India (Source IAEA/WMO, 2019).

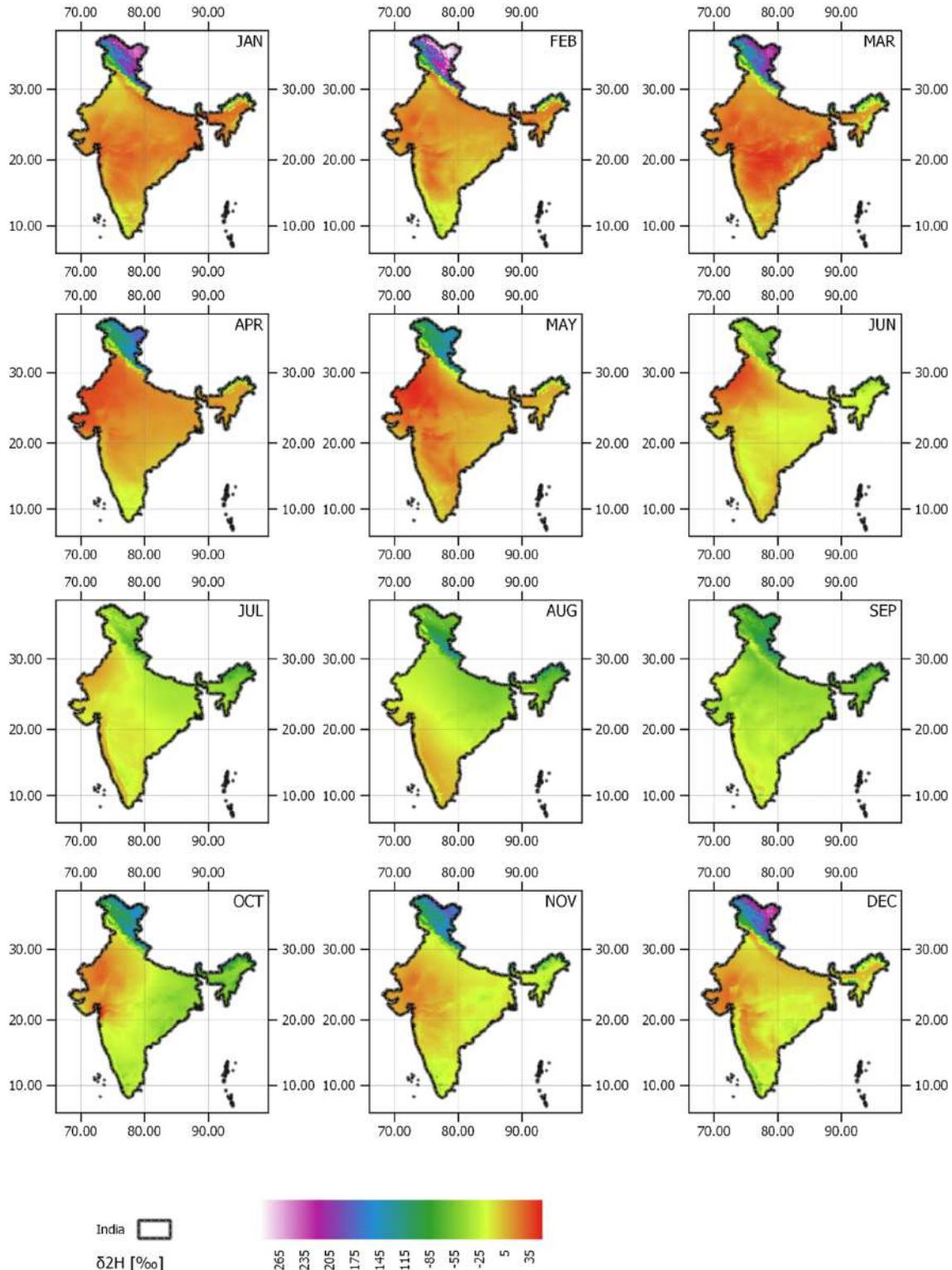
Site	a	b	Stand. error	R ²	N
NEW DELHI	7.18 ± 0.09	4.53 ± 0.49	7.16	0.95	301
MUMBAI	7.94 ± 0.29	8.40 ± 0.75	3.8	0.94	48
SHILLONG	8.02 ± 0.19	11.88 ± 1.19	4.08	0.98	30
KOZHIKODE (CALICUT)	7.69 ± 0.10	9.54 ± 0.47	2.6	0.99	85
HYDERABAD	6.95 ± 0.21	4.46 ± 0.99	5	0.97	33
JAMMU (INDIAN CONTROLLED KASHMIR)	8.31 ± 0.23	11.02 ± 1.18	4.14	0.98	27
KAKINADA	7.86 ± 0.29	10.29 ± 1.61	3.86	0.97	23
ROORKEE	8.28 ± 0.24	11.73 ± 1.61	3.76	0.99	19
SAGAR	7.89 ± 0.29	8.08 ± 1.82	3.95	0.98	14
DEVPRAYAG	8.06 ± 0.30	9.59 ± 2.77	5.35	0.98	15
DOBRANI	8.03 ± 0.39	13.99 ± 3.89	6.14	0.97	13
GANGOTRI	8.01 ± 0.24	12.55 ± 3.39	6.4	0.99	14
GOMUKH	8.23 ± 0.12	17.20 ± 1.85	3.04	1	15
KOLKATA	8.82 ± 1.07	12.57 ± 8.26	5.04	0.87	12
TEHRI	7.93 ± 0.33	9.39 ± 3.02	7.59	0.97	17
UTTARKASHI	8.08 ± 0.26	14.06 ± 1.75	6.26	0.98	27
BELGAUM	7.80 ± 0.62	11.32 ± 2.28	5.66	0.94	12
PATNA	7.81 ± 0.49	3.65 ± 5.63		0.98	5
TIRUNELVELI	7.09 ± 0.54	5.40 ± 1.78	2.26	0.95	12
THARAMANI	8.16 ± 0.12	13.54 ± 0.90		1	5
MANERI	7.06 ± 0.50	2.84 ± 3.06	6.21	0.96	11
RISHIKESH	8.49 ± 0.25	10.74 ± 2.47		0.99	8
BANGLORE	7.81 ± 0.34	11.74 ± 1.78	3.86	0.98	11
GUWAHATI	8.15 ± 0.25	3.60 ± 1.85	4.2	0.99	11
LUCKNOW	7.83 ± 0.56	7.34 ± 4.67		0.96	8
LAKE SASTHAMKOTTA	7.72 ± 0.76	6.27 ± 2.93		0.92	8
NAINITAL	7.54 ± 0.49	6.34 ± 5.08		0.98	6
ALLAHABAD	7.57 ± 0.16	4.67 ± 1.40		1	5
BHOPALPALLI	7.68 ± 0.28	7.54 ± 2.07		0.99	5
CHINPAK	7.38 ± 0.45	5.81 ± 2.73		0.98	5
KAMALAPUR	7.99 ± 0.22	10.14 ± 1.57		1	5
NASARAM	7.93 ± 0.61	4.25 ± 4.06		0.97	5
SALAGIRI	7.07 ± 0.27	2.76 ± 2.04		0.99	5
TUNDLA BUZURG	7.52 ± 0.32	5.78 ± 2.20		0.99	5

Regionalized monthly isotope values for India

Maps of the monthly (January to December) $\delta^{18}\text{O}$ values of precipitation over India. (Data: Regionalized Cluster-Based Water Isotope Prediction from IAEA, 2019).



Maps of the monthly (January to December) $\delta^2\text{H}$ values of precipitation over India. (Data: Regionalized Cluster-Based Water Isotope Prediction from IAEA, 2019).



Field Information Template and Sample list Template for isotope and/or chemical analysis from IAEA

LIST OF SAMPLES FOR ISOTOPE OR CHEMICAL ANALYSIS						
COUNTRY AND PROJECT CODE:						DATE: _____ / _____ / _____
INSTITUTE:						Responsible Officer: _____
No.	Sample Code (local) (a)	Sampling date YY/MM/DD	Type (b)	No. of bottles shipped	Other information	
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

- (a) It is essential that the codes placed on the labels coincide with the sample codes listed in this Table.
 (b) GWB-groundwater (borehole); GWD-groundwater (dug, shallow well); GWS-spring; SLA-lake ; SRE-reservoir; SRI-river; SPR-precipitation.
 (c) For chemical analysis, please indicate M major ions. Other trace analyses (e.g. Li, B, NH₄, Br, PO₄, I, etc.) should be specified separately.

Recommended amount of sample for analysis:

Oxygen-18 + deuterium = 50 ml

Tritium = 500 ml.

For Carbon-14 + carbon-13 follow the instructions for precipitating SrCO₃ in the field.

Chemistry: Please send two bottles (100 ml for cations, acidified with 3 drops of conc. HNO₃, and the second, untreated with 250 ml for other analyses). If samples contain sediments, appropriate filters should be used.



Field Information Template and Sample list Template for isotope and/or chemical analysis from IAEA

ADDITIONAL INFORMATION COLLECTED IN THE FIELD						
COUNTRY AND PROJECT CODE:		DATE: _____ / _____ / _____		Responsible Officer: _____		
INSTITUTE:						
No.	Sample Code (local name)	Aquifer name	Samp. depth (a)	Latitude N/S DDDMMSS.DD	Longitude W/E DDDMMSS.DD	Field data
Altitude (m)	Cond. µS/cm	Temp. °C	pH units	Alk. mg/l		
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						

(a) For samples collected from aquifers, lakes and reservoirs; the sampling catch field (spec. depth, range of depths or screen ranges) should always be filled in.

(b) If possible taken with a GPS, otherwise from a 1:50,000 topographic map.

If relevant, please provide a short description of the lithologies of the aquifers in the study area.
Lithological units:



Appendix B – Pilot areas Haryana and Karnataka

Assessment of stable isotope data

Pilot area: Haryana

Final report

Activity 3: Pilot-testing of the approach/methodology using selected isotope data

Advisory Service for the IEWP Priority Area 4 – Groundwater Use: Support to Assess Groundwater Aquifers by Using Existing Isotope Data in India.

Jochen Wenninger

IHE Delft Institute for Water Education

Final version

2020-09-25

Abbreviations

$\delta^{18}\text{O}$	Delta value of oxygen-18
$\delta^2\text{H}$	Delta value of deuterium
CGWB	Central Ground Water Board
Cl	Chloride
D	Deuterium (also written as H-2)
D_{excess}	Deuterium excess
EC	Electrical conductivity
GNIP	Global Network of Isotopes in Precipitation
GMWL	Global Meteoric Water Line
IAEA	International Atomic Energy Agency
IEWP	India-EU Water Partnership
IMD	India Meteorological Department
LMWL	Local Meteoric Water Line
MWL	Meteoric Water Line
NAQUIM	National Project on Aquifer Management
O-18	Oxygen-18
RMWL	Regional Meteoric Water Line
WTE	Water Table Elevation

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Introduction

This report is part of Activity 3: “Pilot-testing of the approach/methodology using selected isotope data” within the Advisory Service for the IEWP Priority Area 4 – Groundwater Use: Support to Assess Groundwater Aquifers by Using Existing Isotope Data in India.

The objective of this report is to present findings of the pilot testing to interpret and analyse a selected isotope data set in order to identify and verify source areas and water origins of groundwater recharge. Understanding the recharge mechanisms and their variability is a crucial precondition to sustainable aquifer management.

Therefore the data collected during Activity 2 were analysed according to the methodology developed in Activity 1. Results of the analysis are presented with the help of figures and maps. Shortcomings of the analysis and next steps regarding the interpretation and analysis of isotope data are included at the end of this report.

Background information of the pilot area Haryana and the general hydrogeological setting was taken from the document: *Report On Isotopic Interpretation Of National Aquifer Mapping Data Of Haryana* (CGWB 2018).

1. Description of study area

The Haryana pilot area is situated in the Northern part of the State of Haryana in Northwest India. The area spans from 29.5° to 30.5° N and 76.0° to 77.5° E, covering an area of nearly 10,000 km² (see Figure 1). In the Northwest the area is bordered by the Ghaggar River and in the North East by the Yamuna River. The Yamuna River originates in the Himalayas, whereas the Ghaggar River has its headwaters in the Siwalik Hills. Elevation is ranging from 230 m amsl in the South to 320 m amsl in the North, and the majority of the area lies within the Yamuna-Ghaggar plain. Agriculture is the dominant economic sector in the region using groundwater and surface water for irrigation purposes. Groundwater occurs both under confined and unconfined conditions in the alluvial formations of the Siwalik Hills and the piedmont deposits.

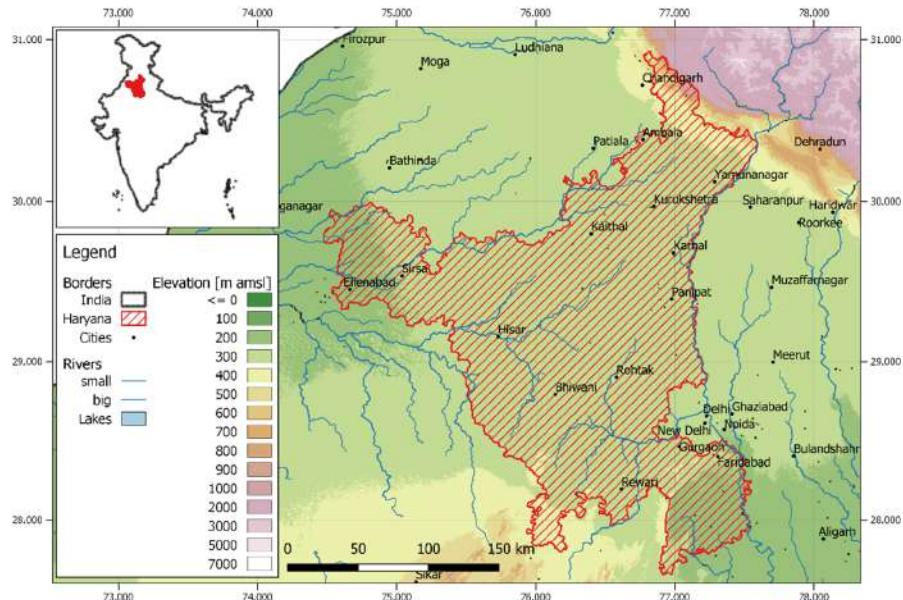


Figure 1: Overview map of the Haryana pilot area.

1.1. Climatic condition

The climate in the pilot area belongs, according to the Köppen–Geiger Climate Classification, to an Arid-Steppe-Hot (BSh) type in the southern part and to a Warm Temperate- Dry Winter- Hot Summer (Cwa) type in the Northern part (Rubel and Kottek, 2010). Long term climatological data of three stations (Chandigarh 1954-1977, New Delhi 1956-2000, and Hissar 1914-2000) were used from the India Meteorological Department (see Figure 2). The most important driving force for precipitation in the area is the Southwest monsoon, with average annual precipitation amounts between 500 mm and 1000 mm. The main rainfall occurs during the monsoon season between June and September, with around 80% of the annual precipitation amount. Generally precipitation increases towards the northern part of the study area. Annual average air temperature is varying between 23.5°C and 25.2°C with monthly variations between 13.3°C and 34.5°C (see Figure 2).

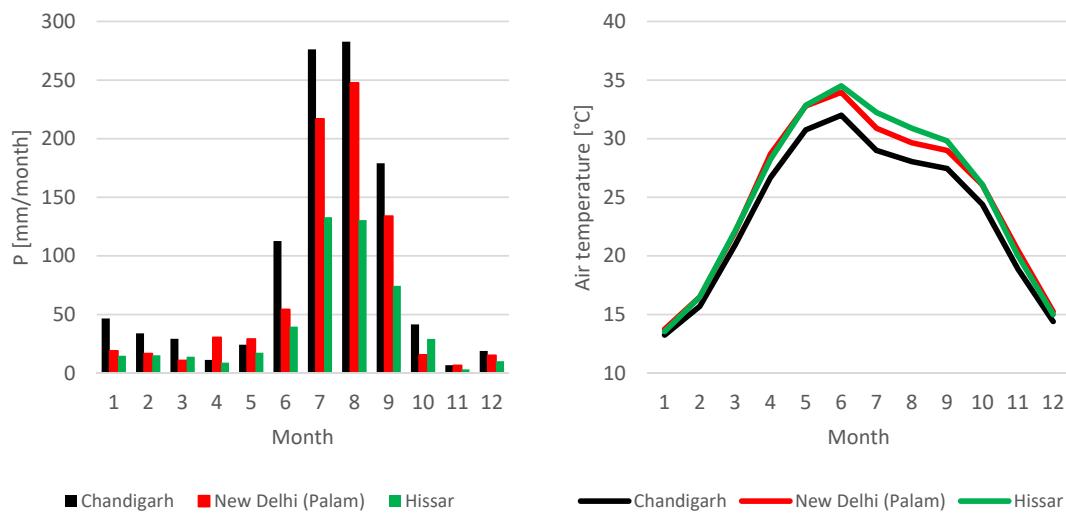


Figure 2: Climatic conditions of the Haryana pilot area (India Meteorological Department, 2019).

1.2. Hydrogeological setting

The majority of the pilot area is build up by unconsolidated quaternary alluvial and aeolian deposits, only in the Northern parts tertiary sandstones and clays are found (see Figure 3). The thickness of the alluvial deposits decrease generally from North to South. The alluvial deposits consist of clay, silt and fine to medium sands, building up the most important aquifers in the area.

Contour lines of the groundwater table follows the general flat topography within the pilot area, resulting in a slow groundwater velocity (see APPENDIX D). The natural groundwater flow direction is towards the Southwest and Southeast. Groundwater depth is varying between 2 m and 66 m, and is increasing towards the South and West. Groundwater at shallow depths occurs under unconfined conditions, but at deeper levels semi- or confined situations prevail. The pilot area exhibits a decline of water table during the last decade.

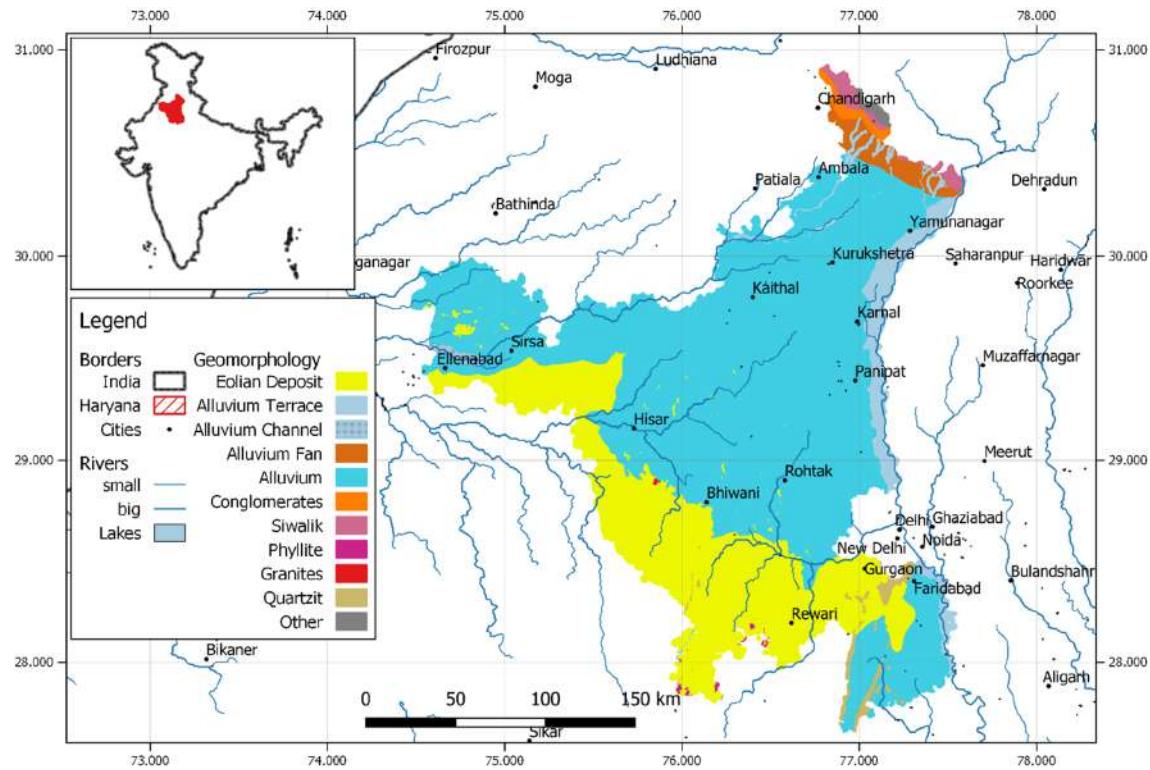


Figure 3: Geomorphology of the study area.

1.3. Aquifer system

Three aquifer systems up to a depth of 450 meters were identified in the study area.

- *Aquifer group I:* Extends from ground level to a depth of approximately 170 m below ground level. Consists of relative coarse materials and is underlain by a 10 m to 15 m thick clay layer. Unconfined and semi-confined conditions are present. Average values for transmissivity (m^2/d), conductivity (m/d) and specific yield (%) are 2200, 24, and 12, respectively.
- *Aquifer group II:* Consists of sand and clay lenses from approximately 65-280 m below ground level. The sediments are finer than those of aquifer group I. Groundwater occurs under confined and semi-confined conditions. The aquifer group II is underlain by a thick clay horizon. Average values for transmissivity (m^2/d) and lateral hydraulic conductivity (m/d) 700 and 7.2, respectively.
- *Aquifer group III:* This group consists of thinner sand layers intermitted by thicker clay layers at variable depth between 200-350 m below ground. Also this group is underlain by a thick clay layer und groundwater occurs under confined conditions. Average values for transmissivity (m^2/d) and lateral hydraulic conductivity (m/d) are 525 and 7.1, respectively.

2. Data collection

Datasets collected for this report correspond to different data scopes and were collected from several sources. Stable isotope values and physio-chemical parameters for groundwater samples and were collected from the Central Ground Water Board (CGWB), and for precipitation from the Global Network of Isotopes in Precipitation (GNIP) database from the International Atomic Energy Agency (IAEA). Climate data was used for long term precipitation and temperature information from the India Meteorological Department (IMD). Geospatial data of the pilot area were either collected from the CGWB or from other public available resources. A detailed overview of the data sets provided by the CGWB and additional data used for the assessment are listed in Appendix A.

Most relevant data and information for a stable isotope assessment include next to stable isotope data (Oxygen-18 and Deuterium) of groundwater and precipitation also metadata of the samples (like location, elevation, water level, borehole depth, filter depth, etc.), in-situ water quality parameters (like temperature, electrical conductivity, TDS, etc.), and other aquifer mapping related data (like topography, geology, hydrogeology, land use, hydro-meteorological information etc.).

In summary 30 groundwater samples containing stable isotope data, in-situ EC and pH values, and water chemistry data are available for the assessment. The dataset originates from the National Project on Aquifer Management (NAQUIM), and isotope values were analysed at the National Institute of Hydrology, Roorkee, Uttarakhand. In total 12 locations were sampled with partly multiple sampling depth in the range of <100 m, 100-200 m, and >300 m. Sampling locations are situated in the Districts of Panchkula, Ambala, Yanuna Nagar, Kurukshetra, Kaithal, Karnal, and Sirsa in the Northern part of Haryana (see Figure 4). Stable isotope data for precipitation was collected for the two stations New Delhi (1960-2012) and Roorkee (2003-2006), which are located close to the pilot area (see Figure 4).

A visual data quality check was carried out to ensure that no outliers are included in the following analysis steps.

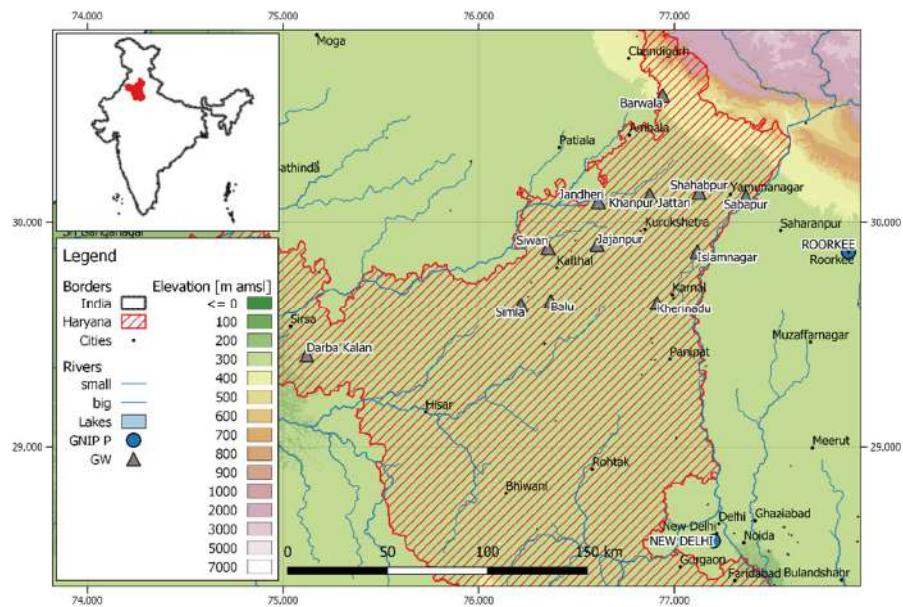


Figure 4: Groundwater sampling points (GW) and GNIP stations (GNIP P) of the Haryana pilot area.

3. Stable isotope analyses

The following section describes the results of the stable isotope analysis. All Oxygen-18 and Deuterium values are reported in the δ -notation (‰) relative to the international standard Vienna Standard Mean Ocean Water (VSMOW) using the formulas (IAEA & UNESCO, 2000):

$$\delta^2H = \frac{\left(\frac{^2H}{^1H}\right)_{\text{Sample}}}{\left(\frac{^2H}{^1H}\right)_{\text{Standard}}} - 1 \quad [\text{‰}] \quad (1)$$

$$\delta^{18}O = \frac{\left(\frac{^{18}O}{^{16}O}\right)_{\text{Sample}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{Standard}}} - 1 \quad [\text{‰}] \quad (2)$$

Deuterium excess (D_{excess}) values were calculated for all samples using a slope of 8 as proposed by Dansgaard (1964):

$$D_{\text{excess}} = \delta^2H - 8 \cdot \delta^{18}O \quad [\text{‰}] \quad (3)$$

On a global scale the D_{excess} has a value of 10‰, but can be different for specific locations due to variations in humidity and temperature during primary evaporation (Clark & Fritz, 1997). Low deuterium excess values of groundwater samples are an indication of either evaporation prior to recharge or precipitation under different climatic conditions under a higher humidity (Kendall & McDonnell, 1998).

3.1. Precipitation

Insights about the groundwater recharge mechanisms can be gained by comparing the stable isotope relationships of the groundwater samples in relation to those of the input from precipitation. Therefore the input signal from precipitation in the pilot area needs to be determined in a temporal way by assessing the monthly and seasonal input function, and by defining Meteoric Water Lines (MWL). Meteoric water lines represent the relationship between oxygen-18 and deuterium values in precipitation.

On a global scale this relationship between the two stable water isotopes in precipitation is characterized by the so called Global Meteoric Water Line (GMWL). The equation of Craig (1961) was used in this assessment:

$$\delta^2H = 8 \cdot \delta^{18}O + 10 \quad [\text{‰}] \quad (4)$$

Due to the fact that the GMWL is based on a global dataset it is only used as a background reference and more site specific Local Meteoric Water Line (LMWL) should be used for the interpretation. Pilot area related Global Network of Isotopes in Precipitation (GNIP) data sets were downloaded from the International Atomic Energy Agency (IAEA) database. The GNIP database contains two stations with sufficient data in the vicinity of the pilot area: New Delhi and Roorkee.

The GNIP data contains Local Meteoric Water Lines (LMWL) describing the relationship between Oxygen-18 and Deuterium composition of precipitation at these specific locations. For New Delhi the LMWL is determined to be:

$$\delta^2H = 7.18 \cdot \delta^{18}O + 4.53 \text{ [‰]} \quad (5)$$

and for Roorkee it is:

$$\delta^2H = 8.28 \cdot \delta^{18}O + 11.73 \text{ [‰]} \quad (6)$$

Additional to the GMWL and the LMWLs the Regional Meteoric Water Line (RMWL) for Northern India published by Kumar *et al.* (2010) was used:

$$\delta^2H = 8.15 \cdot \delta^{18}O + 9.55 \text{ [‰]} \quad (7)$$

Figure 5 below displays the GMWL, LMWLs, and RMWL for the pilot area.

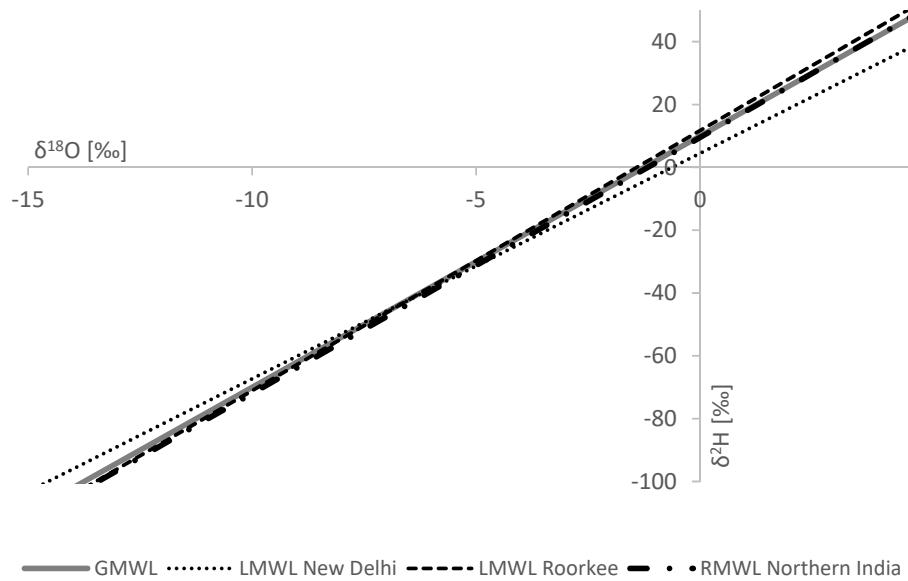


Figure 5: Global Meteoric Water Line (GMWL), Local Meteoric Water Lines (LMWLs) at New Delhi and Roorkee GNIP stations, and RMWL of Northern India.

Values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in precipitation range between -8.26‰ and -55‰ in September and 0.73‰ and 10.4‰ in May at the GNIP station New Delhi (see Figure 6). Generally isotope values are lighter during the monsoon season between July and September and heavier in the dry period. The annual weighted mean values for New Delhi for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are -5.86‰ and -37.5‰ , respectively. The dataset for Roorkee is too short to calculate average monthly or annual values.

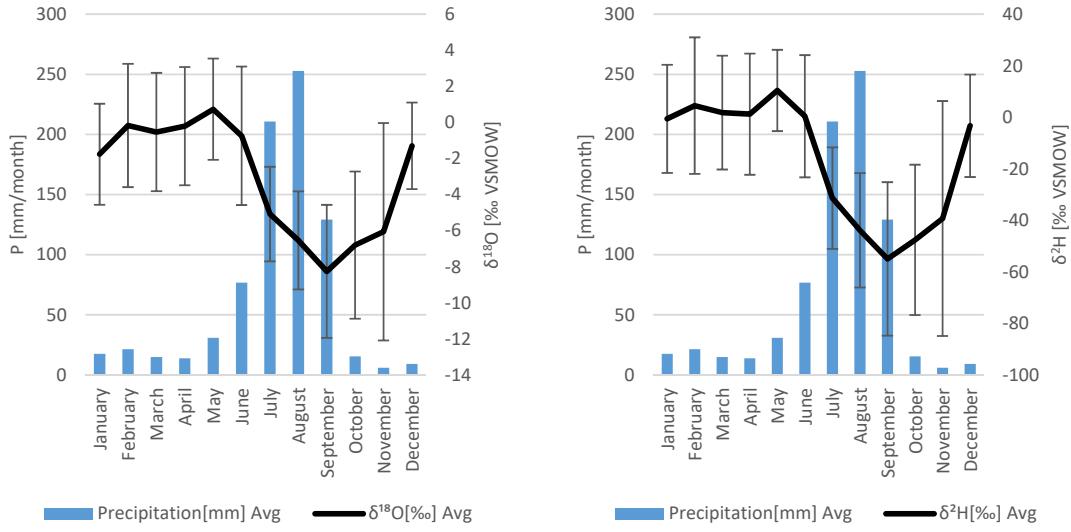


Figure 6: Average monthly amount and isotope composition of precipitation (P) at the GNIP station New Delhi. Left: $\delta^{18}\text{O}$; Right: $\delta^2\text{H}$.

Monthly isotope values in relation to the GMWL and LMWLs are shown in Figure 7.

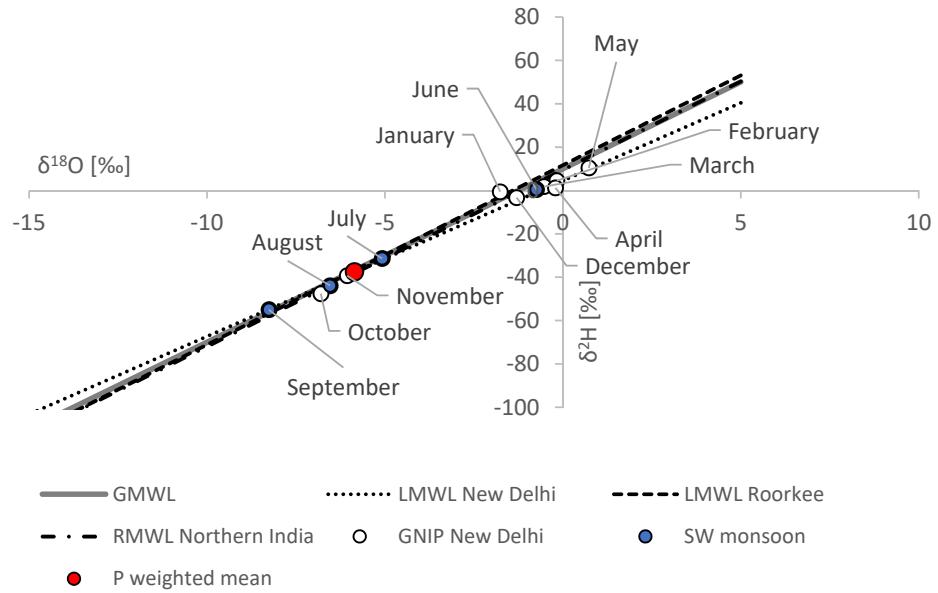


Figure 7: Average monthly precipitation values and annual precipitation weighted mean value at GNIP station New Delhi.

3.2. Groundwater

Stable isotope composition of groundwater varies between -10.1‰ and -5.1‰ for $\delta^{18}\text{O}$ and between -69‰ and -33‰ for $\delta^2\text{H}$. Locations of groundwater samples can be found in Figure 8, Figure 9, and Figure 10. The relationship between the two isotopes are shown in Figure 11. All values of the groundwater samples can be found in APPENDIX B.

3.2.1. Spatial distribution of groundwater samples and grouping

The grouping of groundwater samples was based on the division described in Section 1.3. There three different groups are distinct based on their tapped zones. Aquifer group I up to 100 m below ground level, aquifer group II between 100 and 200 m, and aquifer group III between 200 and 330 m.

Aquifer group I: 100 m

The aquifer group I samples are representing the shallow alluvial aquifer system up to a depth of 100 metres. Isotope values range between -10.1‰ and -5.4‰ for $\delta^{18}\text{O}$ and from -68.8‰ to -41.3‰ for $\delta^2\text{H}$, and fall into both groups of isotopes defined in the section above. Lighter isotope values ($\delta^{18}\text{O} < -8\text{\textperthousand}$) are present in the 3 samples ($\delta^{18}\text{O} < -8\text{\textperthousand}$) of Simla, Islamnagar, and Sabapur, and the remaining locations show heavier values ($\delta^{18}\text{O}$ between -5‰ and -8‰). The lighter values could be linked to a source which is different from local recharge by precipitation like river water or irrigation canal water infiltration. This is confirmed by the location in case of Islamnagar and Sabapur close to the Yamuna River. Table 1 and Figure 8 give an overview of the statistics and locations of the aquifer group I samples.

Table 1: Statistics of groundwater isotope and in-situ parameters of aquifer level I; 100 m

AQUIFER 100 m	ELEVATION [m amsl]	EC [$\mu\text{S}/\text{cm}$]	pH [-]	$\delta^{18}\text{O}$ [‰]	$\delta^2\text{H}$ [‰]	D_{excess} [‰]
MIN	232.0	260.0	7.7	-10.1	-68.8	-1.4
FIRST 25th	249.0	422.0	8.4	-8.6	-59.4	2.6
MEDIAN	258.0	716.0	8.5	-6.6	-47.4	4.8
THIRD 75th	276.0	768.0	8.6	-5.8	-43.9	9.2
MAX	319.0	1673.0	8.6	-5.4	-41.3	11.6
AVERAGE	263.4	730.9	8.4	-7.1	-51.6	5.5
STDEV	25.2	426.5	0.3	1.7	9.7	4.4
COUNT	9	9	9	9	9	9

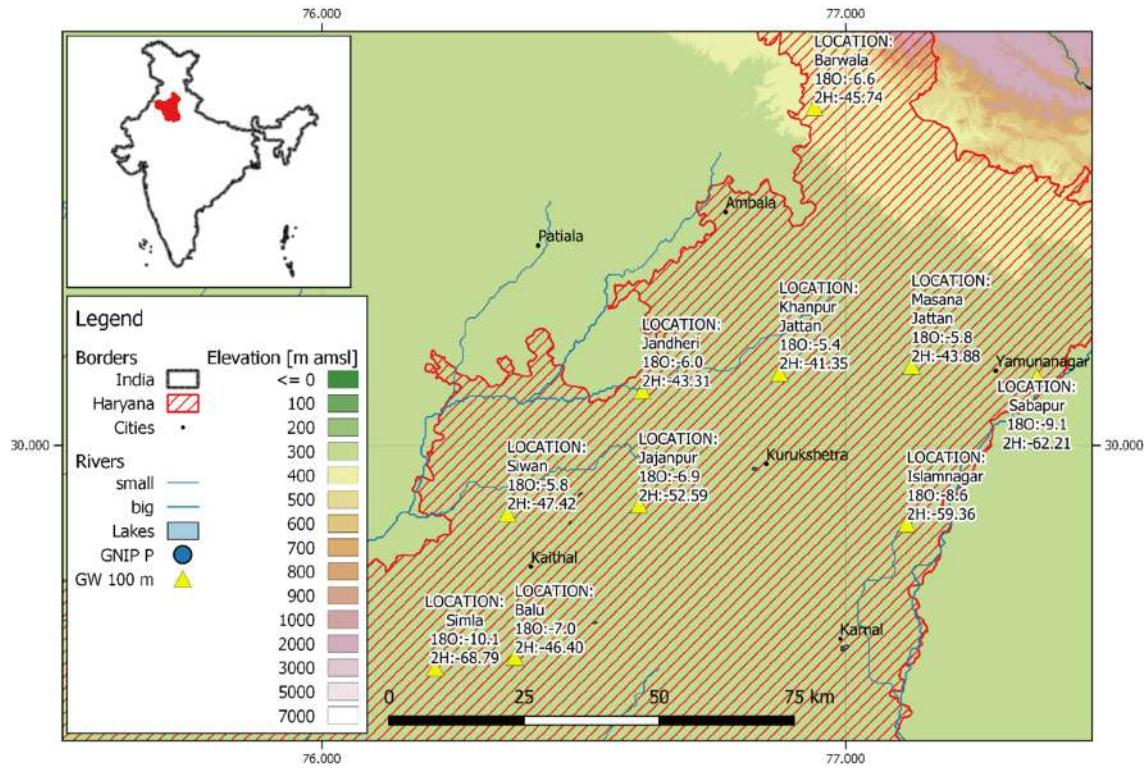


Figure 8: Spatial distribution of groundwater isotope composition for aquifer level 100 m.

Aquifer group II: 200 m

The aquifer group II samples are representing the alluvial aquifer system between 100 and 200 metres. Isotope values range between $-9.3\text{\textperthousand}$ and $-5.1\text{\textperthousand}$ for $\delta^{18}\text{O}$ and from $-63.1\text{\textperthousand}$ to $-37.5\text{\textperthousand}$ for $\delta^2\text{H}$, and fall into both groups of isotopes defined in the section above. Lighter isotope values ($\delta^{18}\text{O} < -8\text{\textperthousand}$) are present in the 2 samples ($\delta^{18}\text{O} < -8\text{\textperthousand}$) of Islamnagar and Sabapur, and the remaining locations show heavier values ($\delta^{18}\text{O}$ between $-5\text{\textperthousand}$ and $-8\text{\textperthousand}$). The lighter values could be linked to a source which is different from local recharge by precipitation like river water or irrigation canal water infiltration. This is confirmed by the location in case of Islamnagar and Sabapur close to the Yamuna River. Table 2 and Figure 9 give an overview of the statistics and locations of the aquifer group II samples.

Table 2: Statistics of groundwater isotope and in-situ parameters of aquifer level II; 200 m

AQUIFER 200 m	ELEVATION [m amsl]	EC [$\mu\text{S}/\text{cm}$]	pH [-]	$\delta^{18}\text{O}$ [%]	$\delta^2\text{H}$ [%]	D_{excess} [%]
MIN	231.0	256.0	8.1	-9.3	-63.1	3.5
FIRST 25th	248.0	429.0	8.4	-6.6	-47.2	5.3
MEDIAN	257.0	482.0	8.5	-6.4	-42.9	9.3
THIRD 75th	275.0	1288.0	8.5	-6.2	-38.6	11.4
MAX	320.0	11780.0	8.7	-5.1	-37.5	13.1
AVERAGE	262.4	1931.9	8.4	-6.8	-46.0	8.7
STDEV	25.9	3732.8	0.2	1.4	10.1	3.4
COUNT	9	9	9	9	9	9

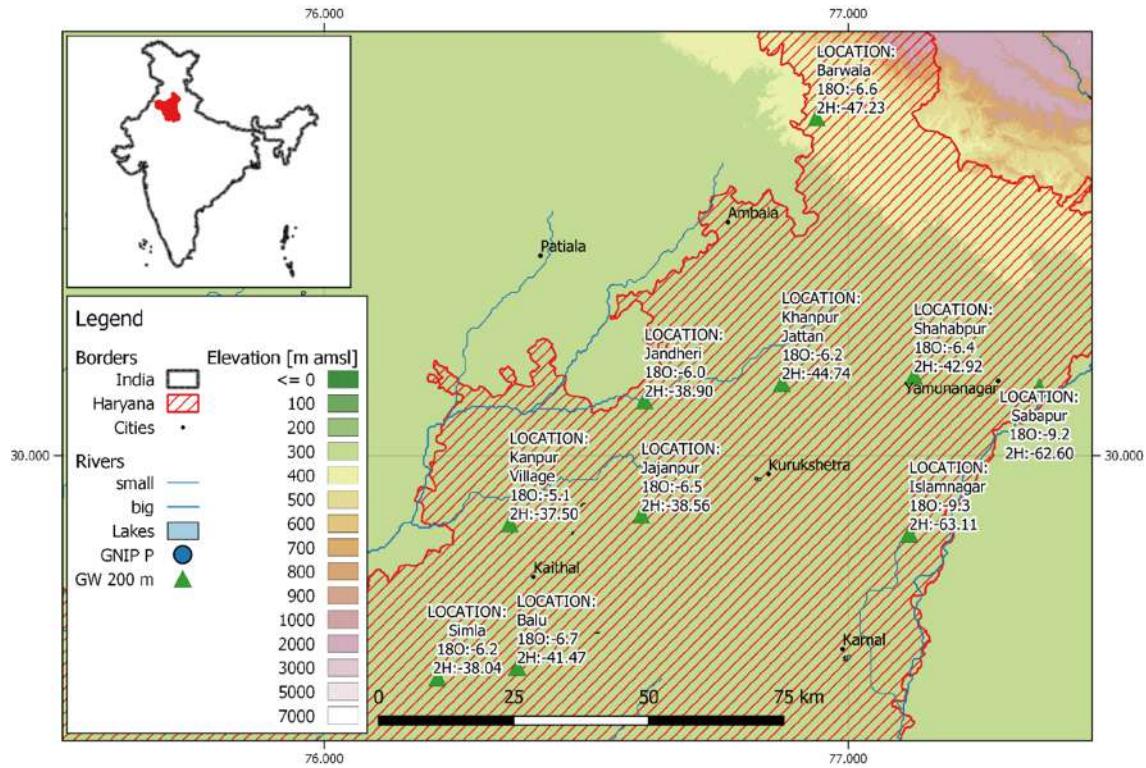


Figure 9: Spatial distribution of groundwater isotope composition for aquifer level 200 m.

Aquifer group III: 300 m

The aquifer group III samples are representing the alluvial aquifer system between 200 and 300 metres. Isotope values range between -9.2‰ and -5.6‰ for $\delta^{18}\text{O}$ and from -60.7‰ to -33.1‰ for $\delta^2\text{H}$, and fall into both groups of isotopes defined in the section above. Lighter isotope values ($\delta^{18}\text{O} < -8\text{\textperthousand}$) are present in the 2 samples ($\delta^{18}\text{O} < -8\text{\textperthousand}$) of Islammagar and Shahabpur, and the remaining locations show heavier values ($\delta^{18}\text{O}$ between -5‰ and -8‰). The lighter values could be linked to a source which is different from local recharge by precipitation like river water or irrigation canal water infiltration. This is confirmed by the location at least in case of Islammagar close to the Yamuna River. Table 3 and Figure 10 give an overview of the statistics and locations of the aquifer group III samples.

Table 3: Statistics of groundwater isotope and in-situ parameters of aquifer level III; 300 m

AQUIFER 300 m	ELEVATION [m amsl]	EC [$\mu\text{S}/\text{cm}$]	pH [-]	$\delta^{18}\text{O}$ [‰]	$\delta^2\text{H}$ [‰]	D_{excess} [‰]
MIN	205.0	260.0	8.0	-9.2	-60.7	1.9
FIRST 25th	246.0	473.0	8.3	-7.0	-44.5	7.7
MEDIAN	247.0	572.0	8.5	-6.4	-41.1	12.9
THIRD 75th	256.0	753.0	8.5	-6.1	-37.7	15.3
MAX	276.0	16510.0	8.7	-5.6	-33.1	16.3
AVERAGE	246.3	2526.9	8.4	-6.9	-43.8	11.5
STDEV	19.9	5298.4	0.2	1.3	10.0	5.0
COUNT	9	9	9	9	9	9

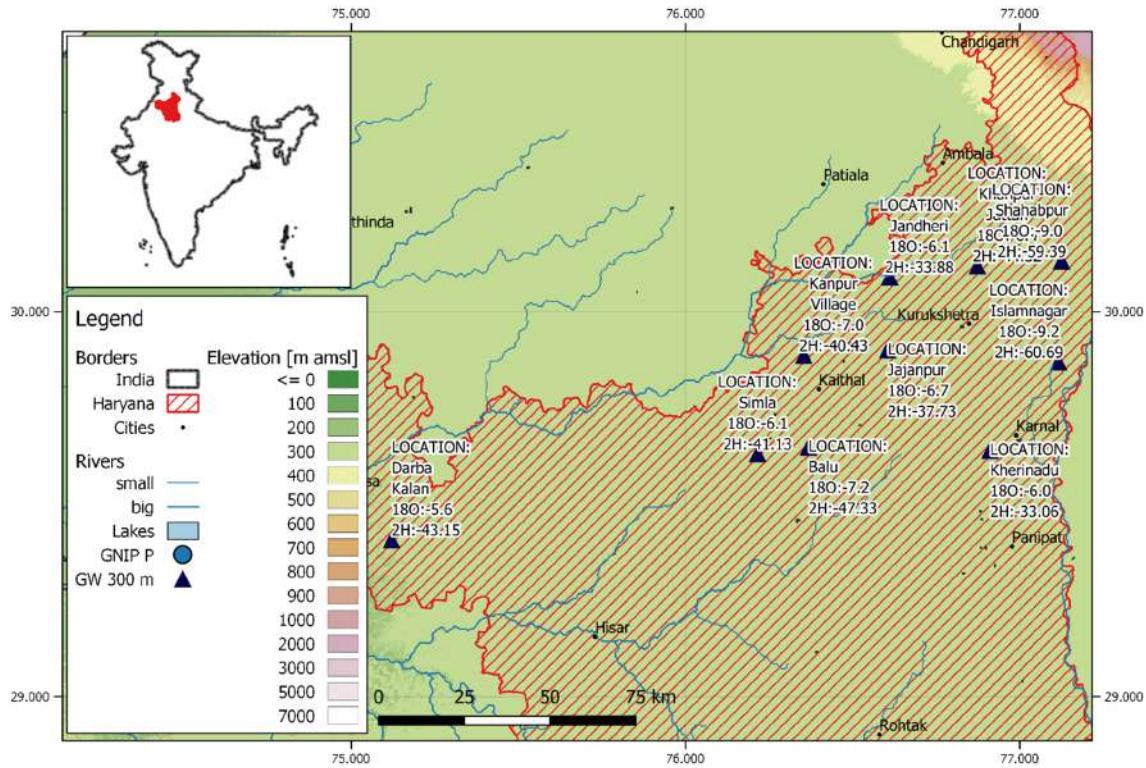


Figure 10: Spatial distribution of groundwater isotope composition for aquifer level 300 m.

3.2.2. Relationship between groundwater samples and MWLs

Most of the groundwater samples plot along the Meteoric Water Lines and imply a groundwater recharge from local meteoric waters which are not affected by evaporation effects. Only a few samples are located slightly above or below the lines. In case values plot below the Meteoric Water Line this could be an indication of evaporation effects and therefore fractionation prior to groundwater recharge. Two distinct groups can be identified with significant differences in their isotopic composition. The first group has $\delta^{18}\text{O}$ values between $-7.22\text{\textperthousand}$ and $-5.13\text{\textperthousand}$ and the second group shows much lighter isotope values between $-10.05\text{\textperthousand}$ and $-8.57\text{\textperthousand}$. The first group of samples is located close to the monthly average value of July and August and the annual precipitation weighted mean value, whereas the second group of samples show much lighter isotope values, which cannot be explained by local precipitation values. Precipitation during the months January to June and December with enriched isotopic signatures seem to have no significant influence on the groundwater recharge.

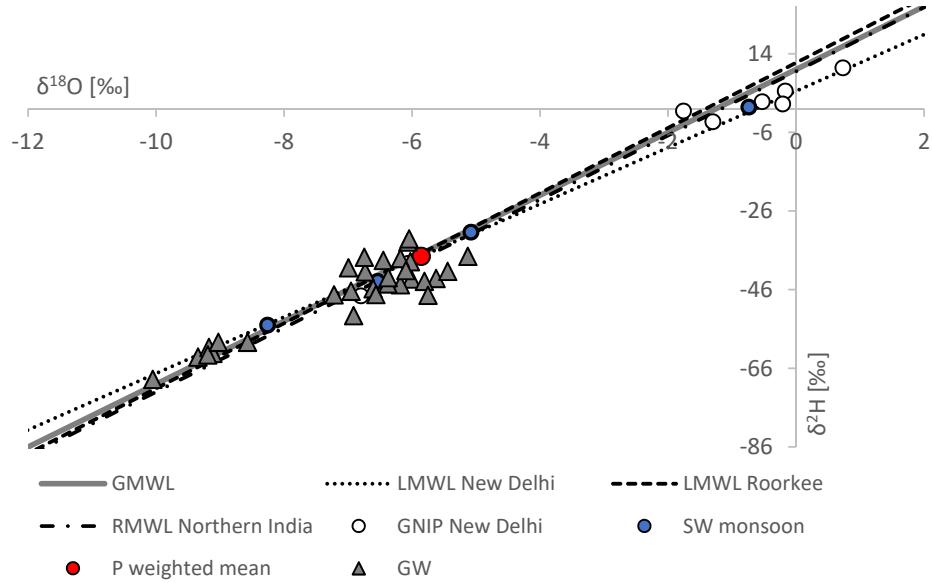


Figure 11: Groundwater isotope composition in comparison to GMWL, LMWLs, and RMWL.

In order to gain further insights in the dataset the samples were grouped according to their sampling depth. The three aquifer groups, defined in Section 1.3, were used to classify and group the samples. Figure 12 gives an overview of the different aquifer groups and their relation to the MWLs. All aquifer groups are found in both ranges of isotope values. For the second group of samples with lighter isotopic compositions local precipitations is unlikely to be the only source of groundwater. Potential other sources of groundwater next to local recharge are interactions with surface water bodies, or return flows from irrigation water.

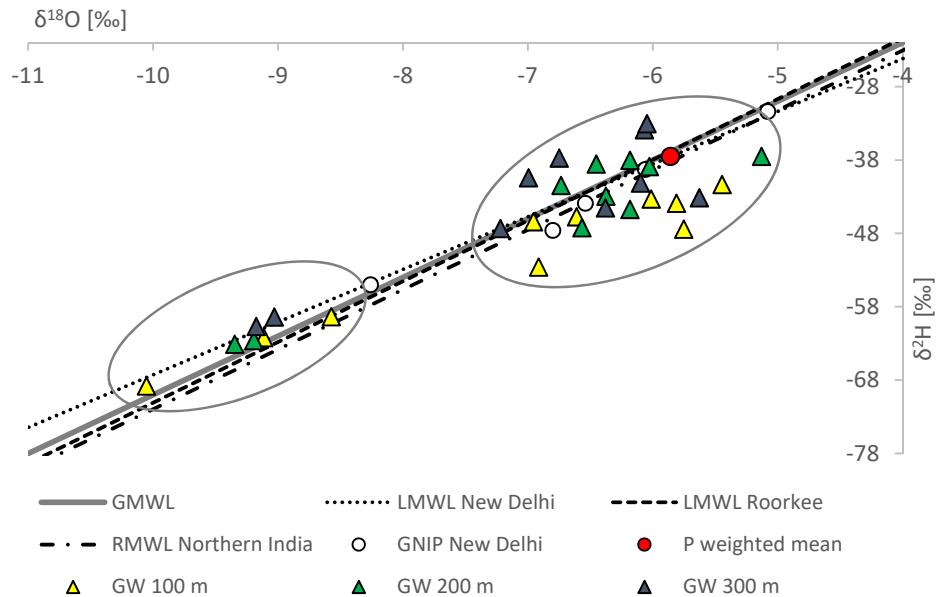


Figure 12: Groundwater isotope composition for different aquifer groups (100 m, 200 m, and 300 m).

3.2.3. Relationship of groundwater samples and surface water

Information about surface water isotopic content was taken from Dalai *et al.* (2002). They studied the stable isotope composition of Yamuna River and reported values ($\delta^{18}\text{O}/\delta^2\text{H}$) at Yamuna Nagar, Saharanpur for the post monsoon -10.3‰/-68.5‰, summer -7.8‰/-54.4‰, and monsoon season 9.5‰/65.5‰ (see Figure 13).

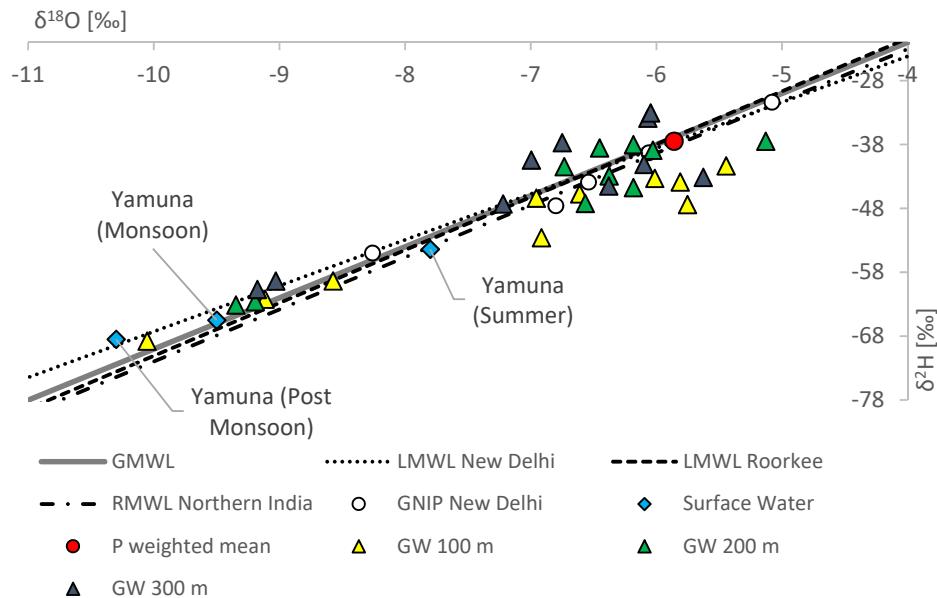


Figure 13: Surface water isotope composition in comparison to ground water samples.

Isotope values for the lighter group correspond well with the relative light values of the surface water samples, and plot close to the monsoon and post-monsoon values in the Yamuna River.

3.2.4. Relationship between isotope values and elevation

Elevation is typically correlated with the values of stable isotopes in precipitation and therefore groundwater recharge. The elevation effect, or altitude effect, results in an increased depletion of isotopes with increasing elevation. Stable isotope values for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ against elevation are plotted in Figure 14. The groundwater samples show however a relative weak linear correlation in the pilot area. The isotopic lapse rates for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are $-0.8\text{‰}/100\text{m}$ and $-8.3\text{‰}/100\text{m}$, respectively. Also the relationship between D_{excess} and elevation does not show correlations (see Figure 15). This is an indication that groundwater recharge in the area is not significantly influenced by an elevation effect or by a strong evaporation effect at lower elevations.

