The relationship between the isotopic composition of precipitation, surface runoff and groundwater for semiarid and arid zones

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Abstract During the transition from precipitation to surface water or groundwater, and while water moves within such systems, selection and isotope fractionation processes modify the isotope composition of the precipitation. Such modifications result from isotope fractionation that accompanies evaporative processes, and also from selective utilization of rainfall of different duration and intensity and during different seasons in the processes of runoff generation and of groundwater recharge. These modifications are controlled by ecological, morphological and climatic factors. The correlation between the isotopic parameters of the precipitation and those of the surface water and groundwater systems acts on a wide spectrum of temporal and spatial scales; they can characterize the hydrological system and any change informs about anthropogenic or climatic changes in its structure. In the arid zone, evaporation processes from the ground and from within a shallow soil or sand cover dominate. There is an almost momentary response within a very small time and space interval. In this case the system is extremely sensitive to details of the surface structure and to changes due to development and urbanization. In the semiarid zone, in contrast, the degree and the nature of the vegetation cover controls the water balance, and the main factor to change the isotope composition is the seasonal pattern of water utilization by the plants (transpiration). Evaporative fractionation of isotopes occurs mainly on the canopy.

INTRODUCTION

The waters falling as precipitation on land are subdivided into three parts. One infiltrates into the ground, eventually forming groundwater; another part runs off on the surface. The third part, namely the return flux to the atmosphere (evapotranspiration) is composed of a fraction of almost immediate evaporation from the land surfaces and the canopy of vegetation, a delayed flux from the surface waters and an important part transpired by the vegetation at the expense of the soil moisture and the groundwater recharge. The climate regions of the world, as defined for example by Thornthwaite (1948), are dictated to a large extent by the relative magnitude of these fluxes and, in particular, the ratio of the (potential) evapotranspiration flux (PET) to the available moisture in the soil column. The arid zone is that area where precipitation is not plentiful enough to sustain
a continuous plant cover \((PET \gg P_{opt})\), whereas in the humid zone there obviously is an excess of precipitation over the seasonally integrated water need of the abundant plant cover. Semiarid zones are to be viewed as ones where a favourable water balance is achieved only seasonally. In this zone, the survival of perennials depends on a deep root system which can draw on subsurface water fed by occasional water excesses.

As discussed before (Gat, 1980), the ratio of the surface to subsurface runoff, which is relatively high under humid conditions, goes through a minimum value in the semiarid zone. Surface runoff achieves renewed significance under arid conditions, mainly as a result of the absence of a developed soil and vegetation cover and the exposure of impervious surfaces.

The stable isotope composition of the precipitation is a rather well-defined parameter at any location and correlated with climate parameters such as temperature and rain amounts (Rozanski et al., 1993). It undergoes modification in the transition from precipitation input to surface runoff or groundwater discharge as a result of the hydrological process involved.

The Isotope Transfer Function (ITF) is defined as a set of rules which relate the isotopic composition of the surface runoff, soil waters and groundwater to that of the precipitation input over the range of time scales from a single shower to annual averages. Being dependent on the totality of the environmental condition, the ITF can be a useful tool for characterizing the ecological system and recognizing changes in it. The isotopic shift imposed by the ITF will be designated \(\Delta\), defined as \(\Delta = \delta_{\text{system}} - \delta_{\text{input}}\) and given in \(^\circ\) units.

**THE ISOTOPIC SIGNATURE OF THE TERRESTRIAL HYDROLOGICAL PROCESSES**

The movement of water through the soil, the aquifers or a plant is, to a first approximation, invariant with respect to its isotopic composition, except as regards mixing with other water bodies. However, changes in the isotopic composition in the terrestrial part of the hydrological cycle result from selective utilization of part of the waters in the process of runoff generation or groundwater recharge. The isotope composition is further modified by the isotopic fractionation which accompanies phase transitions, primarily evaporation, as well as (to a lesser extent) by isotopic exchange with materials in the rock matrix. Evaporation enrichment affects surface waters primarily.

The selection process is of such vast importance because of the pronounced seasonal amplitude in the isotopic composition of precipitation at most sites (Yurtsever & Gat, 1981) as well as large differences in the isotopic composition within a rain shower (Bleeker et al., 1966; Rindsberger et al., 1990; Pioncke & Dewalle, 1992). These interact with the unsteady nature of the hydrological processes.

Let us now follow the waters from a rain shower as they fall on the ground and become incorporated into the terrestrial systems. We must consider a variety of situations, such as bare soils, rock exposures, grassland or forested areas and open waters. Lands affected by human activity, i.e. tilled lands or urban areas, pose a special problem, being inherently changeable and also exposed to the introduction of extraneous waters, e.g. irrigation waters.
The immediate response within the time scale of a rain shower

Only in the case of open water surfaces is there indiscriminate incorporation of all incoming precipitation. The short term inter-storm and intra-storm variability is then damped out completely. In all situations other than that of a wet surface, a partitioning of waters takes place on the surface. For each area there is some threshold of rain amount necessary to initiate runoff or infiltration; lesser amounts just wet the surface and are subsequently lost by evaporation. This threshold amount depends on the surface structure and morphology, but also on the antecedent condition of wetness and thus on the interval between successive rainy spells. In fact there is a hierarchy of interception reservoirs, such as the canopy, the ground surface and its storage depressions, the topsoil, etc.

In most cases an amount effect on the isotopic composition applies (Dansgaard, 1964). The loss of the smaller rain from the ensemble thus results in a negative shift in the isotope composition of either the runoff or infiltration waters relative to the average isotope composition of the precipitation. In the temperate zone such a shift was documented in lysimeter samples (Sauzay, 1974).

Except for the threshold effect, the runoff from bare surfaces, pavements and rock exposures shows a minimum distortion relative to the precipitation input. However, in the temperate zone with its developed soil layer, the surface runoff has been shown to involve waters in the top soil layer (Fritz et al., 1976) and the runoff is constituted with a mixture of previous rainfalls. A negative bias in the isotopic composition, due to the initial selection process discussed above, is inherited in the surface runoff.

Under arid conditions rather intensive momentary rain intensities are required to initiate runoff. