11. Faryab: Stable Isotopes in Groundwater

11.1 Stable isotopes of oxygen and hydrogen

The most common isotope of oxygen has an atomic mass of approximately 16, and is called ^{16}O. Oxygen naturally contains a certain, modest percentage of a heavier isotope, with an atomic mass of 18, termed ^{18}O.

Similarly, the most common isotope of hydrogen comprises a single proton and a single electron, has an atomic mass of approximately 1, and is called ^{1}H. Hydrogen naturally contains a certain, modest percentage of a heavier isotope, comprising a proton, a neutron and an electron, with an atomic mass of 2, termed ^{2}H, or deuterium.

The water molecule H_2O thus has slightly heavier forms, containing either ^{18}O or ^{2}H (or, occasionally, both). The ^{18}O and ^{2}H contents of natural waters are often described by their deviation $\delta^{2}H$ / $\delta^{18}O$ from Standard Mean Ocean Water (SMOW), expressed in parts per thousand (‰).

Chemically, ^{18}O and ^{2}H are very similar to ^{16}O and ^{1}H, respectively, but certain processes cause a *fractionation* (enrichment or depletion). For example, water containing the heavy isotopes of oxygen and hydrogen does not evaporate as readily as "light" water. Thus, the water vapour is enriched in the lighter isotopes (has a lower $\delta^{2}H$ and $\delta^{18}O$), while the non-evaporated liquid residue is enriched in the heavier isotopes (has a higher $\delta^{2}H$ and $\delta^{18}O$).

Rainfall is, of course, derived from water vapour, usually evaporated from sea water. The rain (or snow) that condenses from the vapour thus also has a signature that is an isotopically "lighter" than sea water ($\delta^{2}H$ and $\delta^{18}O$ are negative), but heavier than the vapour from which it formed. Temperature (and altitude) affects the degree of fractionation during condensation of rain: in cold, upland situations, the rain (or snow) is often isotopically light (very negative $\delta^{2}H$ and $\delta^{18}O$), while in warmer, lowland climates the rain is isotopically heavier (less negative $\delta^{2}H$ and $\delta^{18}O$ - blue arrows on Figure 11.1).

It turns out that, on average throughout the world, precipitation samples lie on or around a global meteoric water line GMWL) when plotted on a $\delta^{2}H$ vs. $\delta^{18}O$ diagram. The typical equation for this line is often taken as

$$\delta^{2}H = (8.13 \times \delta^{18}O) + 10.8 \qquad \text{(Clark \& Fritz 1997)} \qquad (11.1)$$

The following websites provide good explanations of stable isotope fractionation in hydrologic systems:

USGS: http://wwwrcamnl.wr.usgs.gov/isoig/period/o_iig.html

SAHRA: http://web.sahra.arizona.edu/programs/isotopes/oxygen.html

If rainfall is highly continental, or not derived from the ocean, it may not fall on the GMWL, but on a local meteoric water line (LMWL), usually close and parallel to the GMWL. In arid regions (according to SAHRA 2014), precipitation tends to lie on a meteoric water line very slightly above, (but approximately parallel to) the GMWL, as shown by the orange dashed line in Figure 11.1. This deviation is often due to a component of locally evapotranspired water vapour (in addition to sea water vapour) and is referred to as the arid zone "deuterium excess" (Pang et al. 2011).

When rain falls on the ground and becomes groundwater or river water, it tends to retain its isotopic signature. If, however, it is subject to intense evaporation, it tends to move away below and to the right of the meteoric water line in a characteristic manner as shown by the green arrow in Figure 11.1. This deviation is simply because a water molecule containing an ^{18}O atom has a molecular weight of 20, while a water molecule containing a ^{2}H atom has a molecular weight of 19. Thus, the residual water subject to intense evaporation becomes enriched in ^{18}O more efficiently than in ^{2}H.

The data collected from Faryab Province clearly illustrates all these features.