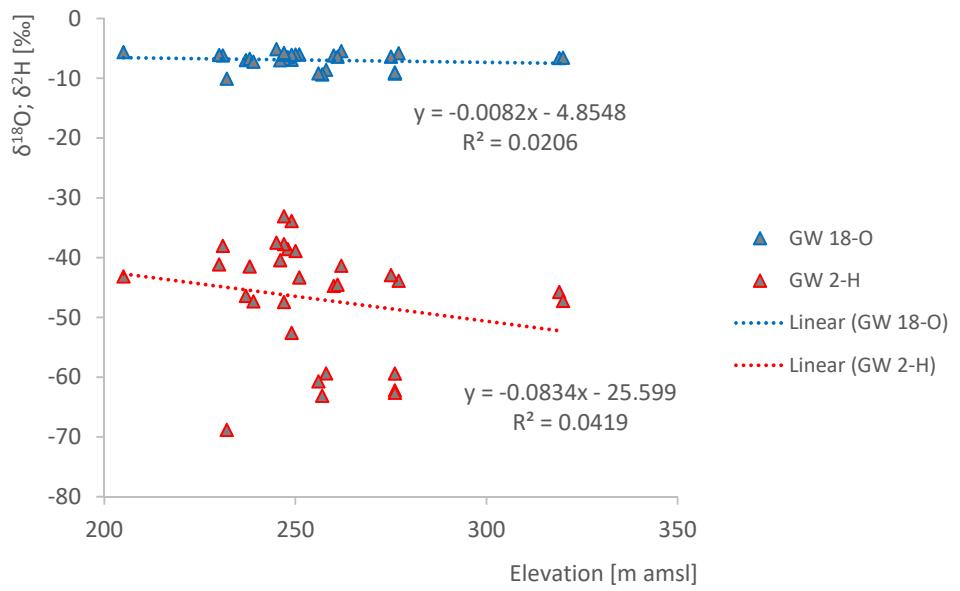


Figure 14: Correlation between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of groundwater samples against elevation.

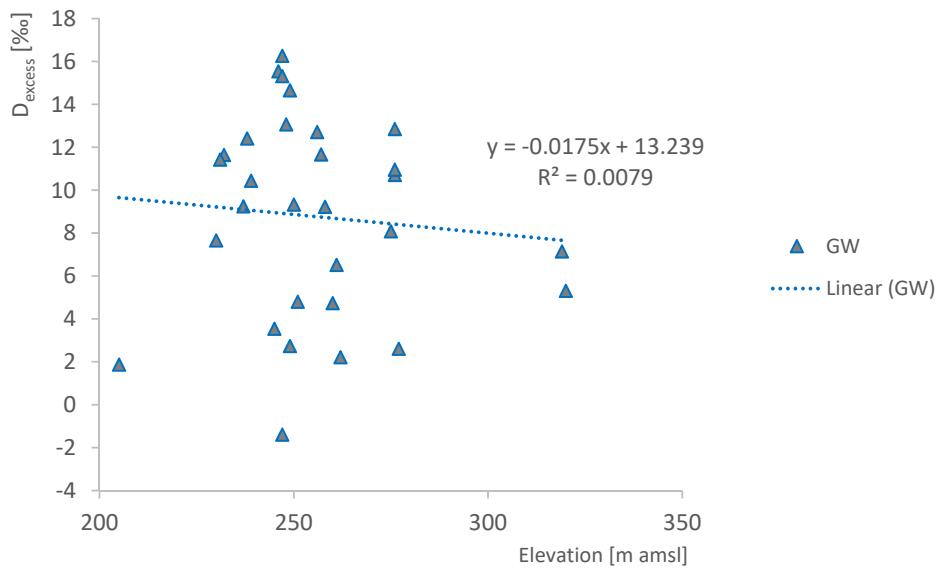


Figure 15: Correlation between $\delta^{18}\text{O}$ and D_{excess} of groundwater samples.

3.2.5. Relationship between isotope values and water table depth

The relationship between isotope values of groundwater and water table depth can give insights in groundwater which is affected by evaporative effects. A shallow water table close to the surface can lead to enrichment of heavy isotopes due to fractionation processes during evaporation. Figure 16 and Figure 17 show the correlations between the stable isotopes and the D_{excess} with the tapped zone in metres below ground level (mbgl).

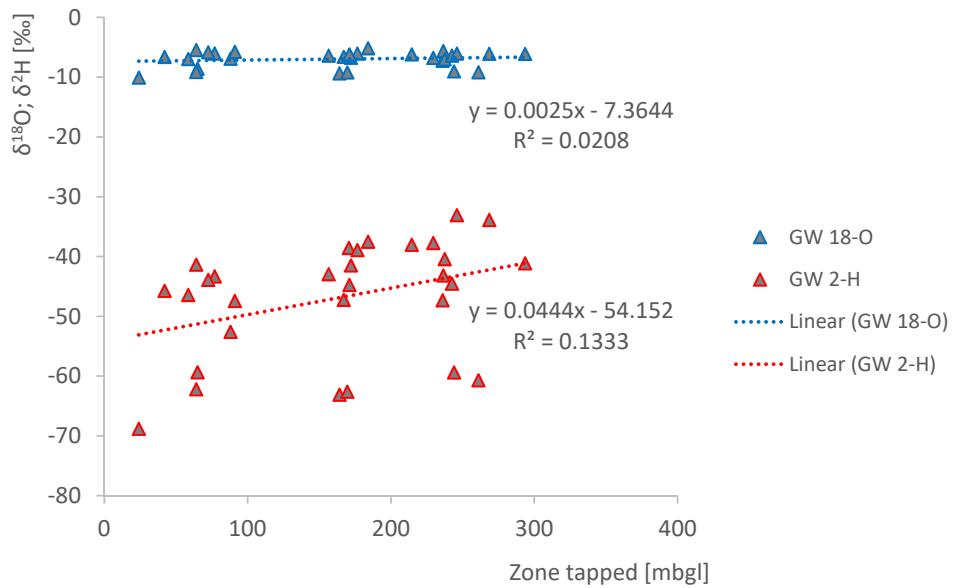


Figure 16: Correlation between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of groundwater samples against tapped zone.

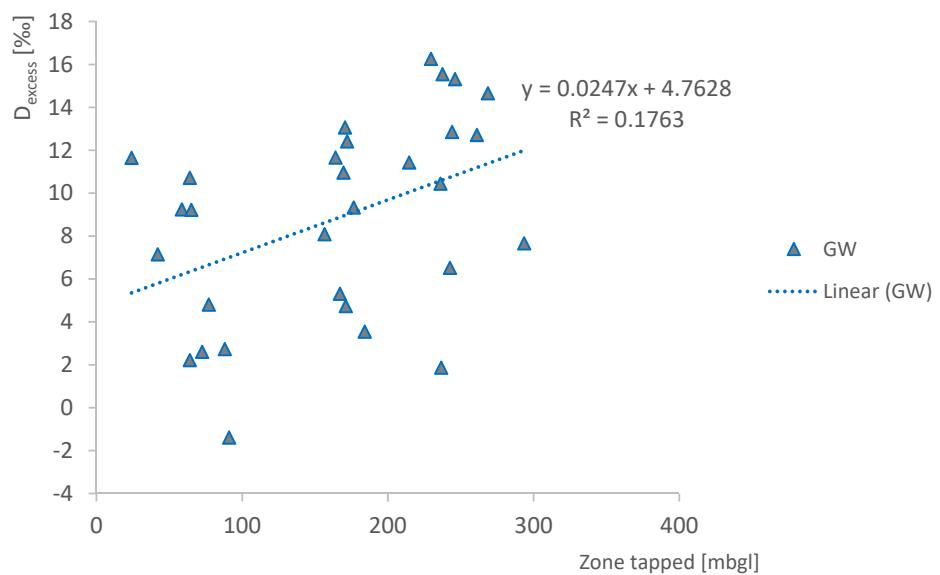


Figure 17: Correlation between D_{excess} of groundwater samples against tapped zone.

From the figures it can be seen that there are only weak correlations present either between the stable isotope values or between D_{excess} and the tapped zone. The generally lower D_{excess} values for shallower tapped zones however indicate a slight fractionation effect at least at some locations. To better understand the stable isotope signatures and the D_{excess} values at different aquifer levels, Figure 18 shows the values at each sampling site for different aquifer groups.

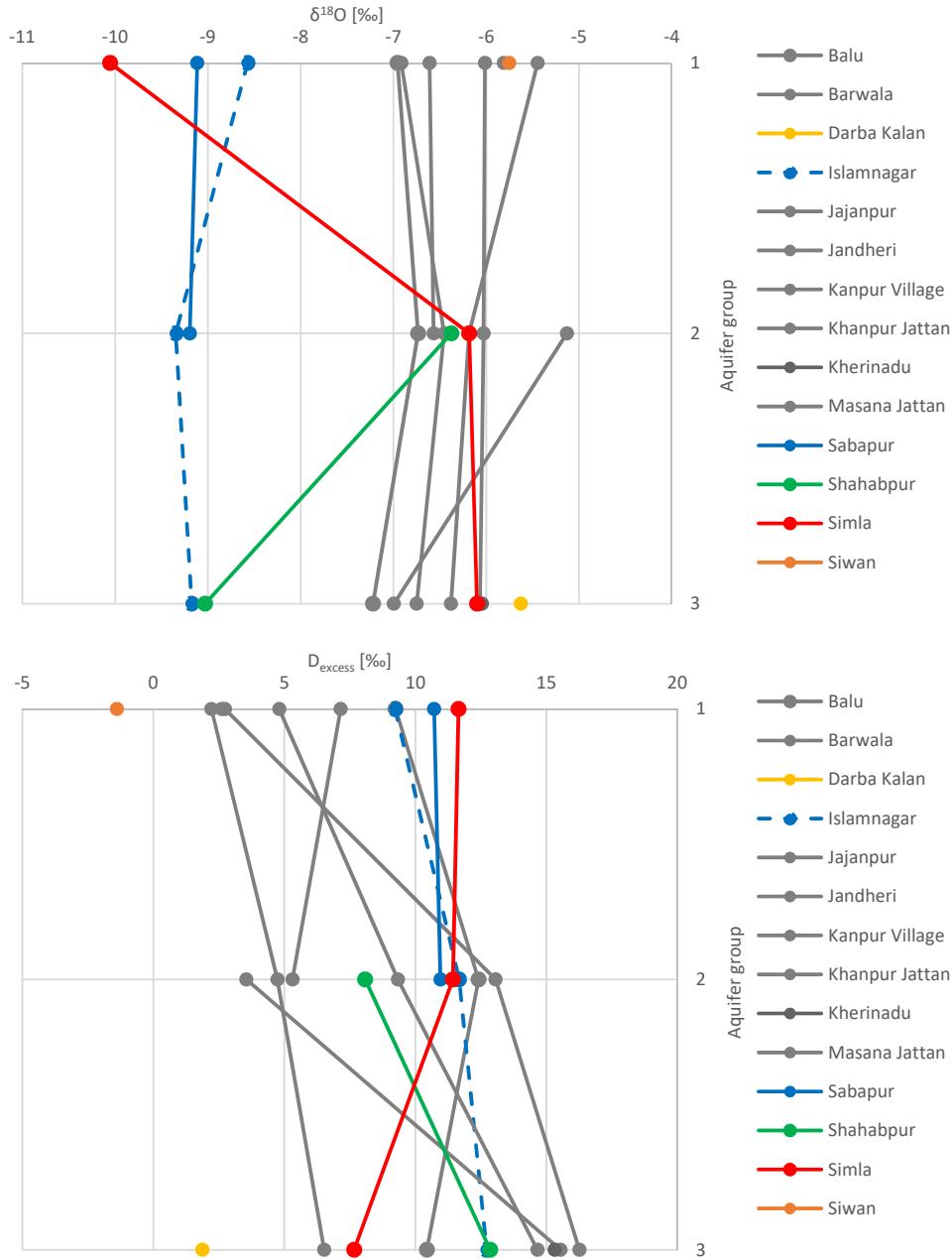


Figure 18: Oxygen-18 [upper] and D_{excess} [lower] values at the sampling sites at different aquifer groups.

The two distinct groups of groundwater samples described in Section 3.2.2 are also visible in Figure 18, upper graph. The first group of samples, blue points and lines, show depleted isotopic signatures

around -9‰ for $\delta^{18}\text{O}$ for all aquifer groups. These values belong to the sampling points Islamnagar and Sabapur, and correspond to values of the Yamuna River. The second group of samples, grey points and lines, have $\delta^{18}\text{O}$ values between -5 and -7‰ for $\delta^{18}\text{O}$ throughout the aquifer groups, and match the local precipitation input values during the monsoon season. In Figure 18, lower graph, the tendency of reduced D_{excess} values for the upper aquifer group is confirmed. At most sampling locations the upper aquifer has a lower D_{excess} values than the deeper aquifers.

Only four sampling locations deviate from this general pattern. Sampling point Simla, red points and lines, shows a depleted value of $\delta^{18}\text{O}$ in the upper aquifer group, whereas the two deeper groups have values comparable to the local precipitation input. The lighter isotope values could be linked to infiltration of surface water. The sampling point Shahabpur, green points and lines, show the opposite phenomenon, with a depleted value in lowest aquifer group. The relative vicinity to the Yamuna River of this site could be the reason for this pattern, and the lowest aquifer could be connected to lighter isotope values of the surface water in contrast to the middle aquifer group which corresponds to local precipitation. The third sampling location deviating from the general pattern is Darba Kalan, orange point. For this location only a sample for the deeper aquifer group is available. This shows not only an enriched value for $\delta^{18}\text{O}$ with -5.6‰, but also a low D_{excess} value with 1.9‰, which is a strong sign of evaporative effects. Darba Kalan is located in the Western part of the study pilot area (see Figure 4) which is experiencing a lower precipitation input and higher air temperatures. The fourth location, Siwan, shows also a low D_{excess} value of -1.39‰, which is a strong sign of evaporative effects.

3.2.6. Relationship between isotope values and water quality parameters

Basic water quality parameters were provided by the CGWB together with the isotope dataset. Some of the water quality values could also be useful in combination with stable water isotopes for the analysis. Values used for this analysis are the electrical conductivity EC [$\mu\text{S}/\text{cm}$] and the chloride concentration Cl [mg/L]. For all groundwater samples EC and Cl show a high variability and are ranging over 256-16510 $\mu\text{S}/\text{cm}$ and 7-4436 mg/L, respectively.

The combination of isotopic data with water quality parameters like EC and Cl help to better understand the groundwater recharge processes. Generally an increased EC or Cl concentration could be an indication for increased evaporation effects. Figure 19 and Figure 20 show the relationships between $\delta^{18}\text{O}$ and electrical conductivity and chloride concentration, respectively.

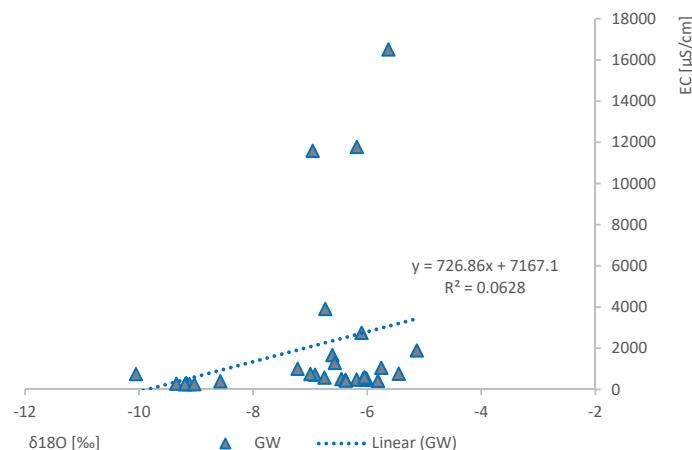


Figure 19: Correlation between $\delta^{18}\text{O}$ and electrical conductivity (EC; $\mu\text{S}/\text{cm}$) of groundwater samples.

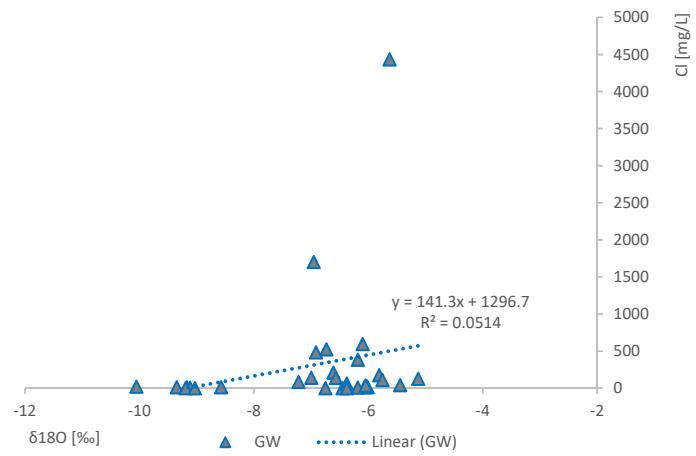


Figure 20: Correlation between $\delta^{18}\text{O}$ and chloride content (Cl ; mg/L) of groundwater samples.

A general trend towards higher EC and Cl values with enriched isotopic values is visible. However no significant correlation could be found between these parameters, because it seems that these relationship is additionally influenced by geological and human effects.

Conclusions

The presented results using stable isotope values of groundwater demonstrated the potential of this method for the assessment and characterization of groundwater aquifers. The spatial analysis of stable isotope signatures in groundwater helped to identify and located the mechanisms of groundwater recharge. From the analysis the importance of groundwater recharge from local precipitation sources as well as from surface water bodies like irrigation canals and rivers could be shown.

Local and regional meteoric water lines were used for the Haryana pilot area to determine the precipitation input values. Global Network of Isotopes in Precipitation (GNIP) datasets enabled to characterize the temporal pattern of groundwater recharge being dominant in the monsoon season between July and November. Knowing the spatio-temporal variability of precipitation and therefore groundwater recharge is a requirement for the assessment of groundwater resources.

Almost all groundwater samples plot along the MWLs of the pilot area. It can be concluded that precipitation, except for a few samples, is less affected by evaporation processes prior to the recharge.

No clear correlations between isotope characteristics and the elevation of the sampling locations could be found. However a slight tendency of having lower D_{excess} values in the upper aquifer group was found.

A large group of samples show isotopic values for all aquifer groups close to the local precipitation input during the monsoon season. These locations are Balu, Barwala, Jajanpur, Jandheri, Kanpur Village, Khanpur Jattan, Kherinadu, and Masana Jattan. This indicates a connected groundwater system recharged by local precipitation water.

In contrast to this the locations Islamnagar and Sabapur have depleted isotope values for all aquifer groups, which is caused by recharge from the close by Yamuna River. Probably also at these locations the aquifer system is interconnected.

In case of the location Simla only the upper aquifer is characterized by depleted isotopic values, whereas the two deeper aquifers have the same signature as local precipitation. Most likely the aquifer groups I and II are not hydraulically connected and the first aquifer group is influenced by infiltration of irrigation canal water.

At location Shahabpur it seems that the aquifer groups II and III are disconnected with depleted isotope values for the deepest aquifer. This could be explained by the relative vicinity to the Yamuna River or by the existence of hydraulically connected paleo channels in the area.

Isotope values for aquifer I of Siwan and aquifer III of Darba Kalan show signs of evaporative effects due to their low D_{excess} values and high EC values. Unfortunately only one sample per site is available which hampers further conclusions.

Overall the results of the isotope analysis indicates three possible controls of the groundwater recharge mechanism: (1) direct recharge of local precipitation input, mainly during the monsoon season, (2) surface water infiltration by rivers, and (3) infiltration of irrigation canal water. However the recharge mechanism can be only fully understood and evaluated with the combination of other groundwater related investigations like geophysical and hydro-geochemical investigations.

The findings of this analysis lead to recommendations for future investigations in the area.

[Shortcoming and next steps](#)

In total only 30 groundwater samples were analysed for their stable water isotope composition and basic physio-chemical parameters. It is recommended to increase the sample number to better characterize the spatial distribution of isotope values in the area. This would help to better characterize the location and extend of the identified recharge mechanisms in the pilot area.

In this context also a better understanding and estimation of isotope values of surface water bodies, like rivers and canals, would be beneficial for the determination of these important factors of groundwater recharge.

As an additional investigation method it is recommended to determine groundwater ages using radioactive isotopes. This could be helpful for the differentiation between recently recharged groundwater and old groundwater which has been recharged under different climate conditions.

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APPENDIX A

Data provided by the CGWB and additional data collected: Pilot area 1 Haryana

DATA SCOPE	DATA TYPE	AREA	SOURCE	SOURCE DETAIL	FILE NAME	FILE TYPE	SAMPLE NO.	MAIN CONTENT	CRS	REMARKS
Precipitation	Point	Haryana	IAEA	GNIP	wiser_gnip-monthly-New Delhi	.xls	624	Lat, Long, Alt, Date, O18, H2, H3, P, Ta	-	Monthly isotope data in precipitation
Precipitation	Point	Haryana	IAEA	GNIP	Wiser_Statistics_GNIP-Monthly_INDIA_NEW DELHI	.xls	-	18-O and 2H data; monthly, annual, long term, LMWL	-	Statistics of isotope data in precipitation
Precipitation	Point	Haryana	IAEA	GNIP	wiser_gnip-monthly-Roorkee	.xls	48	Lat, Long, Alt, Date, O18, H2, H3, P, Ta	-	Monthly isotope data in precipitation
Precipitation	Point	Haryana	IAEA	GNIP	Wiser_Statistics_GNIP-Monthly_INDIA_RORKEE	.xls	-	18-O and 2H data; monthly, annual, long term, LMWL	-	Statistics of isotope data in precipitation
Groundwater	Point	Haryana	IEWP-P4/CGWB	NAQUIM	CGWB Haryana Isotope NAQUIM	.xls	30	S No., LAB ID, INDENTER, PROJECT, STATE, DISTRICT, TEHSIL/TALUK, LOCATION, SAMPLE TYPE, DEPTH, Zone tapped, LATITUDE, LONGITUDE, ALTITUDE, Ec, pH, 618O, 6D, LAB ID O, LAB ID H, (pH, EC, CO3, HC03, Cl, SO4, NO3, F, PO4, Ca, Mg, Na, K, SiO2, TH)	-	Stable isotopes and in-situ EC and pH, plus water chemistry data
Groundwater	Point	Haryana	IEWP-P4/CGWB	NAQUIM	Haryana monitoring well details	.xls	444	SNO, State, District, Tahsil, Block, Well Name, Well Type, Location, OWNER, Latitude, longitude, Depth (m), Aquifer, RL, Local Geology	-	Groundwater monitoring well details
Groundwater	Point	Haryana	IEWP-P4/CGWB	NAQUIM	Haryana Piezometers_COMPILED LIST with WL	.xls	204	State, SI No, State, District, Block, Village, Latitude, Longitude, Depth constructed (m), WL_Premonsoon 2018 (mgb), WL_Post monsoon 2018 (mgb), Tentative depth of installation of DWLR (m), Categorization of Block, Aquifer tapped, fluctuation	-	Groundwater piezometer water level data
Groundwater	Point	Haryana	IEWP-P4/CGWB	NAQUIM	rep110018dist	.xls	-	Pre/Post monsoon water level fluctuations from report Seagate Crystal Reports - REP11	-	Water level fluctuations
Groundwater	Point	Haryana	IEWP-P4/CGWB	IWIN	IWIN_Naquin Haryana, IWIN pre manson 01 (identical files)	.xls	15	Longitude, Latitude, Location, O-18, Deuterium	-	Stable isotope data, pre-monsoon only
Geomorphology	Polygon	Haryana	IEWP-P4/CGWB	CGWB	LGEOM	.shp	1,122	ALNUM-CODE, LG1, LG2	EPSG:4326 - WGS 84	-
Structural properties	Line	Haryana	IEWP-P4/CGWB	CGWB	STRCL	.shp	5348	STRU, SUB_STRU	EPSG:4326 - WGS 84	-
Structural properties	Line	Haryana	IEWP-P4/CGWB	CGWB	STRC2	.shp	281	STRU, SUB_STRU	EPSG:4326 - WGS 84	-
Water Recharge Structures	Point	Haryana	IEWP-P4/CGWB	CGWB	WRDPP	.shp	5031	WRDPP_CODE	EPSG:4326 - WGS 84	-
Water Recharge Structures	Line	Haryana	IEWP-P4/CGWB	CGWB	WRDPL	.shp	94	WRDPP_CODE	EPSG:4326 - WGS 84	-
Administration	Polygon	Haryana	IEWP-P4/CGWB	CGWB	HR-NEW BLOCKS_region	.shp	124	STATE, DISTRICT, TEHSIL, BLOCK	EPSG:3857 - WGS 84	-
Water table	Polygon	Haryana	IEWP-P4/CGWB	CGWB	WTE 10 MAY 2017_region	.shp	451	LOWER, UPPER	EPSG:3857 - WGS 84	-
Digital Elevation Model	Raster	All	CGIAR		DEM_IN_merged_clipped	.tif	-	ELEVATION	EPSG:3857 - WGS 84	-
Borders	Polygon	All	themATICmapping		TMI_WORLD_BORDERS-0.3	.shp	-	COUNTRIES	EPSG:3857 - WGS 84	-
River	Line	All	HydroSheds		as_riv_15s_IN	.shp	-	RIVERS	EPSG:3857 - WGS 84	-
Lake	Polygon	All	HydroSheds		HydroLAKES_poly.v10_clipped	.shp	-	LAKES	EPSG:3857 - WGS 84	-
Places	Point	All	mapcruzin		places	.shp	-	PLACES	EPSG:3857 - WGS 84	-
Report	-	Haryana	IEWP-P4/CGWB	CGWB	Final Report Isotope Haryana	.pdf	1	document and supporting figures and maps	-	-
Report	-	Haryana	IEWP-P4/CGWB	CGWB	Seagate Crystal Reports - REP11	.pdf	1	Pre/Post monsoon water level fluctuations	-	-

.xls = excel table; .shp = shape file; .pdf = Portable Document Format; Lat = Latitude [geogr. coordinates]; Long = Longitude [geogr. coordinates]; Alt = Altitude [m amsl]; O18 = Oxygen-18 [%]; H2 = Deuterium [%]; H3 = Tritium [TU]; P = Precipitation [mm]; Ta = Air temperature [°C]; { } = Laboratory results

APPENDIX B

Isotope data of groundwater samples: Pilot area 1 Haryana

NO	LAB ID	INDENTER	STATE	DISTRICT	TEHSIL/TALUK	LOCATION	SAMPLE TYPE	DEPT H	ZONE TAPPED	LATITUDE	LONGITUDE	ALTITUDE	EC	pH	$\delta^{18}\text{O}$	δD	LAB ID O	LAB ID H	DE	AQUIFER	ZONE TAPPED
[.]	[.]	[.]	[.]	[.]	[.]	[.]	[m]	[.]	[DDEG]	[DDEG]	[m amsl]	[$\mu\text{S}/\text{cm}$]	[.]	[‰]	[‰]	[.]	[.]	[‰]	[no. 1,2,3]	[.]	
16	CGWB CHANDIGARH CGWB-CH-HR-6	CGWB, NWR	Haryana	Kaithal	Kalayat	Balu	GW	100	57-60	29.650478	76.368083	237	11590	8	-6.96	-46	CF 45875	64114	9.25	1	58.5
17	CGWB CHANDIGARH CGWB-CH-HR-7	CGWB, NWR	Haryana	Kaithal	Kalayat	Balu	GW	200	161-164,181-183	29.650478	76.368083	238	3910	8	-6.73	-41	CF 45876	64115	12.4	2	172
18	CGWB CHANDIGARH CGWB-CH-HR-8	CGWB, NWR	Haryana	Kaithal	Kalayat	Balu	GW	300	234-238	29.650478	76.368083	239	1005	9	-7.22	-47	CF 45877	64116	10.4	3	236
10	CGWB Chandigarh HR00100D	CGWB, NWR	Haryana	Panchkula	Barwala	Barwala	GW	57	31-33,41-43,51-53	30.5568	76.939821	319	1673	8	-6.61	-46	CF 40662	58242	7.15	1	42
11	CGWB Chandigarh HR00110D	CGWB, NWR	Haryana	Panchkula	Barwala	Barwala	GW	196	141-144,159-162,191-193	30.5568	76.939821	320	1288	9	-6.57	-47	CF 40663	58243	5.31	2	167
12	CGWB CHANDIGARH CGWB-CH-HR-1	CGWB, NWR	Haryana	Sirsa	Nathu Sari	Darba Kalan	GW	252	225-229, 237-239,242-248	29.409525	75.12097	205	16510	8	-5.63	-43	CF 45870	64109	1.87	3	236.5
22	CGWB CHANDIGARH CGWB-CH-HR-12	CGWB, NWR	Haryana	Karnal	Indri	Islamnagar	GW	100	51-54, 73-79	29.871211	77.116619	258	398	8	-8.57	-59	CF 45881	64120	9.22	1	65
21	CGWB CHANDIGARH CGWB-CH-HR-11	CGWB, NWR	Haryana	Karnal	Indri	Islamnagar	GW	200	152-156, 172-176	29.871211	77.116619	257	285	8	-9.35	-63	CF 45880	64119	11.7	2	164
20	CGWB CHANDIGARH CGWB-CH-HR-10	CGWB, NWR	Haryana	Karnal	Indri	Islamnagar	GW	300	243-247, 277-279	29.871211	77.116619	256	308	9	-9.18	-61	CF 45879	64118	12.7	3	261
28	CGWB CHANDIGARH CGWB-CH-HR-18	CGWB, NWR	Haryana	Kaithal	Pundri	Jajanpur	GW	100	82-85, 91-94	29.902187	76.605167	249	716	9	-6.92	-53	CF 45887	64126	2.73	1	88
27	CGWB CHANDIGARH CGWB-CH-HR-17	CGWB, NWR	Haryana	Kaithal	Pundri	Jajanpur	GW	200	161-164, 176-180	29.902187	76.605167	248	506	8	-6.45	-39	CF 45886	64125	13.1	2	170.5
26	CGWB CHANDIGARH CGWB-CH-HR-16	CGWB, NWR	Haryana	Kaithal	Pundri	Jajanpur	GW	300	226-233	29.902187	76.605167	247	572	8	-6.75	-38	CF 45885	64124	16.3	3	229.5
25	CGWB CHANDIGARH CGWB-CH-HR-15	CGWB, NWR	Haryana	Ambala	Ambala-I	Jandheri	GW	100	74-80	30.090885	76.611247	251	541	8	-6.01	-43	CF 45884	64123	4.8	1	77
24	CGWB CHANDIGARH CGWB-CH-HR-14	CGWB, NWR	Haryana	Ambala	Ambala-I	Jandheri	GW	200	156-160, 179-182, 194-197	30.090885	76.611247	250	465	8	-6.03	-39	CF 45883	64122	9.33	2	176.5
23	CGWB CHANDIGARH CGWB-CH-HR-13	CGWB, NWR	Haryana	Ambala	Ambala-I	Jandheri	GW	300	250-256, 284-287	30.090885	76.611247	249	530	8	-6.07	-34	CF 45882	64121	14.7	3	268.5

NO	LAB ID	INDENTER	STATE	DISTRICT	TEHSIL/TAL UK	LOCATION	SAMPLE TYPE	DEPT H	ZONE TAPPED	LATITUDE	LONGITUDE	ALTITUDE	EC	pH	δ18O	δD	LAB ID O	LAB ID H	DE	AQUIFER	ZONE TAPPED
[•]	[•]	[•]	[•]	[•]	[•]	[•]	[m]	[•]	[DDEG]	[DDEG]	[m amsl]	[µS/cm]	[•]	[‰]	[‰]	[•]	[•]	[•]	[‰]	[no. 1,2,3]	[•]
1	CGWB Chandigarh HR0010D	CGWB, NWR	Haryana	Kaithal	Shahpur	Kanpur Village	GW	192	177-180, 187-191	29.888356	76.353938	245	1896	9	-5.13	-37	CF 40653	58233	3.54	2	184
2	CGWB Chandigarh HR0020D	CGWB, NWR	Haryana	Kaithal	Shahpur	Kanpur Village	GW	300	221-233, 248-254	29.888356	76.353938	246	753	9	-7	-40	CF 40654	58234	15.5	3	237.5
9	CGWB Chandigarh HR0090D	CGWB, NWR	Haryana	Kurukshetra	Shahbad	Khanpur Jattan	GW	100	60-68	30.119668	76.873537	262	768	9	-5.45	-41	CF 40661	58241	2.22	1	64
7	CGWB Chandigarh HR0070D	CGWB, NWR	Haryana	Kurukshetra	Shahbad	Khanpur Jattan	GW	192	153-159, 172-175, 186-189	30.119668	76.873537	260	482	9	-6.18	-45	CF 40659	58239	4.74	2	171
8	CGWB Chandigarh HR0080D	CGWB, NWR	Haryana	Kurukshetra	Shahbad	Khanpur Jattan	GW	300	228-240, 251-257	30.119668	76.873537	261	473	9	-6.38	-45	CF 40660	58240	6.52	3	242.5
29	CGWB CHANDIGARH CGWB-CH-HR-19	CGWB, NWR	Haryana	Karnal	Nissang	Kherinadu	GW	300	236-239, 253-256	29.642204	76.911578	247	586	8	-6.05	-33	CF 45888	64127	15.3	3	246
6	CGWB Chandigarh HR0060D	CGWB, NWR	Haryana	Yamunanagar	Yamunanagar	Masana Jattan	GW	100	56-62, 70-73, 86-89	30.131873	77.125497	277	422	8	-5.81	-44	CF 40658	58238	2.61	1	72.5
31	CGWB CHANDIGARH CGWB-CH-HR-20	CGWB, NWR	Haryana	Yamunanagar	Jagadhri	Sabapur	GW	100	38-42, 53-56, 87-90	30.112762	77.365102	276	260	8	-9.12	-62	CF 45889	64128	10.7	1	64
30	CGWB CHANDIGARH CGWB-CH-HR-5	CGWB, NWR	Haryana	Yamunanagar	Jagadhri	Sabapur	GW	200	155-162, 171-173, 181-184	30.112762	77.365102	276	256	8	-9.19	-63	CF 45874	64113	11	2	169.5
4	CGWB Chandigarh HR0040D	CGWB, NWR	Haryana	Yamunanagar	Yamunanagar	Shahabpur	GW	200	144-151, 158-161, 166-169	30.131873	77.125497	275	429	8	-6.38	-43	CF 40656	58236	8.08	2	156.5
5	CGWB Chandigarh HR0050D	CGWB, NWR	Haryana	Yamunanagar	Yamunanagar	Shahabpur	GW	300	207-210, 239-245, 263-269, 277-281	30.131873	77.125497	276	260	8	-9.03	-59	CF 40657	58237	12.9	3	244
15	CGWB CHANDIGARH CGWB-CH-HR-4	CGWB, NWR	Haryana	Kaithal	Kalayat	Simla	GW	31	20-23, 26-28	29.633194	76.216057	232	750	9	-10.1	-69	CF 45873	64112	11.6	1	24
14	CGWB CHANDIGARH CGWB-CH-HR-3	CGWB, NWR	Haryana	Kaithal	Kalayat	Simla	GW	219	213-216	29.633194	76.216057	231	11780	8	-6.18	-38	CF 45872	64111	11.4	2	214.5
13	CGWB CHANDIGARH CGWB-CH-HR-2	CGWB, NWR	Haryana	Kaithal	Kalayat	Simla	GW	300	292-295	29.633194	76.216057	230	2750	9	-6.1	-41	CF 45871	64110	7.66	3	293.5
3	CGWB Chandigarh HR0030D	CGWB, NWR	Haryana	Kaithal	Siwan	Siwan	GW	100	85-91, 94-97	29.888356	76.353938	247	1050	9	-5.75	-47	CF 40655	58235	-1.4	1	91

Water quality data of groundwater samples: Pilot area 1 Haryana

NO	LOCATION	SAMPLE TYPE	DEPTH	ZONE TAPPED	LATITUDE	LONGITUDE	ALTITUDE	pH ⁺	EC ⁺	CO ₃ ²⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	F ⁻	PO ₄ ³⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	SiO ₂ ⁻	TH'as CaCO ₃	AQUIFER	ZONE TAPPED
[•]	[•]	[•]	[m]	[•]	[DDEG]	[DDEG]	[m amsl]	[•]	[µS/cm at 25°C]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[no. 1,2,3]	[•]
16	Balu	GW	100	57-60	29.650478	76.368083	237	7.9	10250	nill	391	1702	3554	21	1.17	BDL	120	399	2060	16	15	1942	1	58.5
17	Balu	GW	200	161-164,181-183	29.650478	76.368083	238	7.87	3645	nill	220	525	842	BDL	0.23	BDL	160	4.9	632	2	16	420	2	172
18	Balu	GW	300	234-238	29.650478	76.368083	239	8.49	1015	24	366	85	82	BDL	1.75	BDL	16	24	188	2	16	140	3	236
10	Barwala	GW	57	31-33,41-43,51-53	30.5568	76.939821	319	7.51	1956	0	756	211	105	3.4	0.04	0.027	116	43	253	6.5	15	468	1	42
11	Barwala	GW	196	141-144,159-162,191-193	30.5568	76.939821	320	7.3	1328	0	720	137	40	0.15	0.22	0.02	140	26	168	3.9	14	458	2	167
12	Darba Kalan	GW	252	225-229, 237-239,242-248	29.409525	75.12097	205	7.84	15560	0	195	4436	2310	11	2.31	0.02	452	428	2745	9	25	2890	3	236.5
22	Islamnagar	GW	100	51-54, 73-79	29.871211	77.116619	258	8.13	405	nill	195	14	43	BDL	0	BDL	20	10	61	2.5	17	90	1	65
21	Islamnagar	GW	200	152-156, 172-176	29.871211	77.116619	257	8.32	285	12	109	14	43	BDL	0	BDL	4	4.9	62	1.1	12	30	2	164
20	Islamnagar	GW	300	243-247, 277-279	29.871211	77.116619	256	8.18	310	nill	171	14	5.2	BDL	0.34	BDL	8	0	67	1.1	13	20	3	261
28	Jajapur	GW	100	82-85, 91-94	29.902187	76.605167	249	7.6	3510	nill	220	482	965	BDL	0.64	BDL	88	83	600	2	14	560	1	88
27	Jajapur	GW	200	161-164, 176-180	29.902187	76.605167	248																2	170.5
26	Jajapur	GW	300	226-233	29.902187	76.605167	247																3	229.5
25	Jandheri	GW	100	74-80	30.090885	76.611247	251	7.77	534	0	305	14	38	0	0.36	0	26	26	64	3.7	19	172	1	77
24	Jandheri	GW	200	156-160, 179-182, 194-197	30.090885	76.611247	250	8.44	448	12	195	28	30	0	0.33	0	8	2.6	98	0.9	16	31	2	176.5
23	Jandheri	GW	300	250-256, 284-287	30.090885	76.611247	249	8.59	500	24	195	14	74	0	0.37	0	4	4.9	124	0.9	16	31	3	268.5

NO	LOCATION	SAMPLE TYPE	DEPTH	ZONE TAPPED	LATITUDE	LONGITUDE	ALTITUDE	pH ⁺	EC ⁺	CO ₃ ²⁻	HCO ₃ ²⁻	Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	F ⁻	PO ₄ ³⁻	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	SiO ₂ ⁺	TH'as CaCO ₃	AQUIFER	ZONE TAPPE D
[•]	[•]	[•]	[m]	[•]	[DDEG]	[DDEG]	[m amsl]	[•]	[µS/cm at 25°C]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[mg/l]	[no. 1,2,3]	[•]
1	Kanpur Village	GW	192	177-180, 187-191	29.888356	76.353938	245	7.88	1450	0	232	128	336	1	0.23	0	20	15	275	10	12	110	2	184
2	Kanpur Village	GW	300	221-233, 248-254	29.888356	76.353938	246	7.8	1360	0	183	142	499	1.2	0.61	0	20	17	340	10	12	120	3	237.5
9	Khanpur Jattan	GW	100	60-68	30.119668	76.873537	262	8.63	421	24	133	42	40	0	0.071	0.059 ₃	12	9.9	81	2.8	16	72	1	64
7	Khanpur Jattan	GW	192	153-159, 172-175, 186-189	30.119668	76.873537	260	7.5	465	BDL	274	10	18	BDL	0.34	0.03	19	10	78	3.1	16	88	2	171
8	Khanpur Jattan	GW	300	228-240, 251-257	30.119668	76.873537	261	7.92	842	0	483	63	2	8.9	0.385	0.012	54	15	106	6.9	16	247	3	242.5
29	Kherinadu	GW	300	236-239, 253-256	29.642204	76.911578	247	8.35	620	12	171	36	175	1	0.43	<0.10	4	9.7	155	5.7	13	50	3	246
6	Masana Jattan	GW	100	56-62, 70-73, 86-89	30.131873	77.125497	277	7.88	1172	0	519	175	34	0	0.159	0	41	128	35	6.2	20	628	1	72.5
31	Sabapur	GW	100	38-42, 53-56, 87-90	30.112762	77.365102	276	8.02	248	0	122	7.1	22	0.48	0.26	0	30	9.7	6.9	2.6	13	116	1	64
30	Sabapur	GW	200	155-162, 171-173, 181-184	30.112762	77.365102	276																2	169.5
4	Shahabpur	GW	200	144-151, 158-161, 166-169	30.131873	77.125497	275																2	156.5
5	Shahabpur	GW	300	207-210, 239-245, 263-269, 277-281	30.131873	77.125497	276																3	244
15	Simla	GW	31	20-23, 26-28	29.633194	76.216057	232	7.88	783	0	366	21	109	6.5	1.58	BDL	40	34	94	3.4	32	240	1	24
14	Simla	GW	219	213-216	29.633194	76.216057	231	8.23	2004	0	390	386	0	3.2	1.56	0.054	17	13	421	1	32	94	2	214.5
13	Simla	GW	300	292-295	29.633194	76.216057	230	8.51	2680	24	256	597	206	3.8	1.73	0.028	33	18	534	2	23	156	3	293.5
3	Siwan	GW	100	85-91, 94-97	29.888356	76.353938	247	7.99	1130	0	544	110	30	11	0.559	0.009	12	73	140	8.6	9.6	330	1	91

APPENDIX C

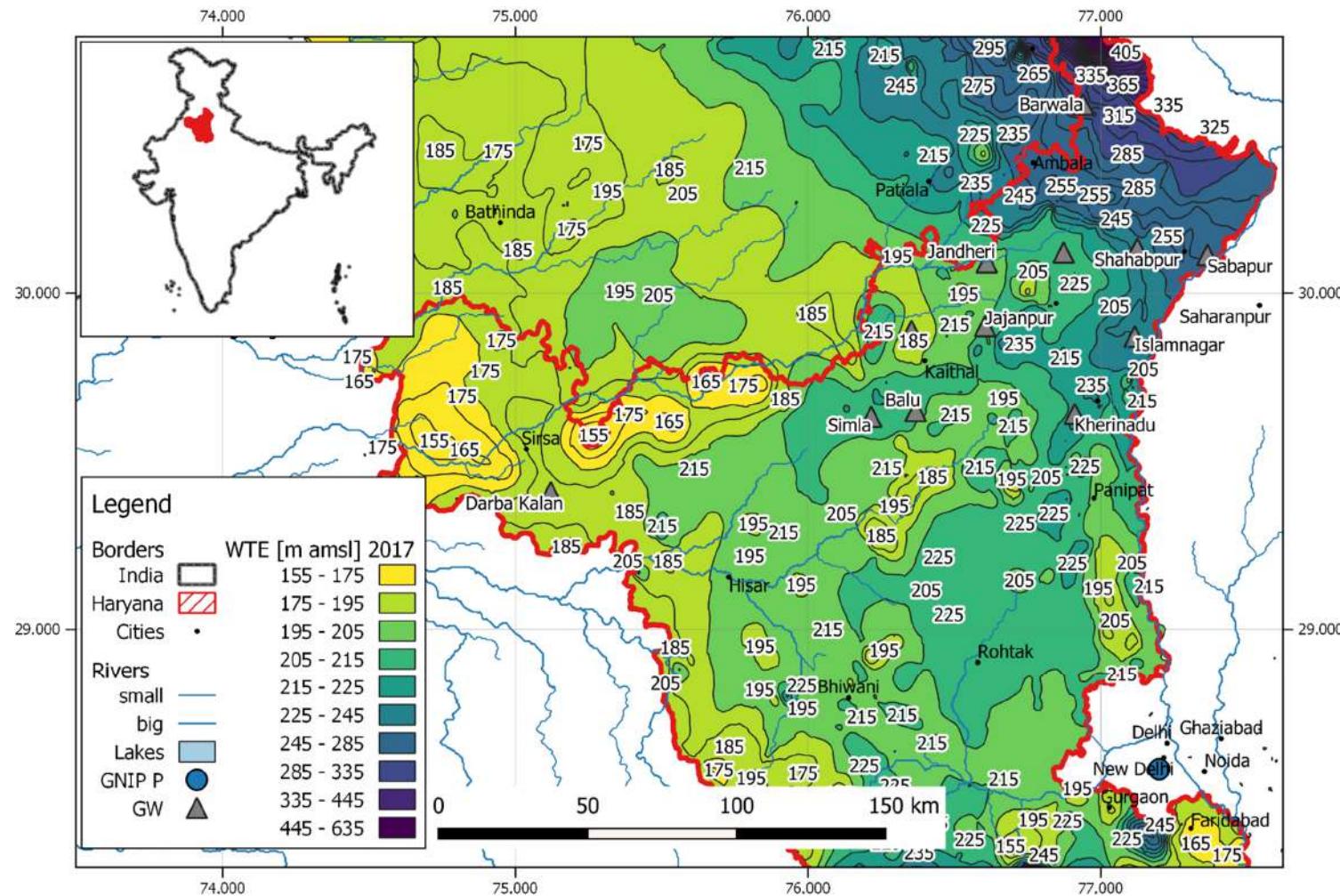
Isotope data of surface water samples: Pilot area 1 Haryana

Source: Dalai, T.K., Bhattacharya, S.K., & S. Krishnaswami (2002)

Surface Water	$\delta^{18}\text{O}$	δD	DE	ALTITUDE
	[‰]	[‰]	[‰]	[m amsl]
Yamuna at 484m Post Monsoon	-10.3	-68.5	13.9	484
Yamuna at 484m Summer	-7.8	-54.4	8	484
Yamuna at 484m Monsoon	-9.5	-65.5	10.5	484

APPENDIX D

Groundwater contour map of the Haryana pilot area; Lower water table elevation (WTE) in m amsl for 2017.



Assessment of stable isotope data

Pilot area: Karnataka

Final report

Activity 3: Pilot-testing of the approach/methodology using selected isotope data

Advisory Service for the IEWP Priority Area 4 – Groundwater Use: Support to Assess Groundwater Aquifers by Using Existing Isotope Data in India.

Jochen Wenninger

IHE Delft Institute for Water Education

Final version

2020-09-25

Abbreviations

$\delta^{18}\text{O}$	Delta value of oxygen-18
$\delta^2\text{H}$	Delta value of deuterium
ANOVA	Analysis of variance
CGWB	Central Ground Water Board
D	Deuterium (also written as H-2)
D_{excess}	Deuterium excess
EC	Electrical conductivity
GNIP	Global Network of Isotopes in Precipitation
GMWL	Global Meteoric Water Line
IAEA	International Atomic Energy Agency
IEWP	India-EU Water Partnership
IMD	India Meteorological Department
LMWL	Local Meteoric Water Line
MWL	Meteoric Water Line
NAQUIM	National Project on Aquifer Management
O-18	Oxygen-18
RCWIP	Regionalized cluster-based water isotope prediction
RMWL	Regional Meteoric Water Line

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Introduction

This report is part of Activity 3: “Pilot-testing of the approach/methodology using selected isotope data” within the Advisory Service for the IEWP Priority Area 4 – Groundwater Use: Support to Assess Groundwater Aquifers by Using Existing Isotope Data in India. The objective of this report is to present findings of the pilot testing to interpret and analyse a selected isotope data set in order to identify and verify source areas and water origins of groundwater recharge. Understanding the recharge mechanisms and their variability is a crucial precondition to sustainable aquifer management.

Therefore the data collected during Activity 2 were analysed according to the methodology developed in Activity 1. Results of the analysis are presented with the help of figures and maps. Shortcomings of the analysis and next steps regarding the interpretation and analysis of isotope data are included at the end of this report.

Background information of the pilot area Karnataka was taken from the document: *Report on Isotopic Data Interpretation for National Aquifer Mapping Area in parts of Karnataka State* (CGWB 2018) and from the report: *Potential of Karnataka, Talukwise Inventory with Management Options* (Ramachandra and Kamakshi 2005).

1. Description of study area

The Karnataka pilot area is situated in the central-western part of India. The area spans from 11.6° to 18.5° N and 74.0° to 78.6° E, covering an area of nearly $192,000 \text{ km}^2$ (see Figure 1). The State is bounded by Kerala and Tamil Nadu in the south, Andhra Pradesh and Telangana in the east, Maharashtra and Goa in the north, and with a coastline of 350 km to the Arabian Sea in the west. Elevation is ranging from sea level to 1930 m amsl at the Mullayanagiri peak, and the majority of the area is located on a tableland between the Western and Eastern Ghat ranges. Five major river basins are draining the State of Karnataka namely the Godavari, Krishna, Cauvery, Pennar and West Flow rivers. More than 99% of Karnataka are build up by hard rock aquifers, only in the coastal areas younger alluvial aquifers are present. Groundwater occurs mainly within fractured aquifer systems.

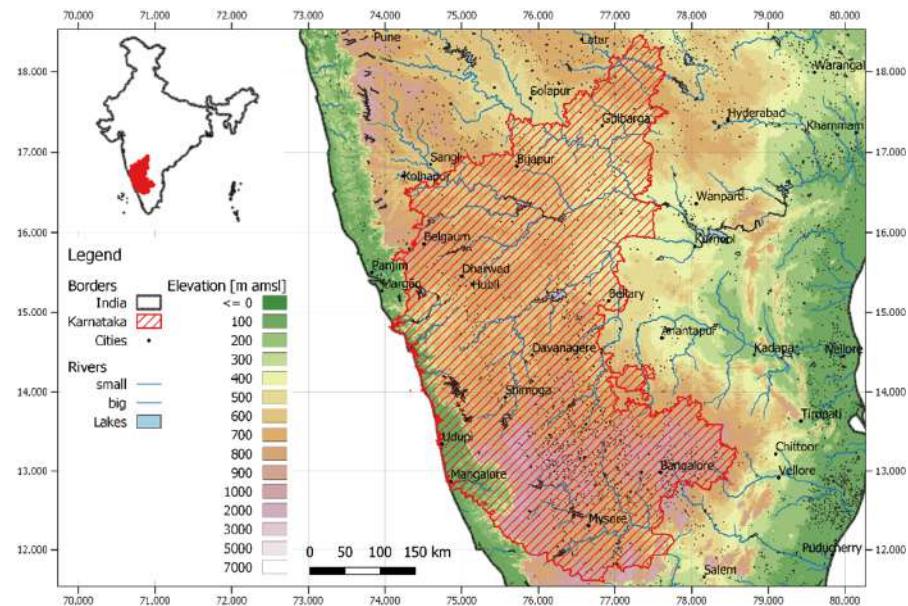


Figure 1: Overview map of the Karnataka pilot area.

1.1. Climatic condition

The physiographic conditions, with an elevation difference of almost 2000 meters, lead to climatic variations in the pilot area ranging from a humid tropical monsoon climate along the coastline over sub-humid conditions in the Ghats to a semi-arid and arid climate in the plateau region. The climate in the pilot area belongs, according to the Köppen-Geiger Climate Classification to an Equatorial Monsoonal type (Am), an Equatorial Desert type (AW), and an Arid-Steppe-Hot (BSh) type (Rubel and Kottek, 2010). Long term climatological data of three stations (Mangalore 1956-2000, Belgaum Samra 1952-2000, and Gulbarga 1901-2000) were used from the India Meteorological Department (see Figure 2). The most important driving force for precipitation in the area is the Southwest monsoon, with average annual precipitation amounts between 760 mm and 3800 mm. The main rainfall occurs during the monsoon season between June and September, with around 80% of the annual precipitation amount. Generally precipitation decreases towards the eastern part of the study area. Annual average air temperature is varying between 24.2°C and 27.3°C with monthly variations between 21.7°C and 33.2°C (see Figure 2).

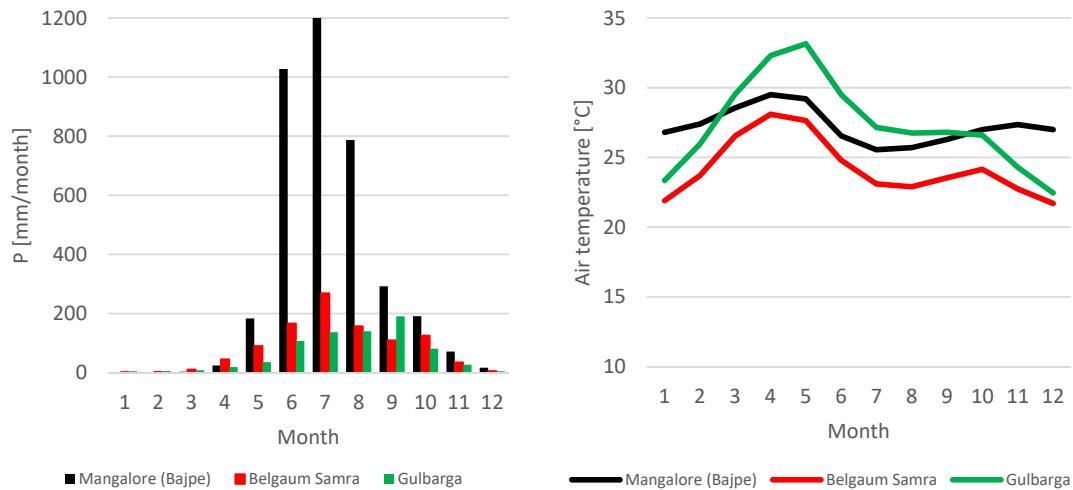


Figure 2: Climatic conditions of the Karnataka pilot area (India Meteorological Department, 2019).

1.2. Hydrogeological setting

The majority of the pilot area is build up by crystalline hard rocks and older sedimentary rocks like gneisses, granites, and phyllites. Only in the northern part limestones and basalts are dominant (see Figure 3). According to Ramachandra and Kamakshi (2005) four main types of geological formations can be classified in Karnataka:

- The *Archean complex* made up of schists and granitic gneisses. This complex consists of gneisses, granites and charnockite rocks and covers around 60% of the study area.
- The *Proterozoic non-fossiliferous sedimentary formations* of the Kaladgi and Bhima series. The series consists mainly of like sandstone, metabasalt, limestone, trapstone, and shale.
- The *Deccan trappean and intertrappean deposits*. These deposits are formed by accumulation of basaltic lava.
- The *tertiary and recent laterites and alluvial deposits*.

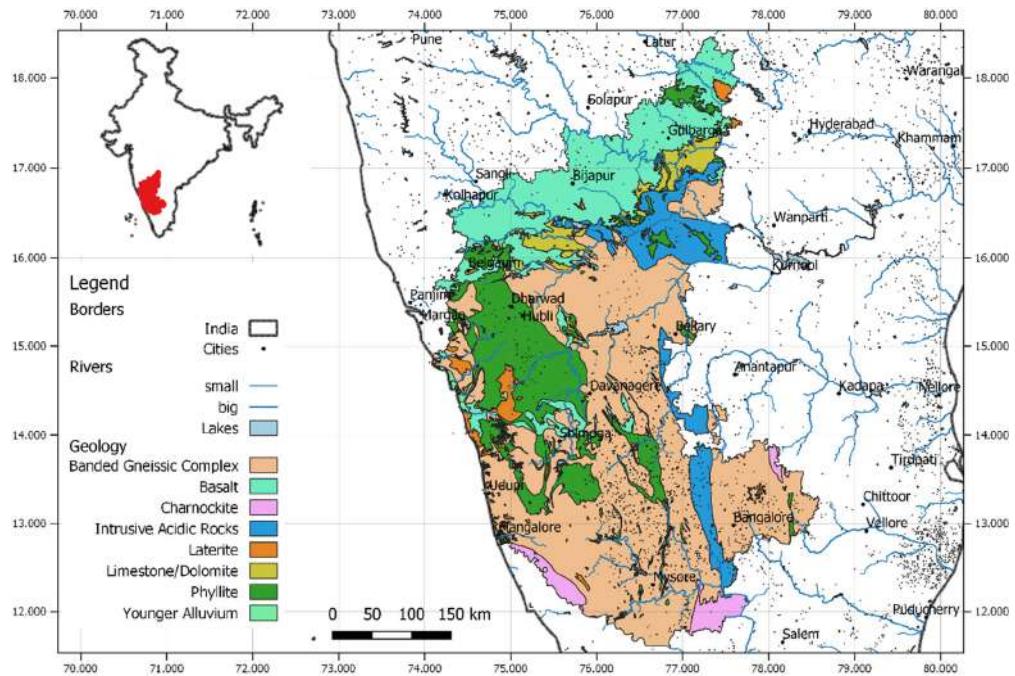


Figure 3: Geology of the study area.

Soils in the pilot area are dominated by moderately drained black soils in the northern part and relatively well drained red sandy/loamy soils in the southern part (see Figure 4).