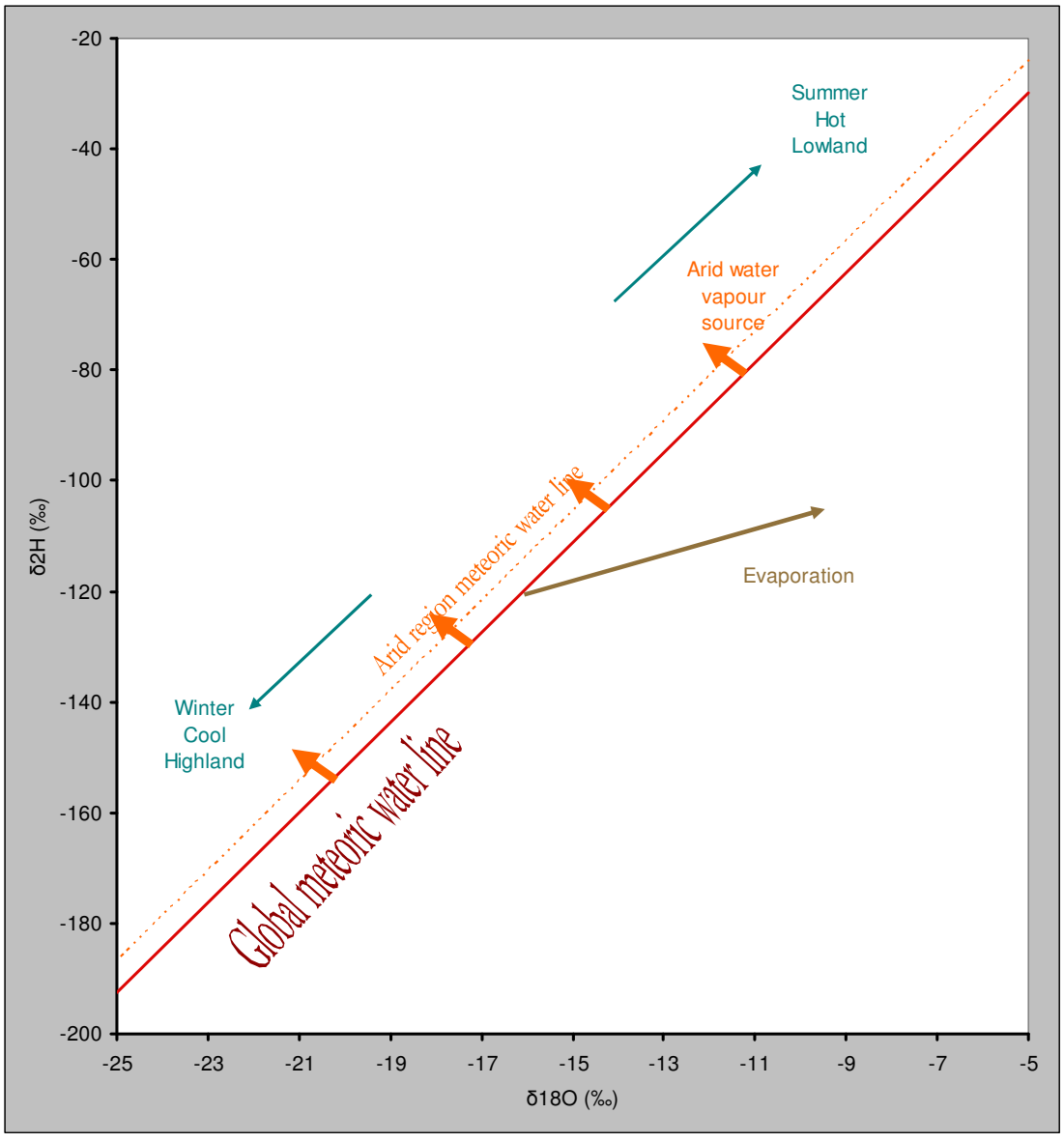

Figure 11.1. Generic stable isotope diagram, showing the global meteoric water line (red), an arid region meteoric water line (orange), seasonal effects (blue) and the effect of evaporation on surface water (or groundwater) bodies.