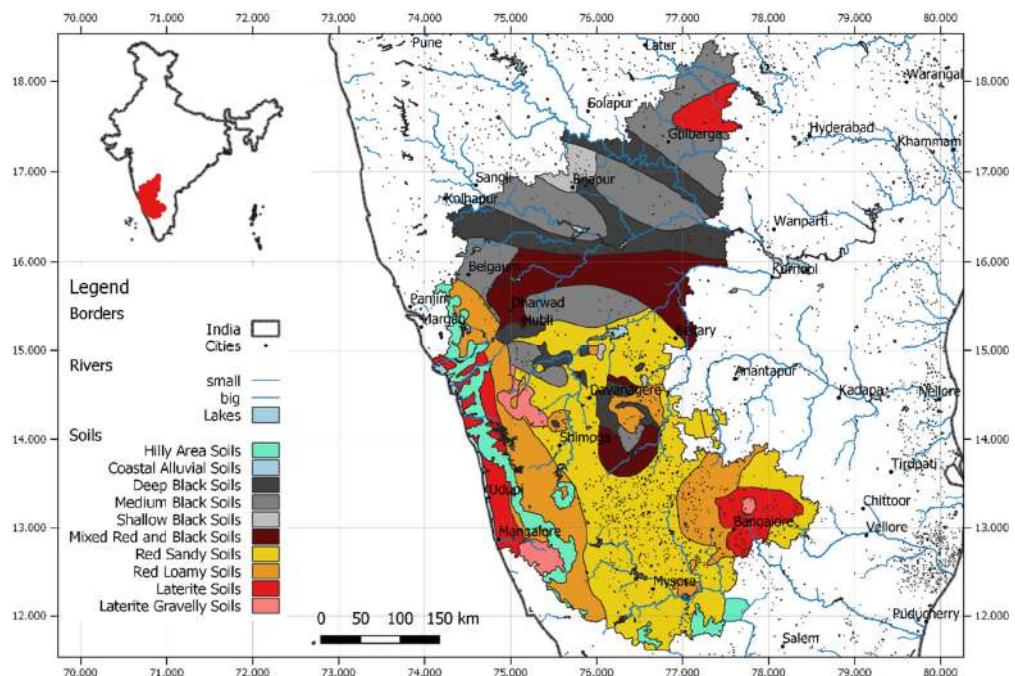


Figure 4: Soils of the study area.

2. Data collection

Datasets collected for this report correspond to different data scopes and were collected from several sources. Stable isotope values and in-situ physio-chemical parameters for groundwater samples were collected from the Central Ground Water Board (CGWB), and for precipitation from the Global Network of Isotopes in Precipitation (GNIP) database from the International Atomic Energy Agency (IAEA). Climate data was used for long term precipitation and temperature information from the India Meteorological Department (IMD). Geospatial data of the pilot area were either collected from the CGWB or from other public available resources. A detailed overview of the data sets provided by the CGWB and additional data used for the assessment are listed in APPENDIX A.

Most relevant data and information for a stable isotope assessment include next to stable isotope data (Oxygen-18 and Deuterium) of groundwater and precipitation also metadata of the samples (like location, elevation, water level, borehole depth, filter depth, etc.), in-situ water quality parameters (like temperature, electrical conductivity, TDS, etc.), and other aquifer mapping related data (like topography, geology, hydrogeology, land use, hydro-meteorological information etc.).

In summary 103 groundwater samples containing stable isotope data, in-situ EC and pH values are available for the assessment. The dataset originates from the National Project on Aquifer Management (NAQUIM), and isotope values were analysed at the National Institute of Hydrology, Roorkee, Uttarakhand. In total 103 locations were sampled from hand pumps from different hydrogeological settings in 19 districts of Karnataka. Sampling locations are limited to the northern and eastern part of the State and no samples were taken at the coastline or in the southern part of the State (see Figure 5). Stable isotope data for precipitation was collected for the three stations Belgaum (2003-2005), Hyderabad (1997-2001), and Bangalore (2003-2004) which are located within or close to the pilot area (see Figure 5). Additional to this regionalized cluster-based water isotope predictions (RCWIP) were used for regional assessment of isotopic values in precipitation (Terzer et al., 2013). A visual data quality check was carried out to ensure that no outliers are included in the following analysis steps.

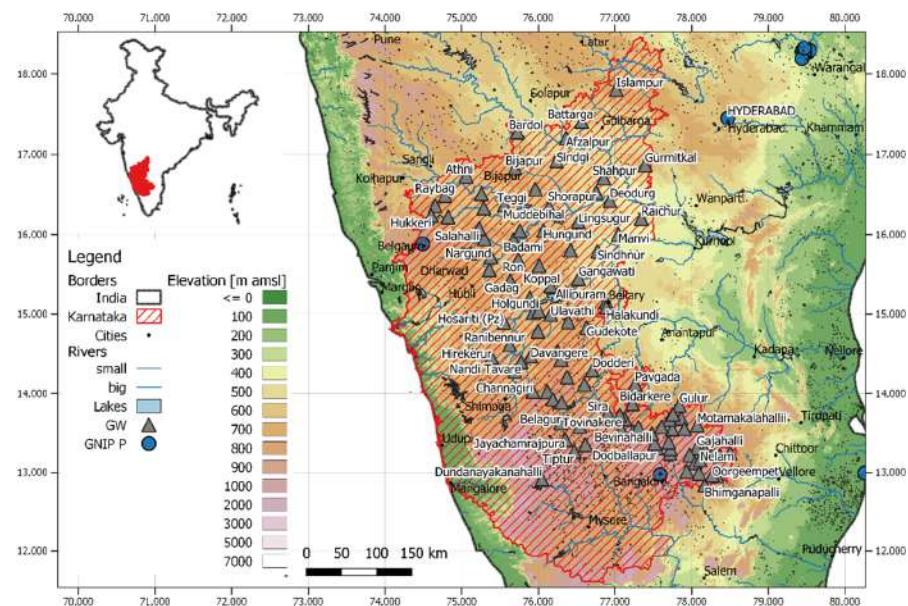


Figure 5: Groundwater sampling points (GW) and GNIP stations (GNIP P) of the Karnataka pilot area.

3. Stable isotope analyses

The following section describes the results of the stable isotope analysis. All Oxygen-18 and Deuterium values are reported in the δ -notation (‰) relative to the international standard Vienna Standard Mean Ocean Water (VSMOW) using the formulas (IAEA & UNESCO, 2000):

$$\delta^2H = \frac{\left(\frac{^2H}{^1H}\right)_{\text{Sample}}}{\left(\frac{^2H}{^1H}\right)_{\text{Standard}}} - 1 \quad [\text{‰}] \quad (1)$$

$$\delta^{18}O = \frac{\left(\frac{^{18}O}{^{16}O}\right)_{\text{Sample}}}{\left(\frac{^{18}O}{^{16}O}\right)_{\text{Standard}}} - 1 \quad [\text{‰}] \quad (2)$$

Deuterium excess (D_{excess}) values were calculated for all samples using a slope of 8 as proposed by Dansgaard (1964):

$$D_{\text{excess}} = \delta^2H - 8 \cdot \delta^{18}O \quad [\text{‰}] \quad (3)$$

On a global scale the D_{excess} has a value of 10‰, but can be different for specific locations due to variations in humidity and temperature during primary evaporation (Clark & Fritz, 1997). Low deuterium excess values of groundwater samples are an indication of either evaporation prior to recharge or precipitation under different climatic conditions under a higher humidity (Kendall & McDonnell, 1998).

3.1. Precipitation

Insights about the groundwater recharge mechanisms can be gained by comparing the stable isotope relationships of the groundwater samples in relation to those of the input from precipitation. Therefore the input signal from precipitation in the pilot area needs to be determined in a temporal way by assessing the monthly and seasonal input function, and by defining Meteoric Water Lines (MWL). Meteoric water lines represent the relationship between oxygen-18 and deuterium values in precipitation.

On a global scale this relationship between the two stable water isotopes in precipitation is characterized by the so called Global Meteoric Water Line (GMWL). The equation of Craig (1961) was used in this assessment:

$$\delta^2H = 8 \cdot \delta^{18}O + 10 \quad [\text{‰}] \quad (4)$$

Due to the fact that the GMWL is based on a global dataset it is only used as a background reference and more site specific Local Meteoric Water Line (LMWL) should be used for the interpretation. Pilot area related Global Network of Isotopes in Precipitation (GNIP) data sets were downloaded from the International Atomic Energy Agency (IAEA) database. The GNIP database contains three stations with sufficient data in or in the vicinity of the pilot area: Belgaum, Hyderabad, and Bangalore.

The GNIP data contains Local Meteoric Water Lines (LMWL) describing the relationship between Oxygen-18 and Deuterium composition of precipitation at these specific locations. For Belgaum the LMWL is determined to be:

$$\delta^2H = 7.80 \cdot \delta^{18}O + 11.32 \text{ [‰]} \quad (5)$$

for Hyderabad it is:

$$\delta^2H = 6.95 \cdot \delta^{18}O + 4.46 \text{ [‰]} \quad (6)$$

and for Bangalore it is:

$$\delta^2H = 7.81 \cdot \delta^{18}O + 11.74 \text{ [‰]} \quad (7)$$

The LMWL of the station Bangalore has a very similar slope and intercept compared with the station Belgaum, and is therefore not considered in the further analysis.

Additional to the GMWL and the LMWLs the Regional Meteoric Water Line (RMWL) for Southern India published by Kumar *et al.* (2010) was used:

$$\delta^2H = 7.82 \cdot \delta^{18}O + 10.23 \text{ [‰]} \quad (8)$$

Figure 6 below displays the GMWL, LMWLs, and RMWL for the pilot area.

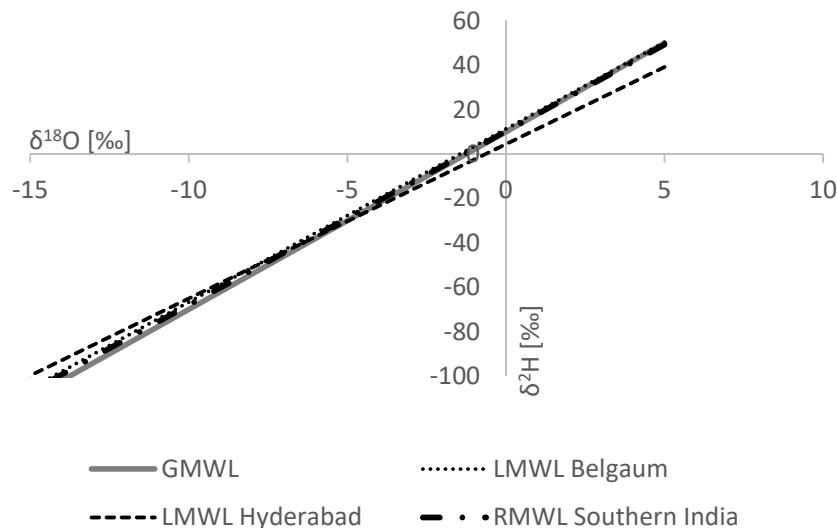


Figure 6: Global Meteoric Water Line (GMWL), Local Meteoric Water Lines (LMWLs) at Belgaum, Hyderabad GNIP stations, and RMWL of Southern India.

Values of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ in precipitation for the pilot area range between -13.16‰ and -94.8‰ for Bangalore in May and 5.41‰ and 44.9‰ for Hyderabad in March (see Figure 7). Generally isotope values are lighter towards the end and after the monsoon season between October and December and heavier in the dry period. The dataset for Belgaum is incomplete and data for the dry months are missing. The annual weighted mean values for Belgaum for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are -1.51‰ and 6.3‰ , respectively. For Hyderabad the isotope values are more negative with $\delta^{18}\text{O}$ of -4.29‰ and -25.1‰ for $\delta^2\text{H}$.

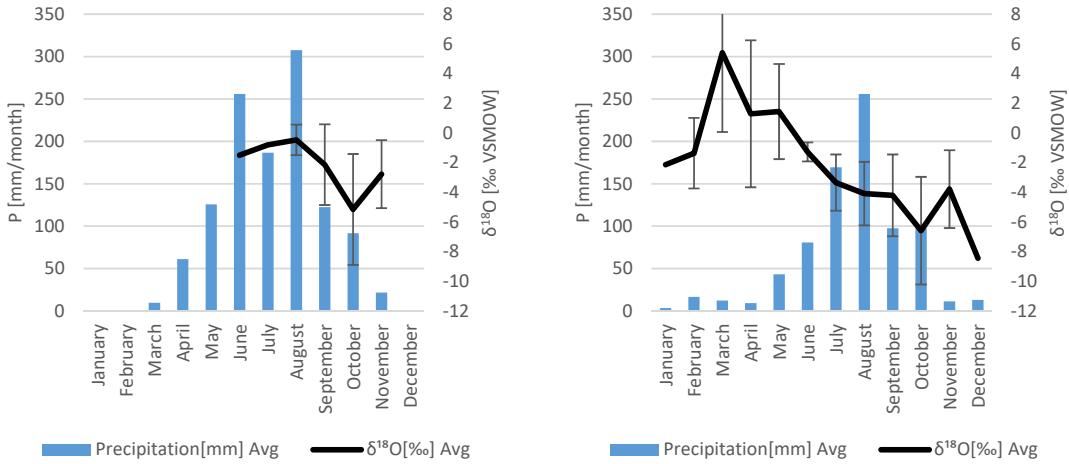


Figure 7: Average monthly amount and isotope composition of precipitation (P) at the GNIP stations Belgaum (left) and Hyderabad (right).

Monthly isotope values (GNIP data set) in relation to the GMWL and LMWLs are shown in Figure 8 for Belgaum, Hyderabad, Bangalore, and as an average for the State Karnataka from the RCWIP data set.

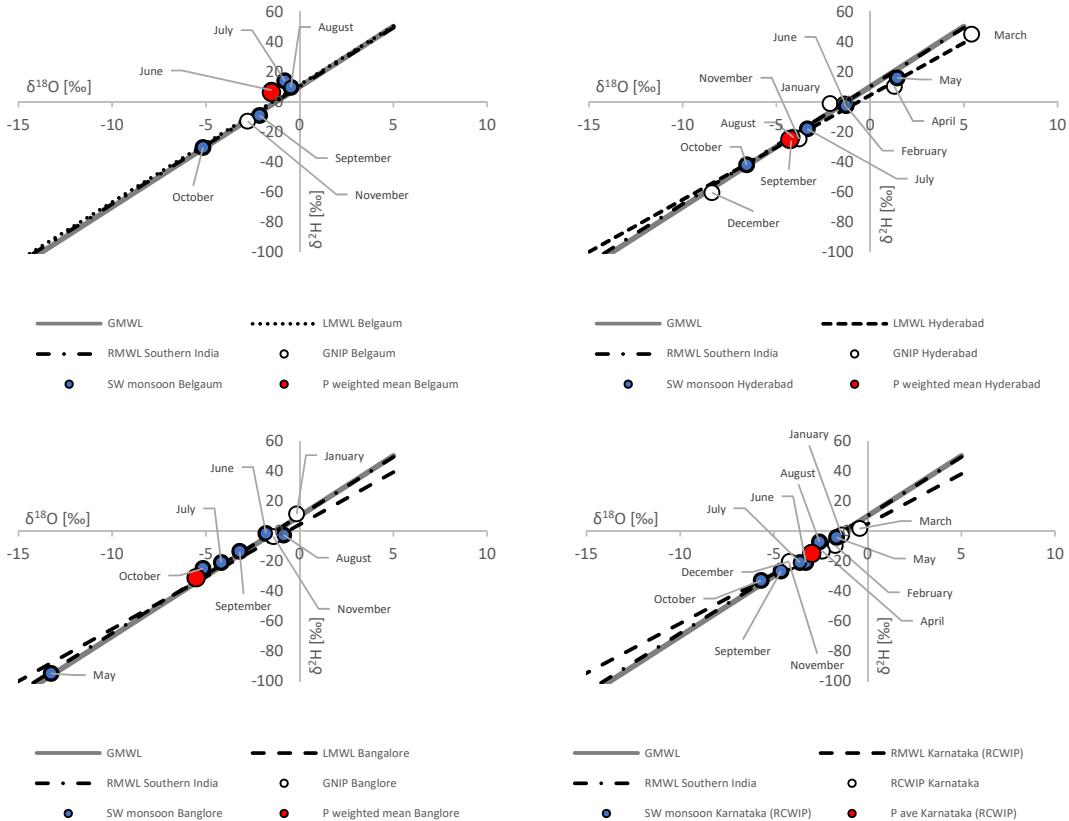


Figure 8: Average monthly precipitation values and annual precipitation weighted mean value at GNIP stations Belgaum (upper left), Hyderabad (upper right), Bangalore (lower left), and average for the State of Karnataka (RCWIP) (lower right).

3.2. Groundwater

Stable isotope composition of groundwater varies between $-6.5\text{\textperthousand}$ and $1.4\text{\textperthousand}$ for $\delta^{18}\text{O}$ and between $-45.7\text{\textperthousand}$ and $5.2\text{\textperthousand}$ for $\delta^2\text{H}$. Locations of groundwater samples can be found in Figure 9, Figure 10, Figure 11, Figure 12, and Figure 13. The relationship between the two isotopes are shown in Figure 14. All values of the groundwater samples can be found in APPENDIX B.

In Figure 9 the $\delta^{18}\text{O}$ values of the groundwater samples are displayed with the underlying geology. Generally the groundwater samples show heavier values towards the northern part of the pilot area and lighter ones in the south-eastern parts. This pattern can partly be explained by the elevation differences between the north-eastern (350-550 m amsl) and south-eastern (700-1000 m amsl) parts of the pilot area and an elevation effect which in causing differences in isotopic composition of precipitation input. In APPENDIX C maps of the regionalized annual isotopic values for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ within the pilot area are shown. However the heavier isotope values of groundwater cannot be explained only based on this effect, and further analysis steps are necessary.

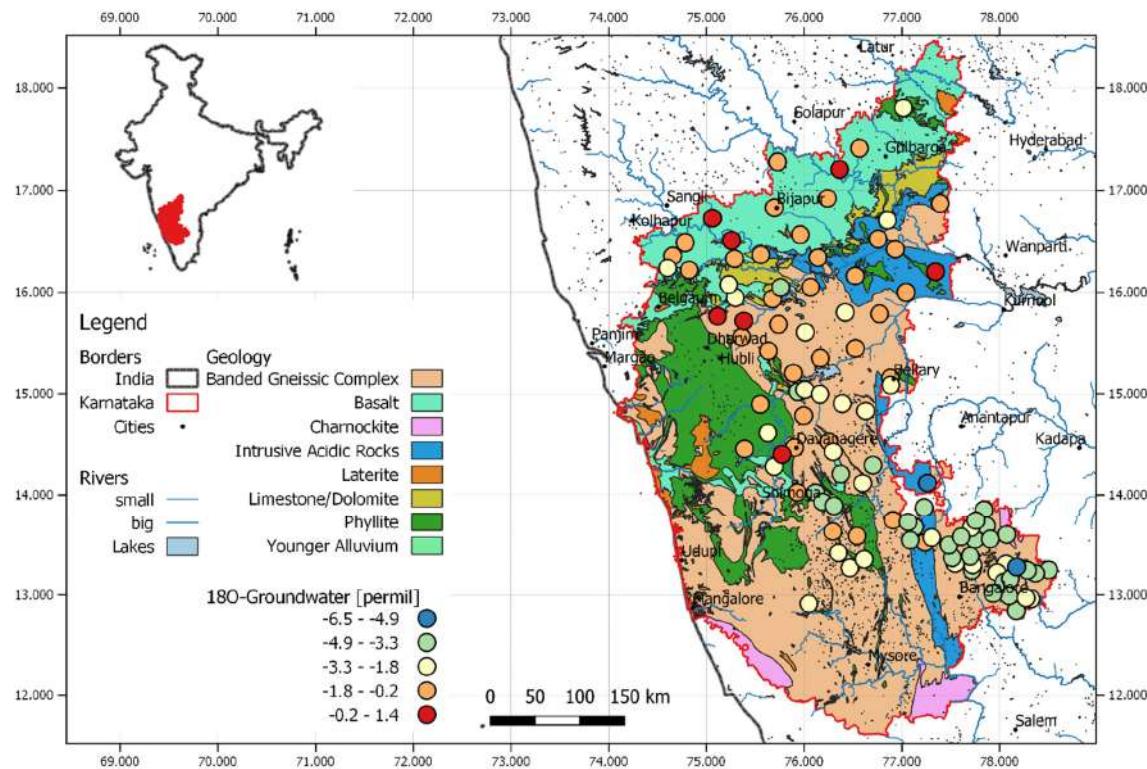


Figure 9: Spatial distribution of groundwater isotope composition for the pilot area.

3.2.1. Spatial distribution of groundwater samples and grouping

The grouping of groundwater samples was based on the geology described in Section 1.2. Samples were available within four different geological groups. A total of 63 samples were taken in the Banded Gneissic Complex (BG01), 18 in the Basalt (BS01) region, 14 in the Intrusive Acidic Rocks (GR02), and 8 samples within the Phyllite (SC02) group.

Aquifer group I: Banded Gneissic Complex (BG01)

The aquifer group I samples are representing the Banded Gneissic Complex BG01. Isotope values range between $-6.5\text{\textperthousand}$ and $0.3\text{\textperthousand}$ for $\delta^{18}\text{O}$ and from $-45.7\text{\textperthousand}$ to $3.1\text{\textperthousand}$ for $\delta^2\text{H}$. Table 1 and Figure 10 give an overview of the statistics and locations of the aquifer group I samples.

Table 1: Statistics of groundwater isotope and in-situ parameters of aquifer group I: Banded Gneissic Complex (BG01)

Banded Gneissic Complex (BG01)	ELEVATION [m amsl]	EC [$\mu\text{S}/\text{cm}$]	pH [-]	$\delta^{18}\text{O}$ [\textperthousand]	$\delta^2\text{H}$ [\textperthousand]	D_{excess} [\textperthousand]
MIN	403.1	150.0	6.7	-6.5	-45.7	-3.8
FIRST 25th	589.6	745.0	7.1	-3.9	-24.6	2.1
MEDIAN	725.7	1070.0	7.2	-3.0	-19.3	5.4
THIRD 75th	829.6	1585.0	7.4	-1.7	-12.9	6.8
MAX	944.9	6200.0	7.8	0.3	3.1	10.7
AVERAGE	711.2	1347.5	7.2	-2.8	-17.5	4.5
STDEV	145.1	1044.6	0.2	1.4	9.9	3.0
COUNT	63	63	63	63	63	63

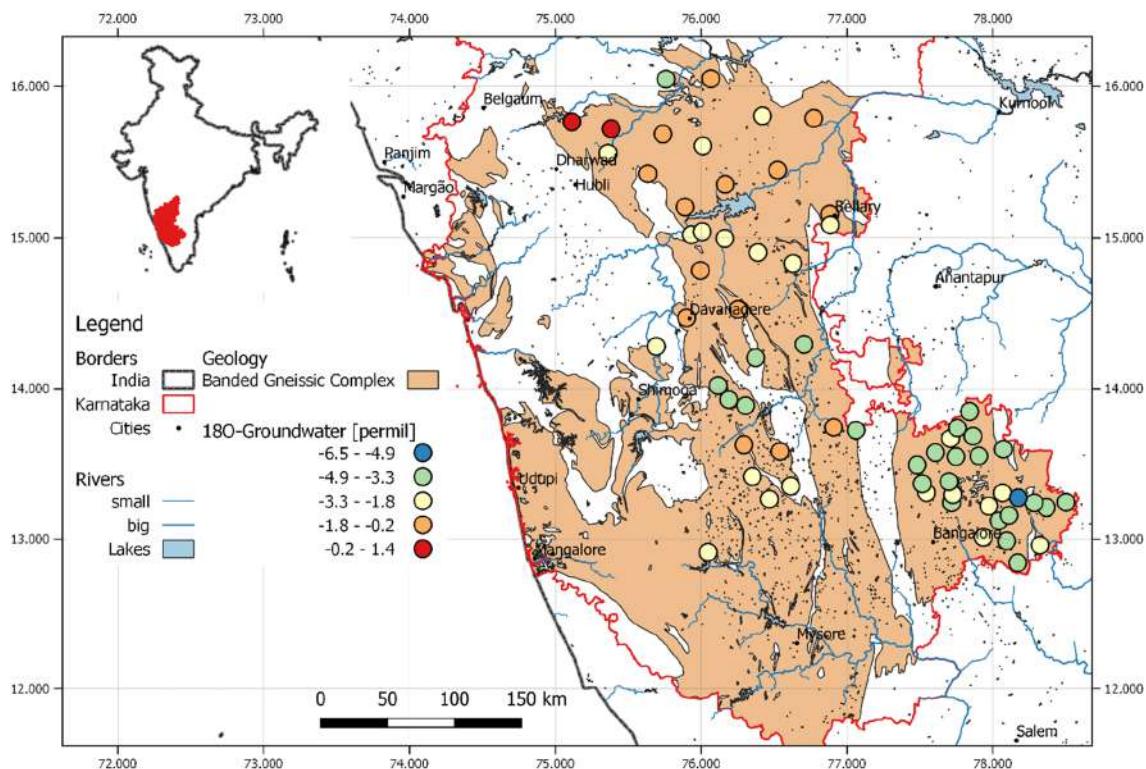


Figure 10: Spatial distribution of groundwater isotope composition for aquifer group I: Banded Gneissic Complex (BG01).

Aquifer group II: Basalt (BS01)

The aquifer group II samples are representing the Basalt aquifer system. Isotope values range between $-3.0\text{\textperthousand}$ and $0.6\text{\textperthousand}$ for $\delta^{18}\text{O}$ and from $-20.1\text{\textperthousand}$ to $2.1\text{\textperthousand}$ for $\delta^2\text{H}$. Table 2 and Figure 11 give an overview of the statistics and locations of the aquifer group II samples.

Table 2: Statistics of groundwater isotope and in-situ parameters of aquifer group II: Basalt (BS01)

Basalt (BS01)	ELEVATION [m amsl]	EC [$\mu\text{S}/\text{cm}$]	pH [-]	$\delta^{18}\text{O}$ [\textperthousand]	$\delta^2\text{H}$ [\textperthousand]	D_{excess} [\textperthousand]
MIN	425.0	640.0	6.9	-3.0	-20.1	-5.6
FIRST 25th	546.0	910.0	7.2	-1.7	-11.1	-2.0
MEDIAN	579.9	990.0	7.3	-1.3	-6.6	2.7
THIRD 75th	643.3	1627.5	7.5	-0.7	-2.8	4.0
MAX	682.7	3200.0	7.8	0.6	2.1	9.8
AVERAGE	579.1	1285.0	7.3	-1.1	-7.3	1.9
STDEV	78.7	661.4	0.2	0.9	6.1	4.5
COUNT	18	18	18	18	18	18

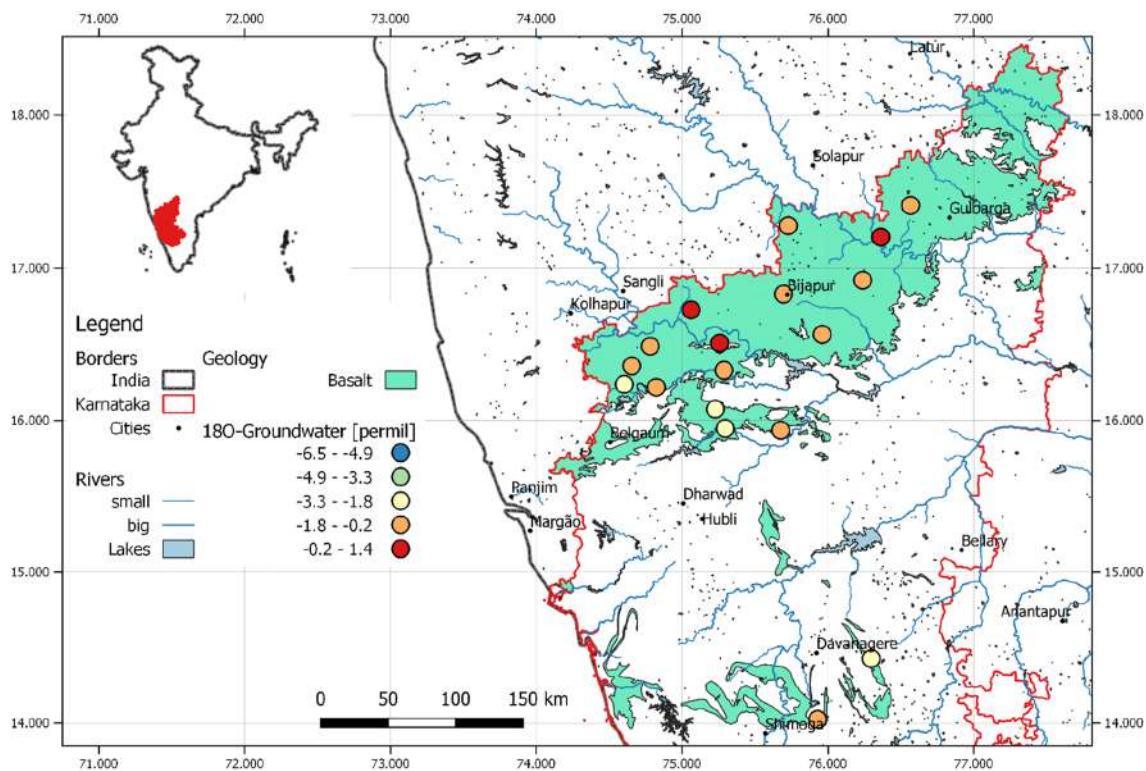


Figure 11: Spatial distribution of groundwater isotope composition for aquifer group II: Basalt (BS01).

Aquifer group III: Intrusive Acidic Rocks (GR02)

The aquifer group III samples are representing the Intrusive Acidic Rocks. Isotope values range between $-4.9\text{\textperthousand}$ and $1.4\text{\textperthousand}$ for $\delta^{18}\text{O}$ and from $-34.0\text{\textperthousand}$ to $5.2\text{\textperthousand}$ for $\delta^2\text{H}$. Table 3 and Figure 12 give an overview of the statistics and locations of the aquifer group III samples.

Table 3: Statistics of groundwater isotope and in-situ parameters of aquifer group III: Intrusive Acidic Rocks (GR02)

Intrusive Acidic Rocks (GR02)	ELEVATION [m amsl]	EC [$\mu\text{S}/\text{cm}$]	pH [-]	$\delta^{18}\text{O}$ [\textperthousand]	$\delta^2\text{H}$ [\textperthousand]	D_{excess} [\textperthousand]
MIN	388.9	330.0	6.8	-4.9	-34.0	-5.9
FIRST 25th	437.9	1060.0	6.9	-3.4	-24.3	2.1
MEDIAN	573.0	1275.0	7.1	-1.6	-9.9	2.8
THIRD 75th	709.3	2097.5	7.3	-0.8	-4.5	4.3
MAX	847.7	6200.0	7.8	1.4	5.2	7.6
AVERAGE	582.2	1761.4	7.1	-2.0	-13.4	2.7
STDEV	155.7	1476.3	0.3	1.8	11.9	3.2
COUNT	14	14	14	14	14	14

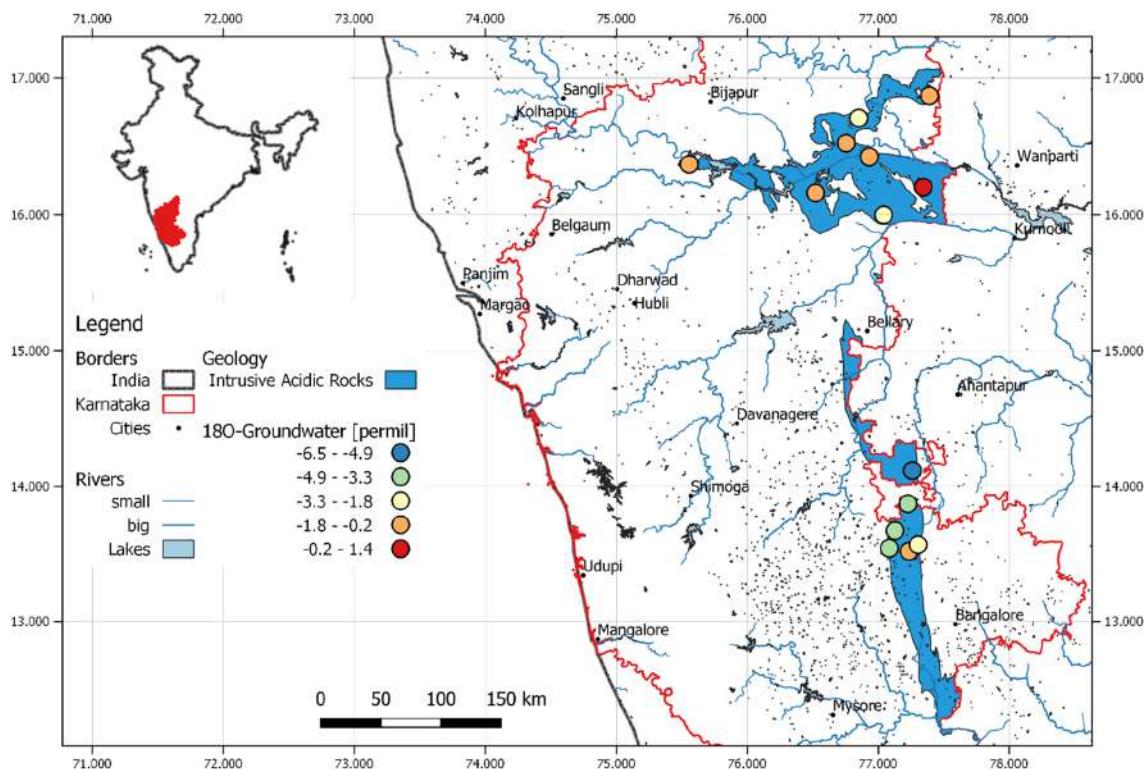


Figure 12: Spatial distribution of groundwater isotope composition for aquifer group III: Intrusive Acidic Rocks (GR02).

Aquifer group IV: Phyllite (SC02)

The aquifer group IV samples are representing the Phyllites. Isotope values range between -2.7‰ and -0.1‰ for $\delta^{18}\text{O}$ and from -23.1‰ to 0.8‰ for $\delta^2\text{H}$. Table 4 and Figure 13 give an overview of the statistics and locations of the aquifer group IV samples.

Table 4: Statistics of groundwater isotope and in-situ parameters of aquifer group IV: Phyllite (SC02)

Phyllite (SC02)	ELEVATION [m amsl]	EC [$\mu\text{S}/\text{cm}$]	pH [-]	$\delta^{18}\text{O}$ [‰]	$\delta^2\text{H}$ [‰]	D_{excess} [‰]
MIN	528.2	390.0	6.7	-2.7	-23.1	-3.7
FIRST 25th	581.2	795.0	7.0	-2.3	-16.3	1.0
MEDIAN	605.0	1215.0	7.2	-1.8	-12.2	1.9
THIRD 75th	644.1	1790.0	7.4	-1.5	-10.6	3.2
MAX	840.3	3200.0	7.8	-0.1	0.8	4.2
AVERAGE	628.5	1400.0	7.2	-1.7	-12.5	1.5
STDEV	94.8	882.1	0.4	0.8	7.0	2.5
COUNT	8	8	8	8	8	8

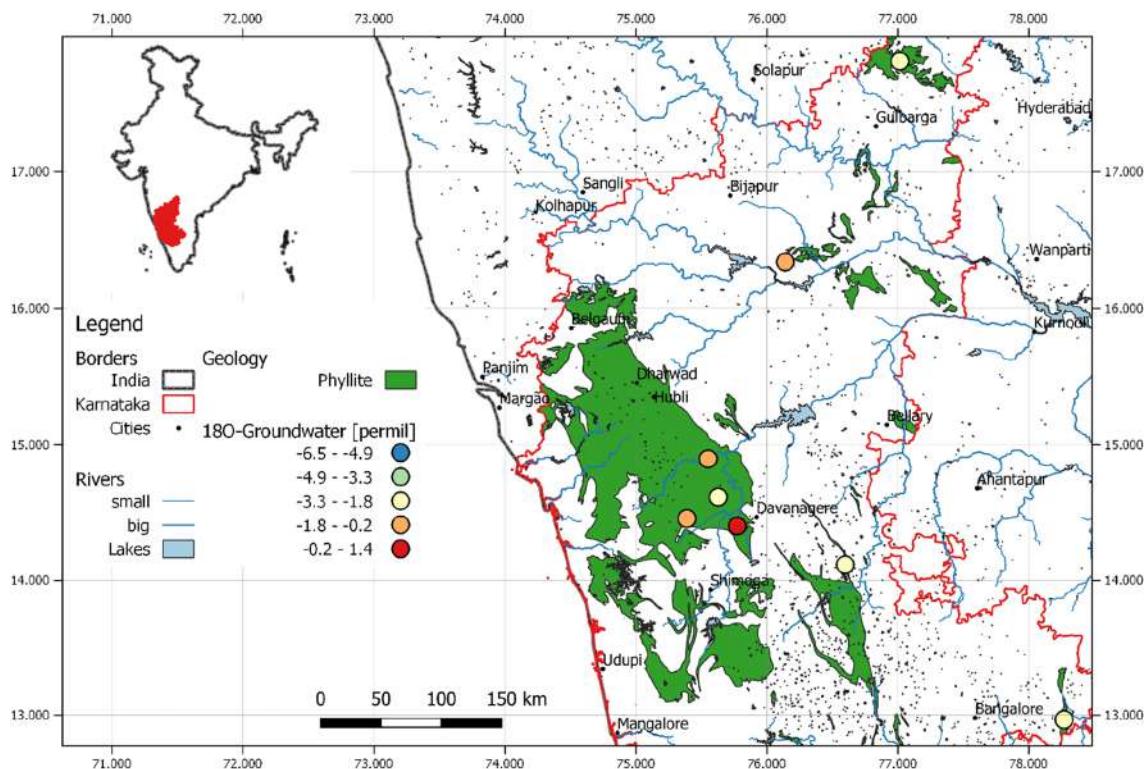


Figure 13: Spatial distribution of groundwater isotope composition for aquifer group IV: Phyllite (SC02).

3.2.2. Relationship between groundwater samples and MWLs

Most of the groundwater samples plot along or slightly below the Meteoric Water Lines and imply a groundwater recharge from local meteoric waters which are not strongly affected by evaporation effects (see Figure 14). In case values plot below the Meteoric Water Line this could be an indication of evaporation effects and therefore fractionation prior to groundwater recharge. A detailed comparison between isotope values of groundwater samples and MWLs based on hydrological catchments is presented in APPENDIX D. However some samples show rather low deuterium excess (D_{excess}) values, with 13 samples even having negative D_{excess} values (see Figure 15). Those samples are clearly affected by evaporative effects, which can be linked in most cases to the location of the sampling points in mixed and black soils and their vicinity to lakes or other surface water bodies.

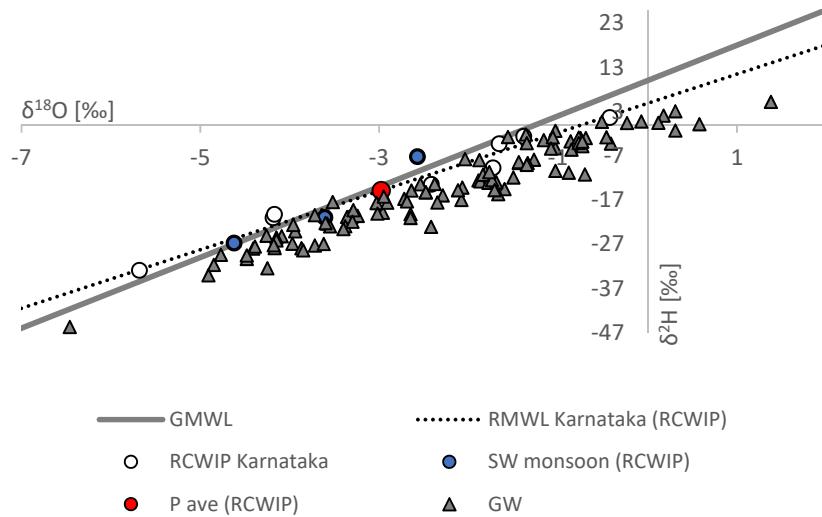


Figure 14: Groundwater isotope composition in comparison to GMWL and RMWL.

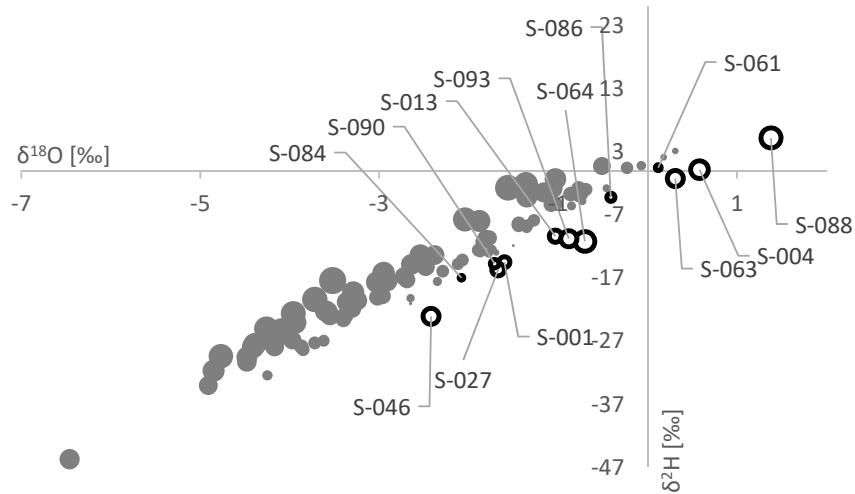


Figure 15: Deuterium excess values in groundwater samples. Open circles indicate negative deuterium excess values.

Other than that no distinct groups within the groundwater samples could be identified with significant differences in their isotopic compositions. In order to gain further insights in the dataset the samples were grouped according to the geological units. The four aquifer groups, defined in Section 3.2.1, were used to classify and group the samples in a first assessment step. Figure 16 gives an overview of the different aquifer groups and their relation to the MWLs. The average values of the four aquifer groups show significant differences (ANOVA: $F_{3,99} = 7.25$; $p < 0.05$). Generally samples from the Banded Gneissic Complex and Intrusive Acidic Rocks are isotopically lighter than the samples from the Basalt and Phyllite areas.

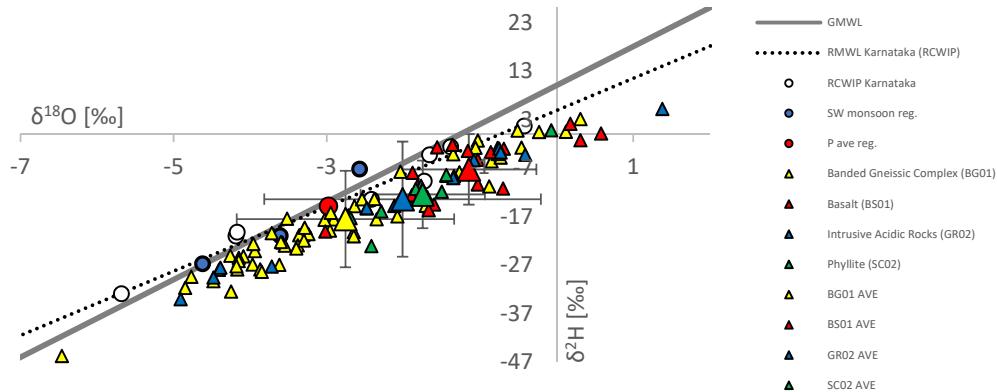


Figure 16: Groundwater isotope composition for different aquifer groups.

In a second assessment step the samples were grouped according to the soil classes described in Section 1.2. The samples were classified in the following four groups: Black soils (deep, medium, and shallow Black soils), Red soils (loamy and sandy Red soils), Mixed soils (Mixed red and Black soils), and Laterite soils (Laterite gravelly and Laterite soils). Also for the soil groups significant differences (ANOVA: $F_{3,99} = 24.33$; $p < 0.05$) of the average isotope values were identified with heavier values for the Black soil and Mixed soil groups and lighter values for the Red soils and Laterites (see Figure 17).

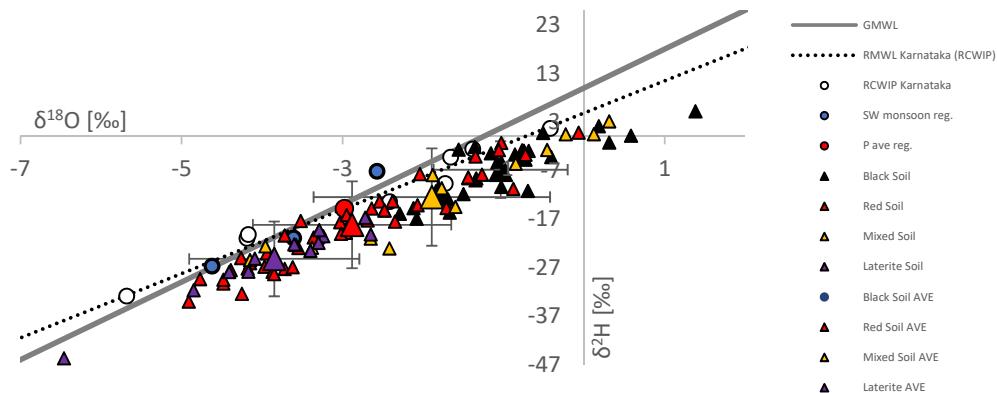


Figure 17: Groundwater isotope composition for different soil groups.

3.2.3. Relationship between isotope values and elevation

Elevation is typically correlated with the values of stable isotopes in precipitation and therefore groundwater recharge. The elevation effect, or altitude effect, results in an increased depletion of isotopes with increasing elevation. Stable isotope values for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ against elevation are plotted in Figure 18. The groundwater samples show a moderate linear correlation within the pilot area with R^2 values of 0.4 and 0.35 for $\delta^{18}\text{O}$ and $\delta^2\text{H}$, respectively. The isotopic lapse rates for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ are $-0.6\text{‰}/100\text{m}$ and $-4.1\text{‰}/100\text{m}$, respectively. However the relationship between D_{excess} and elevation does not show a strong correlation (see Figure 19). This is an indication that groundwater recharge in the area is not significantly influenced by a strong evaporation effect at lower elevations (see Figure 19).

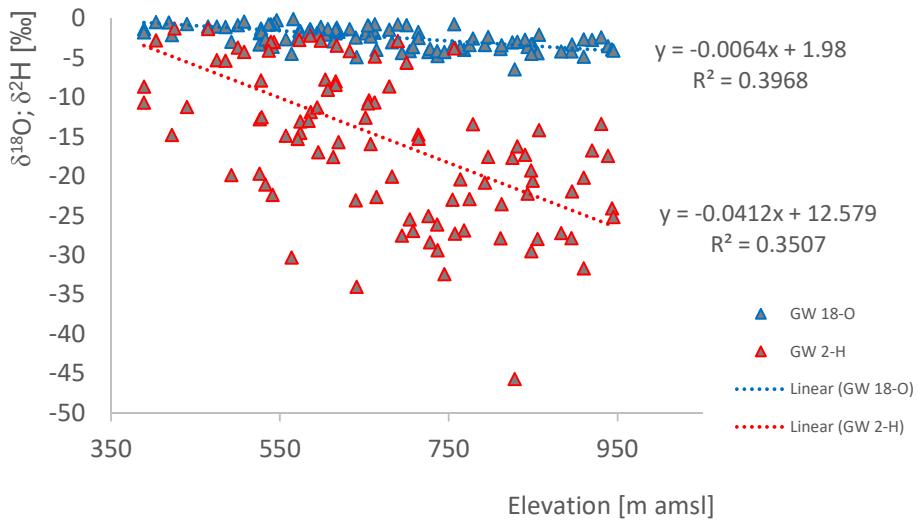


Figure 18: Correlation between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of groundwater samples against elevation.

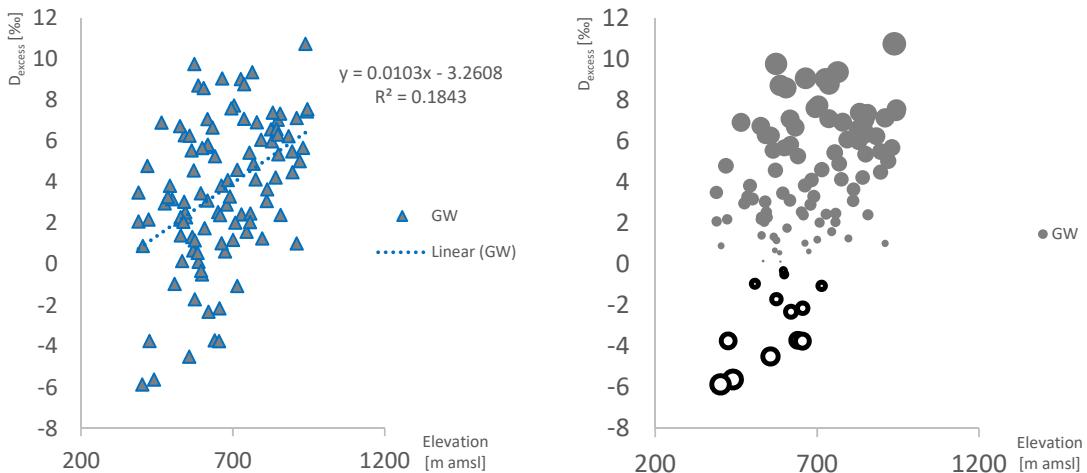


Figure 19: Correlation between $\delta^{18}\text{O}$ and D_{excess} of groundwater samples (left) and D_{excess} of groundwater samples (right); open circles indicate negative deuterium excess values.

3.2.4. Relationship between isotope values and water table depth

The relationship between isotope values of groundwater and water table depth can give insights in groundwater which is affected by evaporative effects. A shallow water table close to the surface can lead to enrichment of heavy isotopes due to fractionation processes during evaporation. Figure 20 and Figure 21 show the correlations between the stable isotopes and the D_{excess} with the tapped zone in metres below ground level (mbgl). From the figures it can be seen that there are only weak correlations present either between the stable isotope values or between D_{excess} and the tapped zone, and no clear conclusions can be drawn. Also there is no pattern visible by using the different aquifer or soil groups.

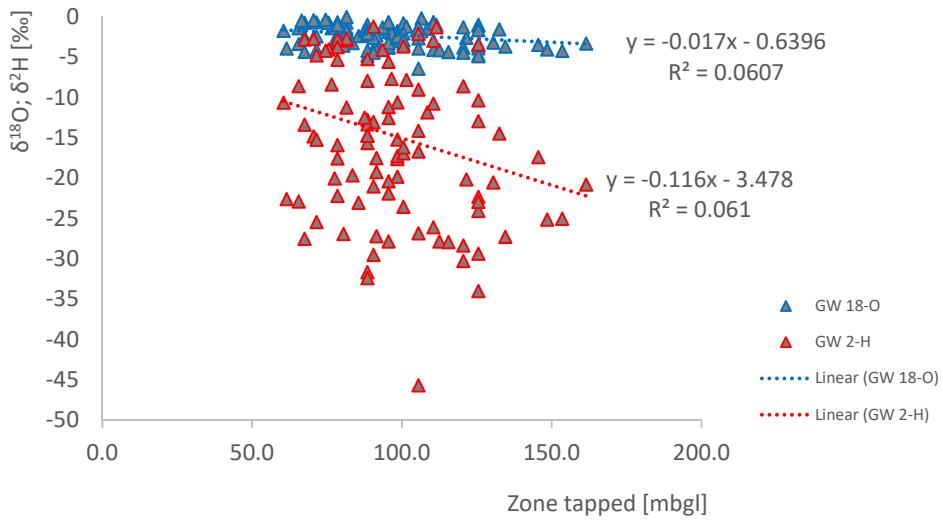


Figure 20: Correlation between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ of groundwater samples against tapped zone.

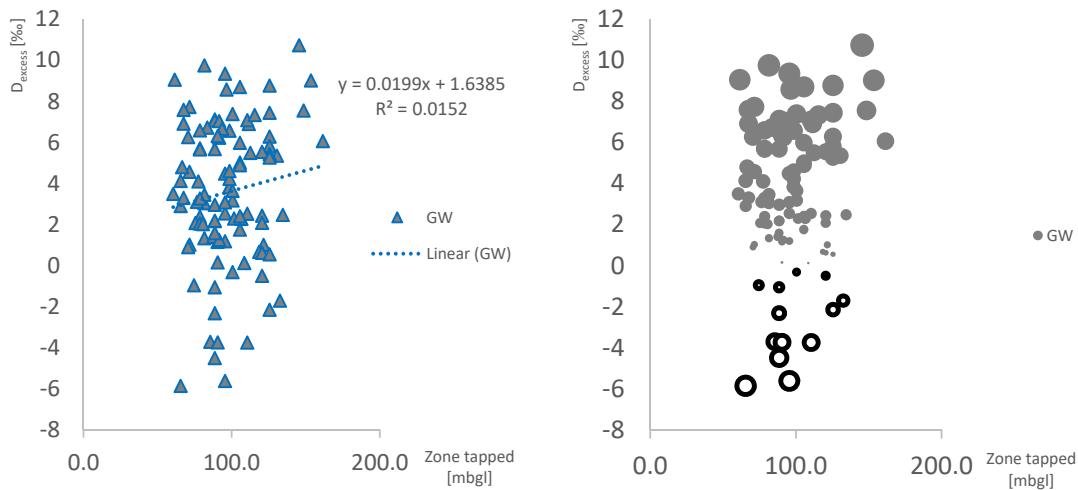


Figure 21: Correlation between D_{excess} of groundwater samples against tapped zone (left) and D_{excess} of groundwater samples (right); open circles indicate negative deuterium excess values.

3.2.5. Relationship between isotope values and water quality parameters

Basic water quality parameters were provided by the CGWB together with the isotope dataset. Some of the water quality values could also be useful in combination with stable water isotopes for the analysis. Only the electrical conductivity EC [$\mu\text{S}/\text{cm}$] values could be used for this analysis due to the lack of other water quality values. Electrical conductivity values for the groundwater samples show a high variability and range between 150 to 6200 $\mu\text{S}/\text{cm}$. The combination of isotopic data with water quality parameters like EC helps to better understand the groundwater recharge processes. Generally an increased EC value could be an indication for increased evaporation effects. Figure 22 and Figure 23 show the relationships between $\delta^{18}\text{O}$ and electrical conductivity.

A general trend towards higher EC values with enriched isotopic values is visible. However no significant correlation could be found between these parameters, because it seems that these relationship is additionally influenced by sampling location, geological and human effects. High EC values $>3000 \mu\text{S}/\text{cm}$ can be linked to locations of the sampling points close or within cities and towns. Unfortunately chemical parameters are missing so that it is not possible to confirm a contamination influence of these samples.

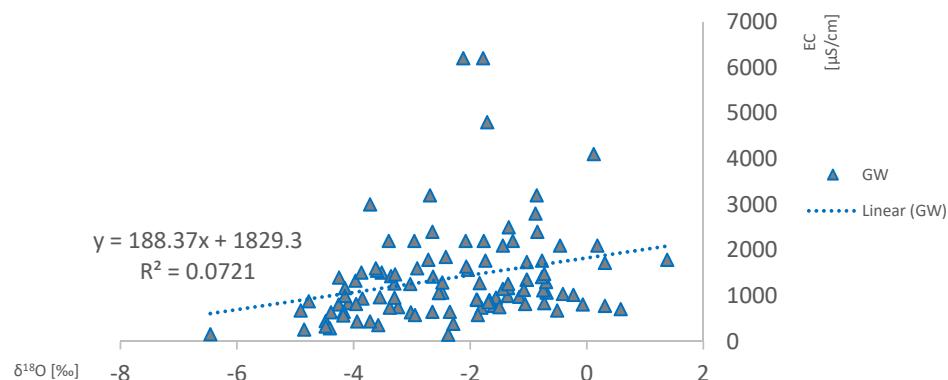


Figure 22: Correlation between $\delta^{18}\text{O}$ and electrical conductivity (EC; $\mu\text{S}/\text{cm}$) of groundwater samples.

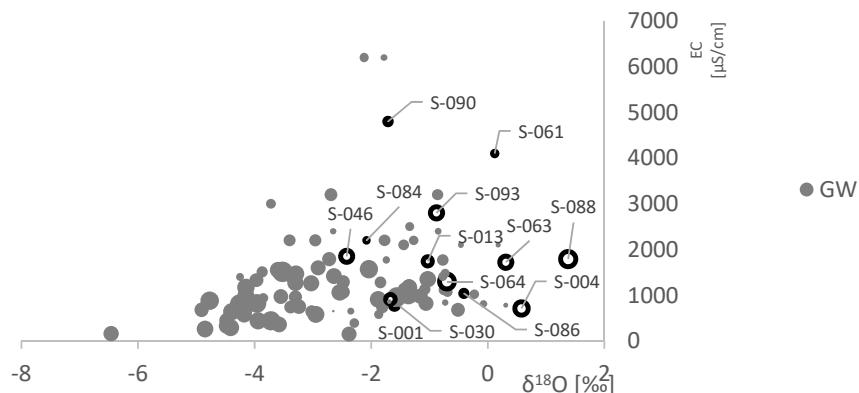


Figure 23: Correlation between $\delta^{18}\text{O}$ and electrical conductivity (EC; $\mu\text{S}/\text{cm}$) of groundwater samples. Open circles indicate negative deuterium excess values.

Conclusions

The presented results using stable isotope values of groundwater demonstrated the potential of this method for the assessment and characterization of groundwater aquifers. The spatial analysis of stable isotope signatures in groundwater helped to identify mechanisms of groundwater recharge. From the analysis the importance of groundwater recharge from local precipitation sources as well as the influence from underlying soil and geological materials and interactions with surface water bodies could be shown.

Local and regional meteoric water lines were used for the Karnataka pilot area to determine the precipitation input values. Global Network of Isotopes in Precipitation (GNIP) datasets enabled to characterize the temporal pattern of groundwater recharge being dominant in the monsoon season between May and October. Regionalized cluster-based water isotope predictions (RCWIP) were used for a regional assessment of isotopic values in precipitation based on catchment level. Knowing the spatio-temporal variability of precipitation and therefore groundwater recharge is a requirement for the assessment of groundwater resources.

Almost all groundwater samples plot along the MWLs of the pilot area. Therefore it can be concluded that precipitation, except for a few samples, is not affected by evaporation processes prior to the groundwater recharge. Moderate correlations between isotope characteristics and the elevation of the sampling locations could be found. However the relationship between D_{excess} and elevation didn't show a strong correlation and indicated that groundwater recharge in the area is not significantly influenced by strong evaporation effects. Almost all groundwater samples show isotopic values close to the local precipitation input during the monsoon season. Stations which are deviating from this pattern are located in the northern part of Karnataka, mainly in catchments 453667, 453650, and 453664. These areas are dominated by mixed and black soils which could lead to evaporative enrichment prior to infiltration and groundwater recharge due to reduced infiltration capacity of those soil materials.