11.2 Precipitation and Rivers

We have already seen in Chapter 2 (Figure 2.8) that, as regards the isotopic signature of precipitation, the snowfall signatures are by far the isotopically lightest, with the

signatures becoming "heavier" throughout spring. The heaviest isotopic rainfall signatures typically come from Andkhoi, as one would expect, due to its hot, lowland climate. All the precipitation samples lie along, but slightly above, the global meteoric water line (GMWL). In fact, one can define a local meteoric water line, parallel to, but above the global meteoric water line, with the equation:

$$\delta^2H = (7.801 \times \delta^{18}O) + 15.08 \qquad (11.2)$$

The deuterium excess is thus around (15.08 - 10.8) = 4.3 ‰ greater than average global rainfall.

We have also seen, from Chapter 3.10d and 3.11d, that the waters of the Rivers Shirin Tagab and Maimana show a general tendency to become isotopically heavier downstream, which is strongly indicative of an evaporative fractionation effect.

We can now add (Figure 11,2) the river water samples from May 2013 to Figure 2.8.

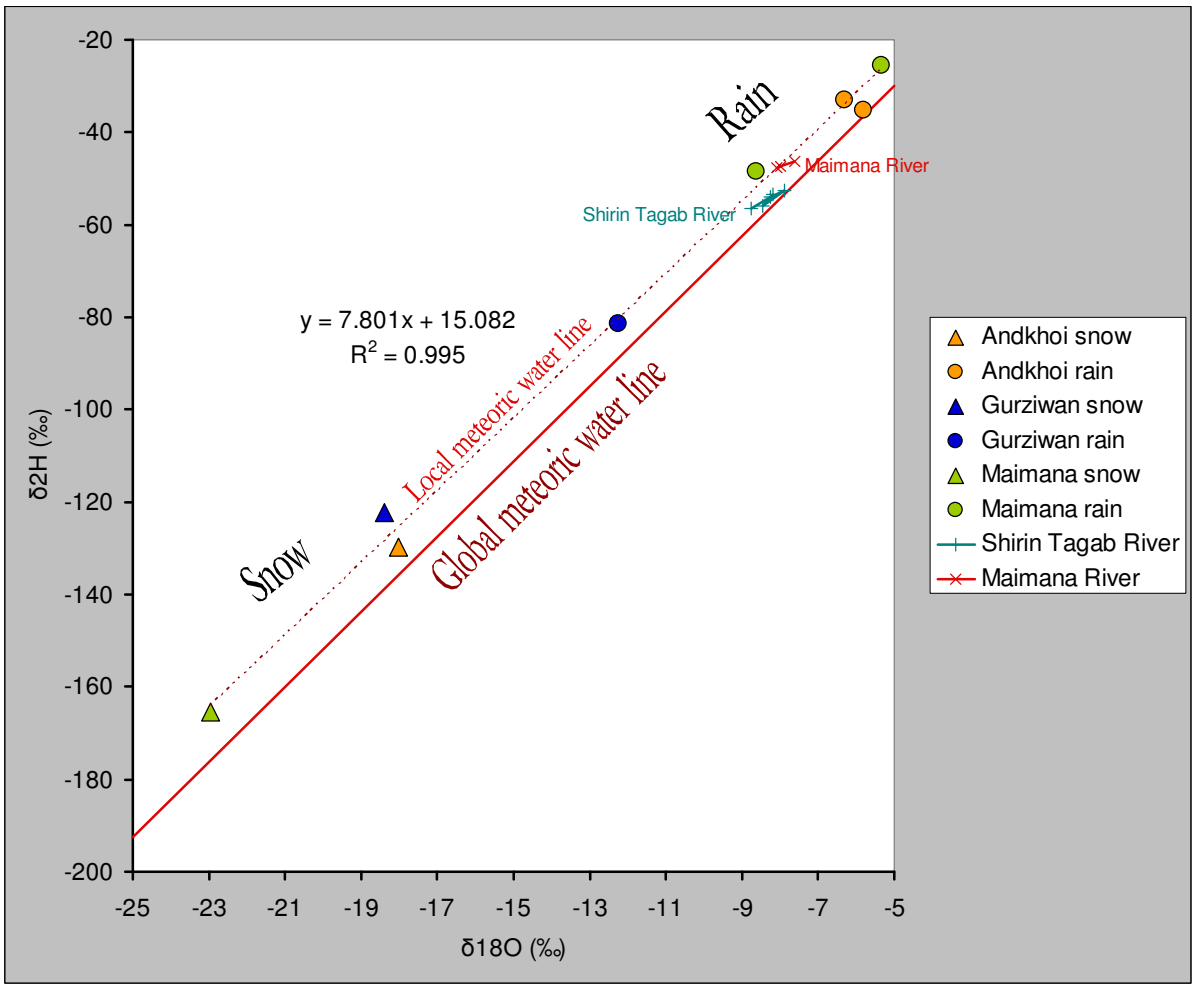

Figure 11.2. Stable isotope diagram comparing the isotopic composition of precipitation samples (from Figure 2.8) with river water samples from May 2013, described in Chapter 3. The GMWL is taken as $\delta^2H = (8.13 \times \delta^{18}O) + 10.8$ (Clark & Fritz 1997). The local meteoric water line is the linear best fit through all precipitation points and is defined by equation (11.2)

We find that the Maimana River samples plot slightly above the GMWL and close to the Maimana rainfall samples. The Shirin Tagab River samples are slightly lighter in ^2H; they plot between the Andkhoi rainfall samples and the Gurziwan rain/snow samples. This is

logical as they are from a location geographically between Gurziwan and Andkhoi in the catchment and will comprise a mixture of runoff with components both of up-catchment (Gurziwan) snowmelt and rain, and lower elevation rainfall. The trajectory described by the river water samples (see Figure 11.3) is characteristic of evaporative concentration of local meteoric water (see green arrow in Figure 11.1).

11.3 Groundwaters

60 of the 132 groundwaters sampled in 2013 were analysed for oxygen and hydrogen isotopes at the NERC Isotope Geosciences Laboratory located on the premises of the British Geological Survey at Keyworth, Nottingham, UK. The results are shown as boxplots in Figure 11.3.