Thirteen samples were found with very low and even negative D_{excess} values, whereof ten are located in the norther part (S-001 Badami, S-004 Jamkhandi, S-013 Belakud, S-027 Basavana Bagewadi, S-061 Nargund, S-063 Afzalpur, S-064 Battarga, S-084 Yelbarga, S-086 Lingsugur, and S-088 Raichur) and three (S-046 Vaddikere, S-090 Huliyar, and S-093 Sira) in the central part of Karnataka. Most of the locations are lying within the mixed and black soils and /or are close to lakes or other surface water bodies which could lead to evaporative enrichment prior to infiltration and groundwater recharge. Several samples (S-031 Sindgi, S-080 Oorgeempet, S-061 Nargund, S-090 Huliyar, S-101 Shahpur, and S-058 Navalgund) also show higher electrical conductivity values with more than 3000 $\mu\text{S}/\text{cm}$. The location of these sampling points are mainly within or close to cities or towns and could be influenced by contamination. Unfortunately additional chemical parameters are missing so that it is not possible to confirm a contamination influence.

Overall the results of the isotope analysis indicate a dominant direct recharge of local precipitation input, mainly during the monsoon season. Especially the analysis using specific catchment based isotope values of precipitation displayed and proved this mechanism. The grouping of groundwater samples based on the underlying soil and geological materials showed that samples in the Black soil and Basalt area tend to have more enriched isotopic values compared to the Laterite and Banded Gneissic Complex regions. However these effects are overlain by influences of the elevation effect.

[Shortcoming and next steps](#)

In total 103 groundwater samples were analysed for their stable water isotope composition and in-situ physio-chemical parameters. It is recommended to include basic water quality parameters like e.g. chloride or nitrate concentrations in the analysis. This would help to better characterize the hydro-chemical characteristics of the sampling location and possible influences of contaminations.

As an additional investigation method it is recommended to determine groundwater ages using radioactive isotopes. This could be helpful for the differentiation between recently recharged groundwater and old groundwater which has been recharged under different climate conditions.

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APPENDIX A

Data provided by the CGWB and additional data collected: Pilot area 2 Karnataka

DATA SCOPE	DATA TYPE	AREA	SOURCE	SOURCE DETAIL	FILE NAME	FILE TYPE	SAMPLE NO.	MAIN CONTENT	CRS	REMARKS
Precipitation	Point	Karnataka	IAEA	GNIP	wiser_gnip-monthly-Banglore	.xls	24	Lat, Long, Alt, Date, O18, H2, H3, P, Ta	-	Monthly isotope data in precipitation
Precipitation	Point	Karnataka	IAEA	GNIP	wiser_gnip-monthly-Belgaum	.xls	36	Lat, Long, Alt, Date, O18, H2, H3, P, Ta	-	Monthly isotope data in precipitation
Precipitation	Point	Karnataka	IAEA	GNIP	wiser_gnip-monthly-Hyderabad	.xls	52	Lat, Long, Alt, Date, O18, H2, H3, P, Ta	-	Monthly isotope data in precipitation
Precipitation	Point	Karnataka	IAEA	GNIP	Wiser_Statistics_GNIP-Monthly_INDIA_BANGLORE	.xls	-	18-O and 2H data; monthly, annual, long term, LMWL	-	Statistics of isotope data in precipitation
Precipitation	Point	Karnataka	IAEA	GNIP	Wiser_Statistics_GNIP-Monthly_INDIA_BELGAUM	.xls	-	18-O and 2H data; monthly, annual, long term, LMWL	-	Statistics of isotope data in precipitation
Precipitation	Point	Karnataka	IAEA	GNIP	Wiser_Statistics_GNIP-Monthly_INDIA_HYDERABAD	.xls	-	18-O and 2H data; monthly, annual, long term, LMWL	-	Statistics of isotope data in precipitation
Precipitation	Raster	All	IAEA	RCWIP	Regionalized Cluster-Based Water Isotope Prediction	.tif	-	gridded monthly and annual 18-O and 2H data	-	http://www.iaea.org/water
Precipitation	-	Karnataka	IEWP-P4/CGWB	CGWB	Rainfall data karnatka	.xls	176	Monthly and annual rainfall 2015	-	Monthly and annual rainfall 2015
Groundwater	Point	Karnataka	IEWP-P4/CGWB	NAQUIM	Karnataka_isotope_data,	.xls	103	Sample Code, District, Taluk, Location, Elevation (m amsl), Depth (m bgl), Zone Tapped (m bgl), Ec, pH, 618O, δD, AQUIFERS	-	Stable isotopes and in-situ EC and pH
Basin	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	basin_boundary_region	.shp	5	G_WATERSHE, WSD	EPSG:3857 - WGS 84	-
River	Line	Karnataka	IEWP-P4/CGWB	CGWB	Drainage_polyline	.shp	94	RIVER_NAME	EPSG:3857 - WGS 84	-
River	Point	Karnataka	IEWP-P4/CGWB	CGWB	Drainage_text	.shp	4	River Names	EPSG:3857 - WGS 84	-
Yield	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Hr_high_yield_brochure_Hatching_region	.shp	56	DISCHARGE	EPSG:3857 - WGS 84	-
Yield	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	HR_low_yield_brochure_Hatching_region	.shp	81	DISCHARGE	EPSG:3857 - WGS 84	-
Yield	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	HR_medium_yield_broucher_Hatching_region	.shp	25	DISCHARGE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_Alluvium_region	.shp	1	AQUI_CODE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_BASALT_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_bgc_rectangle	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_bgc_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_charnockite_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Climate	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_finalagroclimatezone_region	.shp	11	THE_ZONE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_gneiss_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_granite_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_laterite_region	.shp	1	AQUI_CODE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_limestone_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-

.xls = excel table; .shp = shape file; .pdf = Portable Document Format; Lat = Latitude [geogr. coordinates]; Long = Longitude [geogr. coordinates]; Alt = Altitude [m amsl]; O18 = Oxygen-18 [%]; H2 = Deuterium [%]; H3 = Tritium [TU]; P = Precipitation [mm]; Ta = Air temperature [°C]; { } = Laboratory results

DATA SCOPE	DATA TYPE	AREA	SOURCE	SOURCE DETAIL	FILE NAME	FILE TYPE	SAMPLE NO.	MAIN CONTENT	CRS	REMARKS
Climate	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_finalagroclimatezone_region	.shp	11	THE_ZONE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_gneiss_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_granite_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_laterite_region	.shp	1	AQUI_CODE	EPSG:3857 - WGS 84	-
Geology	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_limestone_region	.shp	1	AQUI_CODE, ROCKTYPE	EPSG:3857 - WGS 84	-
Administration	Line	Karnataka	IEWP-P4/CGWB	CGWB	Kar_New_Dist_Bound_polyline	.shp	1	STATE, DIST, DISD	EPSG:3857 - WGS 84	-
Administration	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Kar_New_Dist_Bound_region	.shp	19	STATE, DIST, DISD	EPSG:3857 - WGS 84	-
Precipitation	Line	Karnataka	IEWP-P4/CGWB	CGWB	Rainfall_polyline	.shp	16	IN_MM	EPSG:3857 - WGS 84	-
Reservoir	Line	Karnataka	IEWP-P4/CGWB	CGWB	Reservoir_polyline	.shp	1	ID	EPSG:3857 - WGS 84	-
Reservoir	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	Reservoir_region	.shp	6	ID	EPSG:3857 - WGS 84	-
Soil	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	soil_map_region	.shp	65	SOIL_TYPE, SOILUNIT	EPSG:3857 - WGS 84	-
Administration	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	karnataka-dist-bnd	.shp	30	STATE, DIST, DISD	EPSG:3857 - WGS 84	-
Isotope	Point	Karnataka	IEWP-P4/CGWB	CGWB	kar-isotope-samples	.shp	103	Information from datafile and spatial location	EPSG:3857 - WGS 84	-
Water table	Polygon	Karnataka	IEWP-P4/CGWB	CGWB	wte_contour_region	.shp	29	LOWER, UPPER	EPSG:3857 - WGS 84	-
Digital Elevation Model	Raster	All	CGIAR	http://srtm.csi.cgiar.org	DEM_IN_merged_clipped	.tif	-	ELEVATION	EPSG:3857 - WGS 84	-
Borders	Polygon	All	themeticmapping	http://themeticmapping.org	TM_WORLD_BORDERS-0.3	.shp	-	COUNTRIES	EPSG:3857 - WGS 84	-
River	Line	All	HydroSheds	https://hydrosheds.org/	as_riv_15s_IN	.shp	-	RIVERS	EPSG:3857 - WGS 84	-
Lake	Polygon	All	HydroSheds	https://hydrosheds.org/	HydroLAKES_polys_v10_clipped	.shp	-	LAKES	EPSG:3857 - WGS 84	-
Basin	Polygon	All	HydroSheds	https://hydrosheds.org/	hybas_as_lev06_v01c	.shp	-	BASIN	EPSG:3857 - WGS 84	-
Places	Point	All	mapcruzin	www.mapcruzin.com	places	.shp	-	PLACES	EPSG:3857 - WGS 84	-
Report	-	Karnataka	IEWP-P4/CGWB	CGWB	Report-on-Isotope-data-interpretation-Karnataka	.doc	1	document	-	-

.xls = excel table; .shp = shape file; .pdf = Portable Document Format; Lat = Latitude [geogr. coordinates]; Long = Longitude [geogr. coordinates]; Alt = Altitude [m amsl]; O18 = Oxygen-18 [%]; H2 = Deuterium [%]; H3 = Tritium [TU]; P = Precipitation [mm]; Ta = Air temperature [°C]; { } = Laboratory results

APPENDIX B

Isotope data of groundwater samples: Pilot area 2 Karnataka

NO	DISTRICT	TEHSIL/TALUK	LOCATION	DEPTH	ZONE TAPPED	LATITUDE	LONGITUDE	ALTITUDE	EC	pH	$\delta^{18}\text{O}$	δD	DE	AQUIFERS	SOILS	ZONE TAPPED	GW_LEVEL LOWER	GW_LEVEL UPPER	GW_LEVEL AVERAGE
[-]	[-]	[-]	[-]	[m]	[-]	[DDEG]	[DDEG]	[m amsl]	[$\mu\text{S}/\text{cm}$]	[-]	[‰]	[‰]	[‰]	[-]	[-]	[-]	[m amsl]	[m amsl]	[m amsl]
S-001	Bagalkot	Badami	Badami	Upto 145	132-133	15.9354444	75.6756111	574.1	780	7.6	-1.6	-14.51	-1.71	Basalt (BS01)	Mixed Red and Black Soils	132.5	531.8	581.8	556.8
S-002	Bagalkot	Badami	Guledugudda Sunnety	Upto 145	125-126	16.0469722	75.759	542.2	360	7.4	-3.58	-22.36	6.28	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	125.5	481.8	531.8	506.8
S-003	Bagalkot	Hungund	Hungund	Upto 145	106-107	16.0495833	76.0653889	546	1020	7.8	-0.23	0.44	2.28	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	106.5	531.8	581.8	556.8
S-004	Bagalkot	Jamkhandi	Jamkhandi	Upto 145	88-89	16.5091111	75.2570278	555.7	710	7.8	0.58	0.14	-4.5	Basalt (BS01)	Medium Black Soils	88.5	531.8	581.8	556.8
S-005	Bagalkot	Mudhol	Mudhola	Upto 145	110-111	16.3308333	75.2865278	542.8	1070	7.5	-0.69	-2.99	2.53	Basalt (BS01)	Deep Black Soils	110.5	531.8	581.8	556.8
S-006	Bagalkot	Bilgi	Teggi	Upto 145	81-82	16.3693333	75.5562778	539.2	1120	7.3	-0.75	-2.96	3.04	Intrusive Acidic Rocks (GR02)	Medium Black Soils	81.5	531.8	581.8	556.8
S-007	Bangalore Rural	Devanahalli	Devanahalli	Upto 160	88-89	13.2428056	77.7178333	909.7	260	7.1	-4.85	-31.68	7.12	Banded Gneissic Complex (BG01)	Laterite Gravelly Soils	88.5	881.8	931.8	906.8
S-008	Bangalore Rural	Devanahalli	Avathi	Upto 160	105-106	13.2960278	77.7251944	919.5	1790	7	-2.72	-16.74	5.02	Banded Gneissic Complex (BG01)	Laterite Gravelly Soils	105.5	881.8	931.8	906.8
S-009	Bangalore Rural	Doddballapur	Doddballapur	Upto 160	121-122	13.309199	77.544697	909.7	2400	7	-2.65	-20.19	1.01	Banded Gneissic Complex (BG01)	Laterite Soils	121.5	881.8	931.8	906.8
S-010	Bangalore Rural	Doddballapur	Gollahalli	Upto 160	145-146	13.368797	77.515644	938.4	1510	7.1	-3.52	-17.43	10.73	Banded Gneissic Complex (BG01)	Red Loamy Soils	145.5	881.8	931.8	906.8
S-011	Belgaum	Athni	Athni	Upto 130	118-119	16.7272222	75.0608333	569	2100	7.2	0.18	2.11	0.67	Basalt (BS01)	Medium Black Soils	118.5	531.8	581.8	556.8
S-012	Belgaum	Saundatti	Saundatti	Upto 130	120-121	15.7655556	75.1130556	674	780	7.1	0.31	3.1	0.62	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	120.5	631.8	681.8	656.8
S-013	Belgaum	Chikodi	Belakud	Upto 130	125-126	16.358889	74.6541666	655.3	1740	7.3	-1.03	-10.39	-2.15	Basalt (BS01)	Deep Black Soils	125.5	631.8	681.8	656.8
S-014	Belgaum	Gokak	Arabhavi	Upto 130	81-82	16.2186111	74.8227778	572.8	960	7.4	-1.56	-2.73	9.75	Basalt (BS01)	Medium Black Soils	81.5	531.8	581.8	556.8
S-015	Belgaum	Hukkeri	Hukkeri	Upto 130	98-99	16.2380167	74.602425	661.9	740	7.3	-1.81	-10.65	3.83	Basalt (BS01)	Medium Black Soils	98.5	631.8	681.8	656.8
S-016	Belgaum	Ramdurg	Ramdurg	Upto 130	88-89	15.94794	75.29506	616	910	7.6	-1.88	-7.97	7.07	Basalt (BS01)	Mixed Red and Black Soils	88.5	581.8	631.8	606.8
S-017	Belgaum	Ramdurg	Salahalli	Upto 130	95-96	16.0747222	75.2272222	651.3	920	7.4	-1.89	-12.58	2.54	Basalt (BS01)	Mixed Red and Black Soils	95.5	631.8	681.8	656.8
S-018	Belgaum	Raybag	Raybag	Upto 130	105-106	16.4880556	74.7808333	585.7	1000	6.9	-1.36	-2.18	8.7	Basalt (BS01)	Deep Black Soils	105.5	531.8	581.8	556.8
S-019	Bellary	Bellary	Allipuram	Upto 120	111-112	15.1573611	76.8817056	464.8	1350	7.1	-1.03	-1.34	6.9	Banded Gneissic Complex (BG01)	Red Sandy Soils	111.5	431.8	481.8	456.8
S-020	Bellary	Bellary	Halakundi	Upto 120	98-99	15.0856056	76.8849222	492.4	2200	7.4	-2.96	-19.86	3.82	Banded Gneissic Complex (BG01)	Red Sandy Soils	98.5	481.8	531.8	506.8
S-021	Bellary	Hadgallu	Hadahalli	Upto 120	83-84	15.0206278	75.9324444	525.7	1270	7	-3.3	-19.68	6.72	Banded Gneissic Complex (BG01)	Red Loamy Soils	83.5	481.8	531.8	506.8
S-022	Bellary	Hadgallu	Holgundi	Upto 120	70-71	15.0406194	76.0066111	556.9	1420	7.1	-2.64	-14.86	6.26	Banded Gneissic Complex (BG01)	Red Loamy Soils	70.5	531.8	581.8	556.8
S-023	Bellary	Hagaribommanahalli	Ulavathi	Upto 120	88-89	14.9961944	76.1614778	526.2	580	7.1	-1.87	-12.79	2.17	Banded Gneissic Complex (BG01)	Red Sandy Soils	88.5	481.8	531.8	506.8
S-024	Bellary	Hagaribommanahalli	Gudekote	Upto 120	78-79	14.8302278	76.6285056	613.2	1600	7.2	-2.91	-17.57	5.71	Banded Gneissic Complex (BG01)	Red Sandy Soils	78.5	581.8	631.8	606.8
S-025	Bellary	Kudligi	Kudligi	Upto 120	96-97	14.9034583	76.3892417	603.7	1570	7.4	-2.04	-7.74	8.58	Banded Gneissic Complex (BG01)	Red Sandy Soils	96.5	581.8	631.8	606.8
S-026	Bidar	Basavakalyan	Islampur	Upto 110	78-79	17.8038611	77.0157222	657.4	390	7.1	-2.29	-15.93	2.39	Phyllite (SC02)	Medium Black Soils	78.5	631.8	681.8	656.8
S-027	Bijapur	Basavana Bagewadi	Basavana Bagewadi	Upto 130	88-89	16.5654444	75.9597778	619.3	910	7.3	-1.67	-15.68	-2.32	Basalt (BS01)	Medium Black Soils	88.5	581.8	631.8	606.8
S-028	Bijapur	Bijapur	Bijapur	Upto 130	125-126	16.8300833	75.6948333	617.3	980	7.3	-1.16	-3.46	5.82	Basalt (BS01)	Shallow Black Soils	125.5	581.8	631.8	606.8
S-029	Bijapur	Indi	Bardol	Upto 130	88-89	17.27775	75.7279167	475.2	1350	7.5	-1.03	-5.28	2.96	Basalt (BS01)	Shallow Black Soils	88.5	431.8	481.8	456.8
S-030	Bijapur	Muddebihal	Muddebihal	Upto 130	108-109	16.3411944	76.1405278	586.4	750	7.4	-1.5	-11.88	0.12	Phyllite (SC02)	Deep Black Soils	108.5	581.8	631.8	606.8

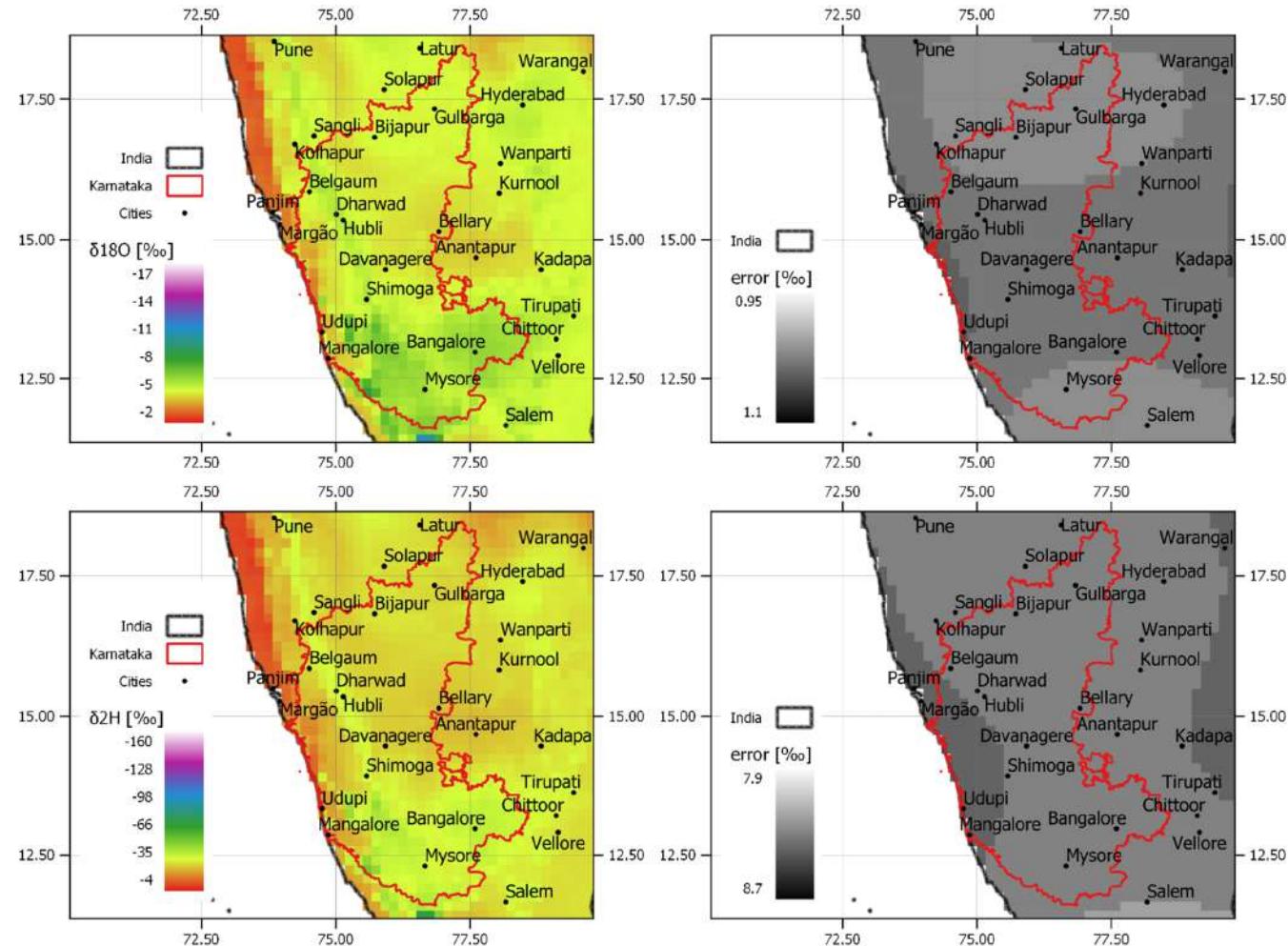
NO	DISTRICT	TEHSIL/TALUK	LOCATION	DEPTH	ZONE TAPPED	LATITUDE	LONGITUDE	ALTITUDE	EC	pH	δ18O	δD	DE	AQUIFERS	SOILS	ZONE TAPPED	GW_LEVEL LOWER	GW_LEVEL UPPER	GW_LEVEL AVERAGE
[--]	[--]	[--]	[--]	[m]	[--]	[DDEG]	[DDEG]	[m amsl]	[μS/cm]	[--]	[‰]	[‰]	[‰]	[--]	[--]	[--]	[m amsl]	[m amsl]	[m amsl]
S-031	Bijapur	Sindgi	Sindgi	Upto 130	100-101	16.9205	76.2376111	500.1	3200	7.4	-0.86	-3.71	3.17	Basalt (B501)	Medium Black Soils	100.5	481.8	531.8	506.8
S-032	Chikballapur	Bagepalli	Gulur	Upto 170	153-154	13.84925	77.8403889	725.7	810	7.1	-4.26	-25.06	9.02	Banded Gneissic Complex (BG01)	Red Loamy Soils	153.5	681.8	731.8	706.8
S-033	Chikballapur	Bagepalli	Mittemari (Pz)	Upto 170	161-162	13.6858333	77.8632778	792.7	1430	6.9	-3.36	-20.82	6.06	Banded Gneissic Complex (BG01)	Red Sandy Soils	161.5	781.8	831.8	806.8
S-034	Chikballapur	Chikballapur	Settigere	Upto 170	125-126	13.5498056	77.7475556	943.3	440	7.3	-3.94	-24.08	7.44	Banded Gneissic Complex (BG01)	Red Sandy Soils	125.5	931.8	943.0	937.4
S-035	Chikballapur	Chikballapur	Nandi (Oz)	Upto 170	148-149	13.3828333	77.6994167	944.9	840	7.1	-4.09	-25.17	7.55	Banded Gneissic Complex (BG01)	Laterite Soils	148.5	931.8	943.0	937.4
S-036	Chikballapur	Chintamani	Motamakalahallii	Upto 170	125-126	13.5983333	78.0714167	736.7	880	7.3	-4.77	-29.39	8.77	Banded Gneissic Complex (BG01)	Red Sandy Soils	125.5	731.8	781.8	756.8
S-037	Chikballapur	Chintamani	Gajahalli	Upto 170	130-131	13.3076667	78.0655833	849.4	750	7.3	-3.24	-20.57	5.35	Banded Gneissic Complex (BG01)	Laterite Soils	130.5	831.8	881.8	856.8
S-038	Chikballapur	Gudibanda	Gudibanda	Upto 170	98-99	13.6701667	77.7097222	825.2	1260	7.3	-3.03	-17.67	6.57	Banded Gneissic Complex (BG01)	Red Loamy Soils	98.5	781.8	831.8	806.8
S-039	Chikballapur	Gudibanda	Hampasandra	Upto 170	105-106	13.7396111	77.75675	768	1330	6.9	-3.97	-26.87	4.89	Banded Gneissic Complex (BG01)	Red Loamy Soils	105.5	731.8	781.8	756.8
S-040	Chikballapur	Sidlaghatta	Madivala (Pz)	Upto 170	91-92	13.2208333	77.9719444	847.3	1470	7.1	-3.29	-19.28	7.04	Banded Gneissic Complex (BG01)	Laterite Soils	91.5	831.8	881.8	856.8
S-041	Chikballapur	Sidlaghatta	Dibburahalli (Pz)	Upto 170	95-96	13.5540278	77.9039722	811.1	1510	7.2	-3.87	-27.88	3.08	Banded Gneissic Complex (BG01)	Red Sandy Soils	95.5	781.8	831.8	806.8
S-042	Chikballapur	Gauribidanur	Bevinahalli	Upto 170	120-121	13.4940833	77.4801944	727.8	940	7	-3.85	-28.37	2.43	Banded Gneissic Complex (BG01)	Red Loamy Soils	120.5	681.8	731.8	706.8
S-043	Chikballapur	Gauribidanur	Namagondalu	Upto 170	125-126	13.5764167	77.6059722	754.3	970	7	-3.55	-22.97	5.43	Banded Gneissic Complex (BG01)	Red Loamy Soils	125.5	731.8	781.8	756.8
S-044	Chitradurga	Challakere	Dodderi	Upto 125	120-121	14.2949722	76.7042778	563.7	450	7.2	-4.48	-30.3	5.54	Banded Gneissic Complex (BG01)	Red Loamy Soils	120.5	531.8	581.8	556.8
S-045	Chitradurga	Chitradurga	Kirubanakallu	Upto 125	95-96	14.2066389	76.3736389	763.5	440	7.2	-3.72	-20.41	9.35	Banded Gneissic Complex (BG01)	Red Loamy Soils	95.5	731.8	781.8	756.8
S-046	Chitradurga	Hiriyur	Vaddikere	Upto 125	85-86	14.1152778	76.5988333	639.7	1850	7.4	-2.42	-23.07	-3.71	Phyllite (SC02)	Mixed Red and Black Soils	85.5	631.8	681.8	656.8
S-047	Chitradurga	Holalkere	Basapura	Upto 125	61-62	14.0220556	76.1159167	664.2	820	7.4	-3.96	-22.63	9.05	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	61.5	631.8	681.8	656.8
S-048	Chitradurga	Holalkere	R.Gollarahalli	Upto 125	65-66	13.9278333	76.1891111	774.5	740	7.3	-3.38	-22.91	4.13	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	65.5	731.8	781.8	756.8
S-049	Chitradurga	Hosdurga	Benakanahalli Bus Stand	Upto 125	71-72	13.8888611	76.3047222	703.7	1170	7.4	-4.15	-25.47	7.73	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	71.5	681.8	731.8	706.8
S-050	Chitradurga	Hosdurga	Belagur	Upto 125	95-96	13.6283333	76.2926111	700	2400	7.5	-0.85	-5.61	1.19	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	95.5	681.8	731.8	706.8
S-051	Davangere	Channagiri	Channagiri	Upto 110	65-66	14.0245611	75.92855	679.4	2100	7.2	-1.44	-8.62	2.9	Basalt (B501)	Red Sandy Soils	65.5	631.8	681.8	656.8
S-052	Davangere	Davangere	Davangere	Upto 110	78-79	14.4704083	75.8998583	598.4	820	7.3	-1.06	-2.82	5.66	Banded Gneissic Complex (BG01)	Red Sandy Soils	78.5	581.8	631.8	606.8
S-053	Davangere	Harpanahalli	Harpanahalli	Upto 110	93-94	14.7842167	75.9943444	632.5	1170	7.3	-1.35	-4.14	6.66	Banded Gneissic Complex (BG01)	Red Sandy Soils	93.5	631.8	681.8	656.8
S-054	Davangere	Honnali	Arakere	Upto 110	71-72	14.2816278	75.6920583	571	1070	7.1	-2.48	-15.27	4.57	Banded Gneissic Complex (BG01)	Red Sandy Soils	71.5	531.8	581.8	556.8
S-055	Davangere	Jagalur	Basavapura	Upto 110	67-68	14.5270639	76.2522	689.6	1770	7.6	-0.77	-2.86	3.3	Banded Gneissic Complex (BG01)	Deep Black Soils	67.5	681.8	731.8	706.8
S-056	Davangere	Jagalur	Bidarkere (Pz)	Upto 110	77-78	14.4278444	76.2963833	682.7	640	7.2	-3.02	-20.06	4.1	Basalt (B501)	Red Loamy Soils	77.5	631.8	681.8	656.8
S-057	Davangere	Harihar	Nandi Tavare	Upto 110	81-82	14.4013583	75.7737194	565.7	810	7.2	-0.07	0.77	1.33	Phyllite (SC02)	Red Sandy Soils	81.5	531.8	581.8	556.8
S-058	Dharwad	Navalgund	Navalgund	Upto 110	90-91	15.55925	75.3608333	574.1	6200	7.5	-1.78	-13.08	1.16	Banded Gneissic Complex (BG01)	Medium Black Soils	90.5	531.8	581.8	556.8
S-059	Gadag	Gadag	Gadag	Upto 95	71-72	15.4235278	75.6338889	662.4	840	7.4	-0.73	-4.82	1.02	Banded Gneissic Complex (BG01)	Medium Black Soils	71.5	631.8	681.8	656.8
S-060	Gadag	Mundargi	Mundargi	Upto 130	101-102	15.2039444	75.8886667	527.5	2200	7.3	-1.27	-7.87	2.29	Banded Gneissic Complex (BG01)	Red Sandy Soils	101.5	481.8	531.8	506.8