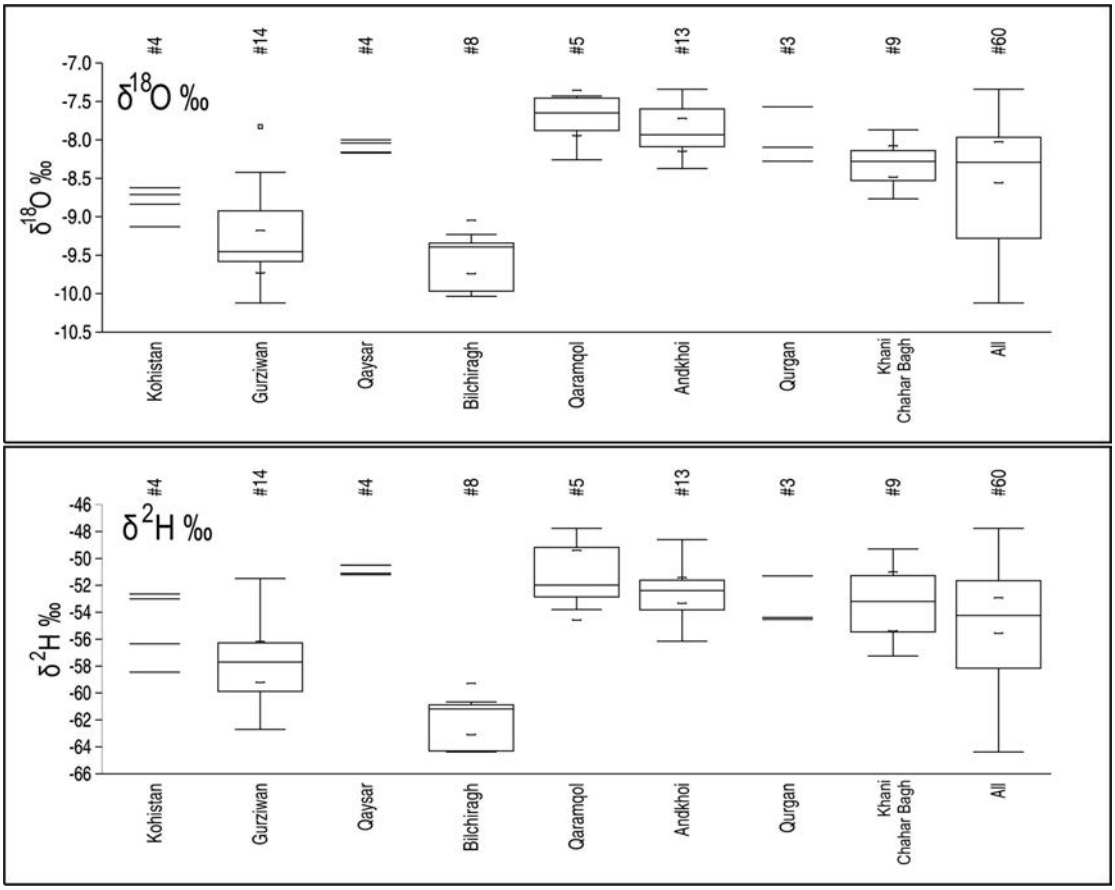

Figure 11.3. Boxplots showing distribution of oxygen-18 and deuterium in N=60 groundwater samples from Faryab.

On the δ^2H vs. $\delta^{18}O$ diagram (Figure 11.4), the groundwaters lie rather close to the Rivers. Thus, a small quadrant of Figure 11.2 has been taken and expanded to illustrate the stable isotopic composition of groundwaters.

The groundwaters from the upland districts (Kohistan, Bilchiragh, Gurziwan) plot, with isotopically lighter compositions, close to the local meteoric water line (LMWL). Further to the north, in the four northern districts around Andkhoi, the samples are isotopically heavier (which is consistent with the influence of either evaporation or isotopically heavier precipitation). However, the trajectory of the northern groundwater samples

(and those from the Shirin Tagab River) angles away from the meteoric water line in a direction that is wholly characteristic of evaporation (see green arrow in Figure 11.1).

The samples from the Shirin Tagab River lie within the groundwater field, strongly suggesting that there is an intimate linkage between groundwater and surface water (the Shirin Tagab being fed by groundwater baseflow to the north of Araba and in the Dowlatabad area, with groundwater resources being recharged by river infiltration in the Shirin Tagab delta area around Andkhoi).

Samples from Khani Chahar Bagh tend to have a slightly isotopically heavier δ^2H signature, relative to their $\delta^{18}O$ content, than the other samples from the Andkhoi area.