NO	DISTRICT	TEHSIL/TALUK	LOCATION	DEPTH	ZONE TAPPED	LATITUDE	LONGITUDE	ALTITUDE	EC	pH	$\delta^{18}\text{O}$	δD	DE	AQUIFERS	SOILS	ZONE TAPPED	GW_LEVEL LOWER	GW_LEVEL UPPER	GW_LEVEL AVERAGE
[-]	[-]	[-]	[m]	[-]	[[Ddeg]	[[Ddeg]	[m amsl]	[[μS/cm]	[-]	[‰]	[‰]	[‰]	[-]	[-]	[-]	[-]	[m amsl]	[m amsl]	[m amsl]
S-061	Gadag	Nargund	Nargund	Upto 130	120-121	15.7196111	75.3818333	598.2	4100	7.2	0.12	0.46	-0.5	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	120.5	581.8	631.8	606.8
S-062	Gadag	Ron	Ron	Upto 130	125-126	15.6856389	75.7373333	583.8	860	7.2	-1.69	-12.97	0.55	Banded Gneissic Complex (BG01)	Medium Black Soils	125.5	531.8	581.8	556.8
S-063	Gulbarga	Afzalpur	Afzalpur	Upto 130	90-91	17.2035556	76.3616944	425	1720	7	0.31	-1.26	-3.74	Basalt (BS01)	Deep Black Soils	90.5	381.8	431.8	406.8
S-064	Gulbarga	Aland	Battarga	Upto 130	95-96	17.4103056	76.5657778	439.8	1300	7.2	-0.7	-11.22	-5.62	Basalt (BS01)	Medium Black Soils	95.5	431.8	481.8	456.8
S-065	Hassan	Arsikere	Jayachamrajpura	Upto 110	67-68	13.4163056	76.3506944	778.6	1060	7.2	-2.54	-13.41	6.91	Banded Gneissic Complex (BG01)	Red Sandy Soils	67.5	731.8	781.8	756.8
S-066	Hassan	Hassan	Dundanayakanahalli	Upto 110	88-89	12.9123611	76.0472778	930.5	150	7.4	-2.38	-13.37	5.67	Banded Gneissic Complex (BG01)	Red Sandy Soils	88.5	881.8	931.8	906.8
S-067	Haveri	Haveri	Hosariti (Pz)	Upto 110	87-88	14.8967222	75.5516389	528.2	1770	7	-1.74	-12.52	1.4	Phyllite (SC02)	Deep Black Soils	87.5	481.8	531.8	506.8
S-068	Haveri	Hirekerur	Hirekerur	Upto 110	76-77	14.4559833	75.389475	616	1150	6.7	-1.44	-8.42	3.1	Phyllite (SC02)	Red Sandy Soils	76.5	581.8	631.8	606.8
S-069	Haveri	Ranibennur	Ranibennur	Upto 110	81-82	14.6140556	75.628	594	1280	6.8	-1.84	-11.27	3.45	Phyllite (SC02)	Medium Black Soils	81.5	581.8	631.8	606.8
S-070	Kolar	Bangarpet	Garudadrihalli	Upto 125	91-92	12.9590833	78.3230556	796.5	650	7.1	-2.35	-17.55	1.25	Banded Gneissic Complex (BG01)	Red Sandy Soils	91.5	781.8	831.8	806.8
S-071	Kolar	Bangarpet	Bhimganapalli	Upto 125	110-111	12.8416944	78.1700556	736.2	1000	7	-4.15	-26.12	7.08	Banded Gneissic Complex (BG01)	Red Sandy Soils	110.5	731.8	781.8	756.8
S-072	Kolar	Kolar	Arabi Kottanuru	Upto 125	112-113	13.1222222	78.0413611	895.1	650	7	-4.17	-27.87	5.49	Banded Gneissic Complex (BG01)	Laterite Soils	112.5	881.8	931.8	906.8
S-073	Kolar	Kolar	Nelam	Upto 125	115-116	13.1579167	78.1103611	855.1	290	7.1	-4.41	-27.95	7.33	Banded Gneissic Complex (BG01)	Laterite Soils	115.5	831.8	881.8	856.8
S-074	Kolar	Malur	Mitiganahalli	Upto 125	91-92	12.9879722	78.0948056	883	570	7.5	-4.18	-27.21	6.23	Banded Gneissic Complex (BG01)	Red Sandy Soils	91.5	831.8	881.8	856.8
S-075	Kolar	Malur	Malur (Pz)	Upto 125	95-96	13.0118611	77.9339722	895.8	960	7.4	-3.3	-21.92	4.48	Banded Gneissic Complex (BG01)	Laterite Soils	95.5	881.8	931.8	906.8
S-076	Kolar	Mulbagal	Pethanodahalli	Upto 125	88-89	13.2460833	78.5014444	744.7	1400	7	-4.25	-32.42	1.58	Banded Gneissic Complex (BG01)	Red Sandy Soils	88.5	0.0	0.0	0.0
S-077	Kolar	Mulbagal	Kurudmale	Upto 125	78-79	13.2114167	78.3667222	843.3	1550	7.5	-3.6	-22.22	6.58	Banded Gneissic Complex (BG01)	Laterite Soils	78.5	831.8	881.8	856.8
S-078	Kolar	Srinivaspur	Laksmisagara (Pz)	Upto 125	100-101	13.2424722	78.2830833	812.4	2200	7.3	-3.4	-23.56	3.64	Banded Gneissic Complex (BG01)	Laterite Soils	100.5	781.8	831.8	806.8
S-079	Kolar	Srinivaspur	Dalsanur	Upto 125	105-106	13.275	78.1736667	828	160	7.3	-6.46	-45.7	5.98	Banded Gneissic Complex (BG01)	Laterite Soils	105.5	781.8	831.8	806.8
S-080	Kolar	Bangarpet	Oorgeempet	Upto 125	98-99	12.9669444	78.2697222	840.3	3200	7.8	-2.69	-17.3	4.22	Phyllite (SC02)	Red Sandy Soils	98.5	831.8	881.8	856.8
S-081	Koppal	Gangavati	Gangavati	Upto 110	66-67	15.4476389	76.5241667	418.2	680	7.6	-0.51	0.71	4.79	Banded Gneissic Complex (BG01)	Medium Black Soils	66.5	381.8	431.8	406.8
S-082	Koppal	Koppal	Koppal	Upto 110	75-76	15.3535	76.1646667	536.6	1410	7.6	-0.77	-4.09	2.07	Banded Gneissic Complex (BG01)	Medium Black Soils	75.5	531.8	581.8	556.8
S-083	Koppal	Kushtagi	Umalimilur	Upto 110	90-91	15.8042222	76.4195556	532.8	650	7.3	-2.65	-21.05	0.15	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	90.5	481.8	531.8	506.8
S-084	Koppal	Yelbarga	Yelbarga	Upto 110	100-101	15.6070556	76.0109167	595.3	2200	7.4	-2.08	-16.96	-0.32	Banded Gneissic Complex (BG01)	Medium Black Soils	100.5	581.8	631.8	606.8
S-085	Raichur	Devadurga	Deodurg	Upto 100	120-121	16.424	76.9323611	389.1	2500	6.9	-1.34	-8.64	2.08	Intrusive Acidic Rocks (GR02)	Medium Black Soils	120.5	381.8	431.8	406.8
S-086	Raichur	Lingsugur	Lingsugur	Upto 100	74-75	16.1601944	76.5217222	507.6	1040	6.9	-0.41	-4.24	-0.96	Intrusive Acidic Rocks (GR02)	Deep Black Soils	74.5	481.8	531.8	506.8
S-087	Raichur	Manvi	Manvi	Upto 100	60-61	15.9988889	77.0416389	388.9	2200	6.9	-1.77	-10.67	3.49	Intrusive Acidic Rocks (GR02)	Mixed Red and Black Soils	60.5	381.8	431.8	406.8
S-088	Raichur	Raichur	Raichur	Upto 100	65-66	16.2021667	77.3436111	401.3	1790	7	1.38	5.18	-5.86	Intrusive Acidic Rocks (GR02)	Deep Black Soils	65.5	381.8	431.8	406.8
S-089	Raichur	Sindhur	Sindhur	Upto 100	70-71	15.7890278	76.7713889	403.1	2100	7.1	-0.46	-2.79	0.89	Banded Gneissic Complex (BG01)	Mixed Red and Black Soils	70.5	381.8	431.8	406.8
S-090	Tumkur	C.N.Halli	Huliyar	Upto 140	88-89	13.5843611	76.5405833	713.8	4800	6.8	-1.71	-14.74	-1.06	Banded Gneissic Complex (BG01)	Red Sandy Soils	88.5	681.8	731.8	706.8

NO	DISTRICT	TEHSIL/TALUK	LOCATION	DEPTH	ZONE TAPPED	LATITUDE	LONGITUDE	ALTITUDE	EC	pH	$\delta^{18}\text{O}$	δD	DE	AQUIFERS	SOILS	ZONE TAPPED	GW_LEVEL LOWER	GW_LEVEL UPPER	GW_LEVEL AVERAGE
[-]	[-]	[-]	[-]	[m]	[-]	[DEG]	[DEG]	[m amsl]	[μS/cm]	[-]	[‰]	[‰]	[‰]	[-]	[-]	[-]	[m amsl]	[m amsl]	[m amsl]
S-091	Tumkur	Tiptur	Tiptur	Upto 140	105-106	13.2665556	76.4676111	856.8	1640	6.7	-2.07	-14.16	2.4	Banded Gneissic Complex (BG01)	Red Sandy Soils	105.5	831.8	881.8	856.8
S-092	Tumkur	Pavagada	Pavgada	Upto 140	125-126	14.1174167	77.2611389	640.7	680	7	-4.91	-34.02	5.26	Intrusive Acidic Rocks (GR02)	Red Sandy Soils	125.5	631.8	681.8	656.8
S-093	Tumkur	Sira	Sira	Upto 140	110-111	13.74375	76.9084444	654.2	2800	7.4	-0.88	-10.79	-3.75	Banded Gneissic Complex (BG01)	Red Sandy Soils	110.5	631.8	681.8	656.8
S-094	Tumkur	Madhugiri	Dabbeghatta	Upto 140	134-135	13.6744167	77.1278889	757.1	3000	7	-3.72	-27.29	2.47	Intrusive Acidic Rocks (GR02)	Red Sandy Soils	134.5	731.8	781.8	756.8
S-095	Tumkur	Madhugiri	Bidarkere	Upto 140	67-68	13.8718889	77.2274444	694.5	640	6.8	-4.39	-27.53	7.59	Intrusive Acidic Rocks (GR02)	Red Sandy Soils	67.5	681.8	731.8	706.8
S-096	Tumkur	Koratagere	Koratagere	Upto 140	78-79	13.5201667	77.2364722	756.2	1480	7.3	-0.73	-3.79	2.05	Intrusive Acidic Rocks (GR02)	Red Loamy Soils	78.5	731.8	781.8	756.8
S-097	Tumkur	Koratagere	Akkirampura	Upto 140	98-99	13.56925	77.3048056	714.2	1290	7.8	-2.48	-15.24	4.6	Intrusive Acidic Rocks (GR02)	Red Loamy Soils	98.5	681.8	731.8	706.8
S-098	Tumkur	C.N.Halli	Arasanahalli	Upto 140	100-101	13.3528056	76.6134722	831.2	580	7.3	-2.95	-16.22	7.38	Banded Gneissic Complex (BG01)	Red Sandy Soils	100.5	781.8	831.8	806.8
S-099	Tumkur	Madhugiri	Shivanagere	Upto 140	80-81	13.7246944	77.0620556	707.6	1600	7.3	-3.62	-26.94	2.02	Banded Gneissic Complex (BG01)	Red Sandy Soils	80.5	681.8	731.8	706.8
S-100	Tumkur	Koratagere	Tovinakere	Upto 140	90-91	13.5425556	77.08525	847.7	330	7.3	-4.48	-29.53	6.31	Intrusive Acidic Rocks (GR02)	Red Loamy Soils	90.5	831.8	881.8	856.8
S-101	Yadgir	Shahpur	Shahpur	Upto 110	88-89	16.7075278	76.8520833	422	6200	7.2	-2.12	-14.78	2.18	Intrusive Acidic Rocks (GR02)	Medium Black Soils	88.5	381.8	431.8	406.8
S-102	Yadgir	Shorapur	Shorapur	Upto 110	78-79	16.5239722	76.7559167	485.5	1130	7.2	-1.08	-5.37	3.27	Intrusive Acidic Rocks (GR02)	Medium Black Soils	78.5	481.8	531.8	506.8
S-103	Yadgir	Yadgir	Gurmitkal	Upto 110	105-106	16.8707222	77.3913611	606.7	1260	7.3	-1.35	-9.05	1.75	Intrusive Acidic Rocks (GR02)	Medium Black Soils	105.5	581.8	631.8	606.8

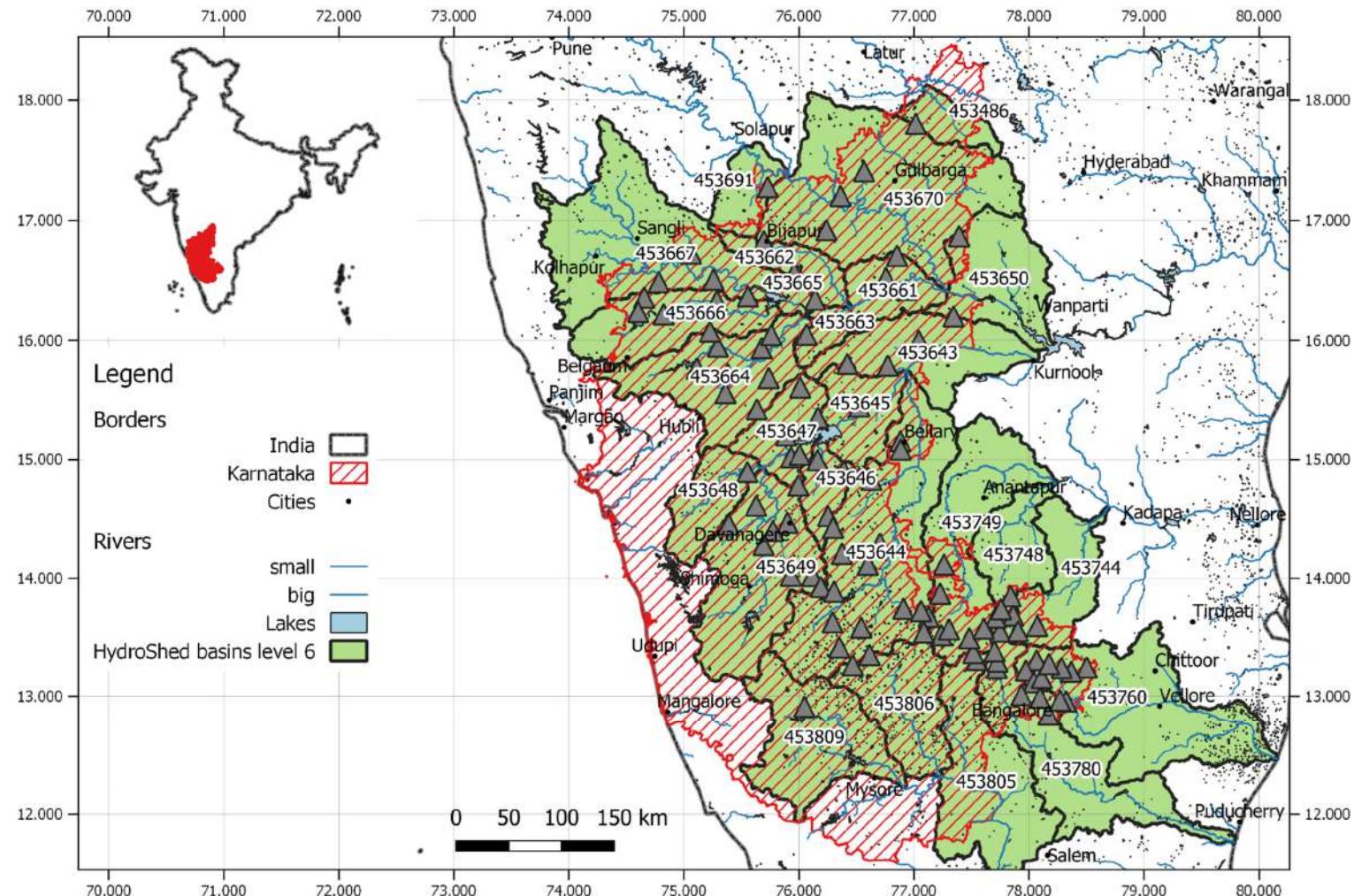
APPENDIX C

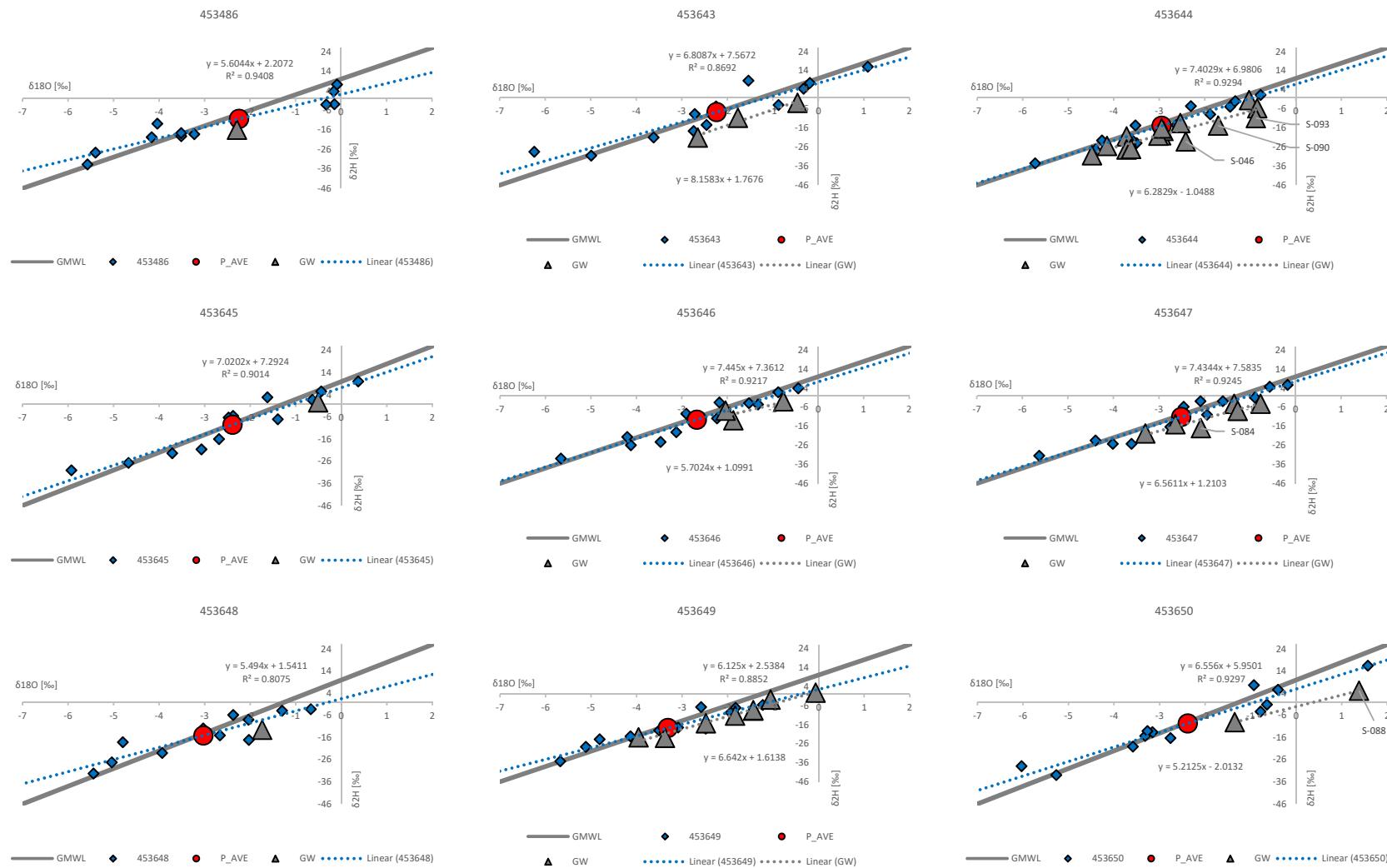
Maps of the mean annual $\delta^{18}\text{O}$ (upper) and $\delta^2\text{H}$ (lower) values of precipitation over Karnataka (left) and error of modelled values (right); (RCWIP model output; IAEA, 2019).

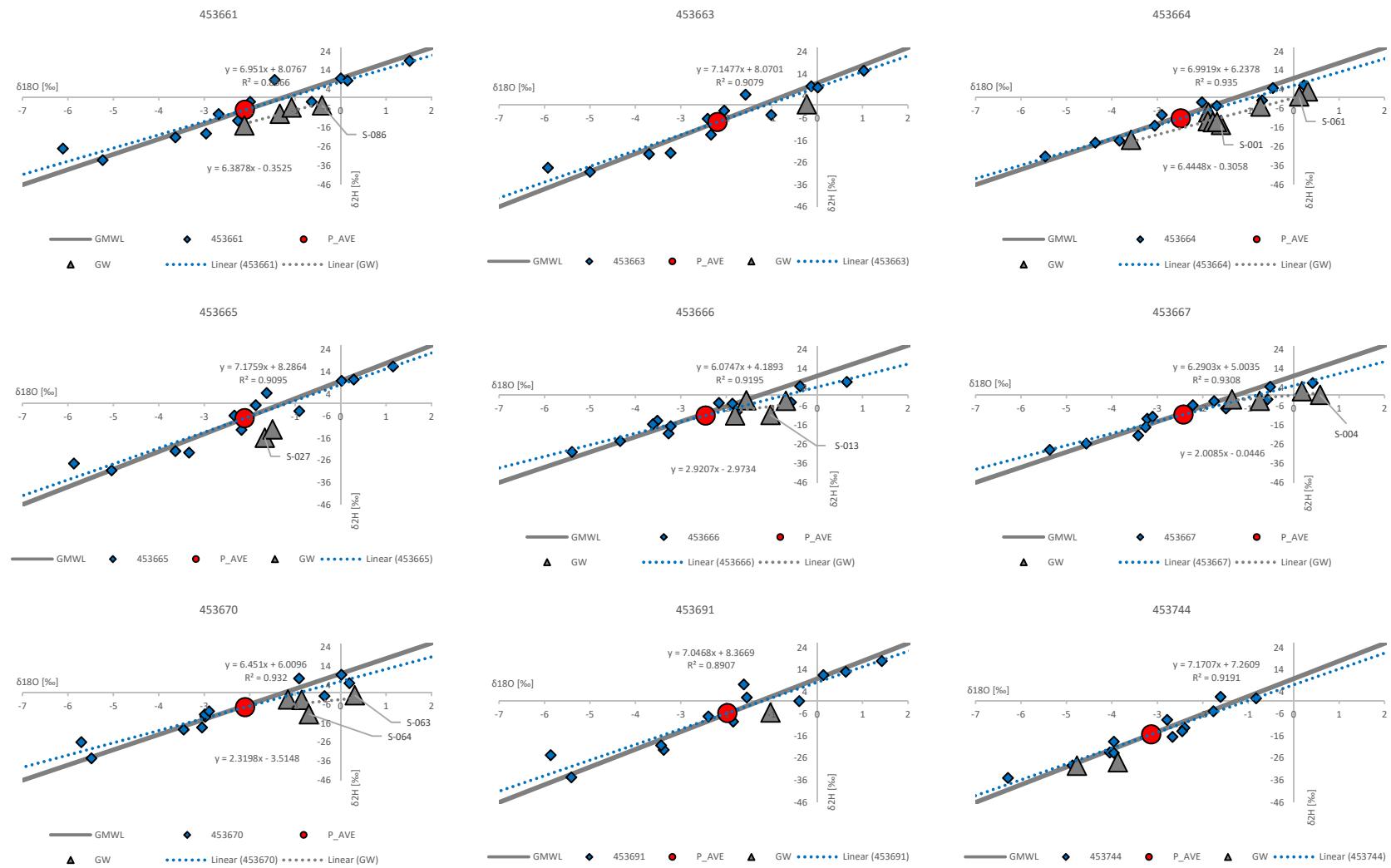


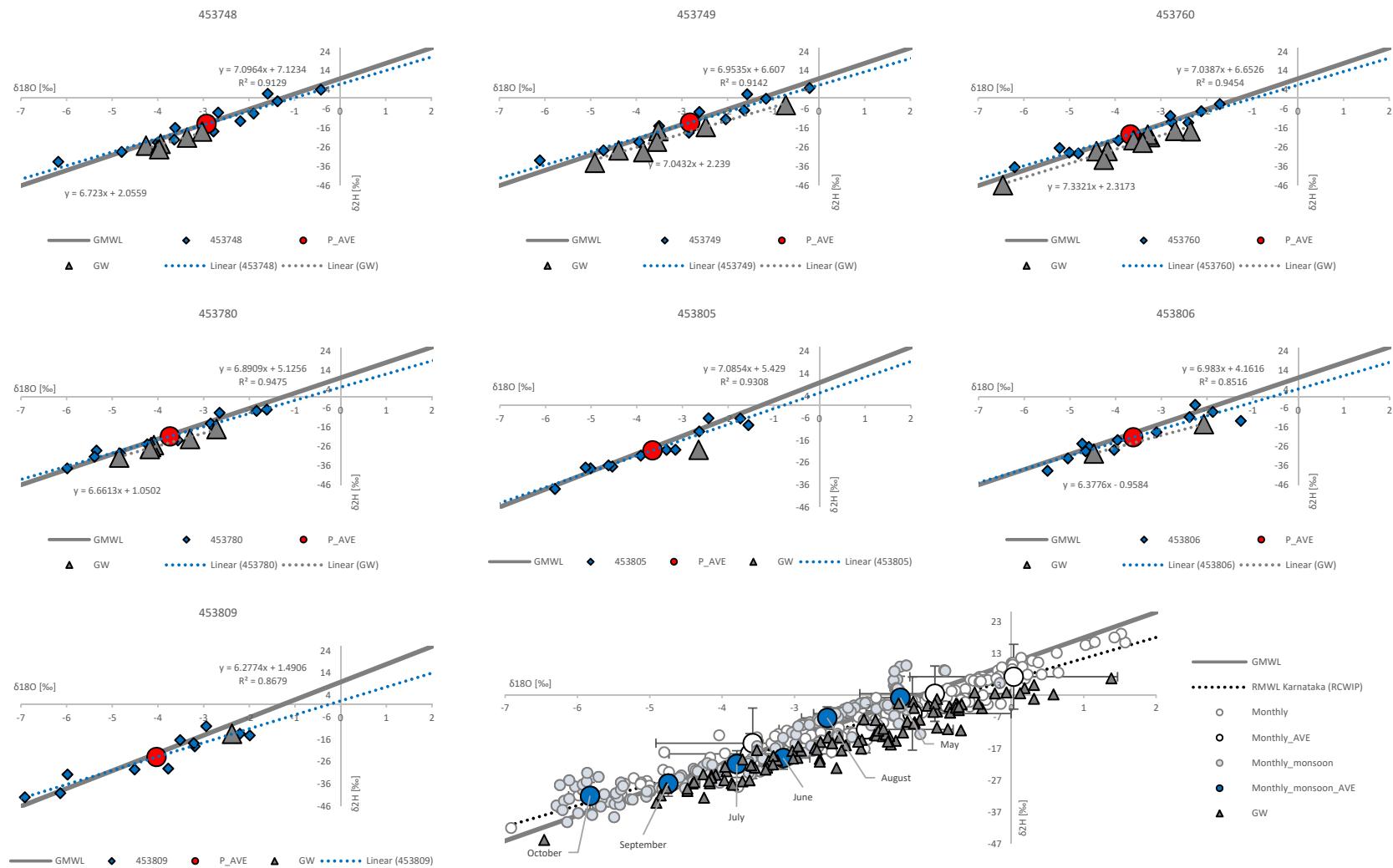
APPENDIX D

Map of the hydrological catchments (HydroSheds level 6) used to locate and group the groundwater samples for comparison with the MWLs.











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