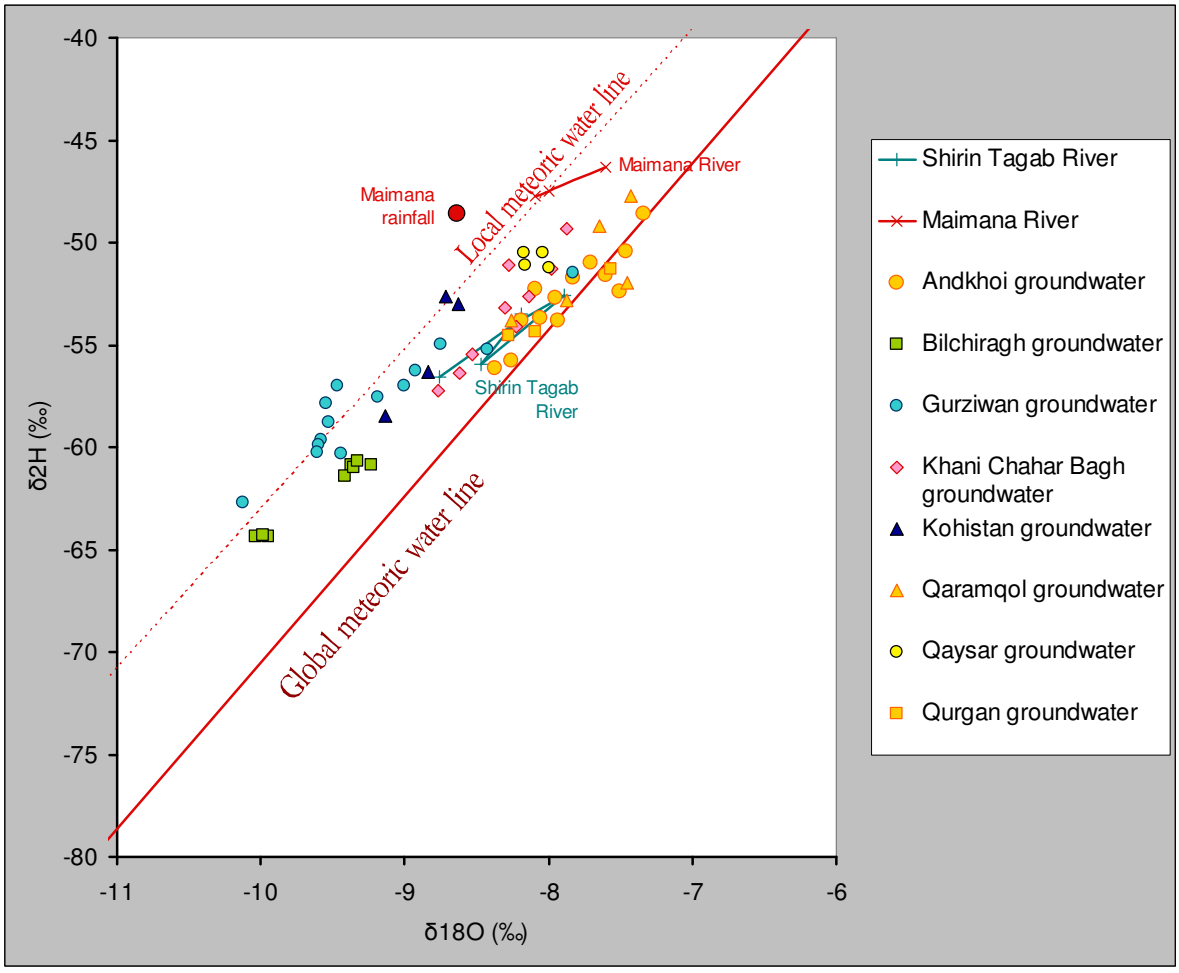

Figure 11.4. Stable isotope diagram comparing the isotopic composition of groundwater samples with river water samples from May 2013 and Maimana rainfall. The GMWL is taken as $\delta^2H = (8.13 \times \delta^{18}O) + 10.8$ (Clark & Fritz 1997). The local meteoric water line is taken from Figure 11.1.

The samples from Qaysar tend to lie slightly above the other groundwater samples in Figure 11.4, closer to the Maimana River, which is consistent with the samples being derived from the Maimana / Qaysar, rather than the Shirin Tagab, catchment).

In summary, stable isotope data confirms that groundwaters in the area appear to be ultimately derived from precipitation, but that, towards the north, groundwaters and river waters are strongly influenced by evapotranspirative effects.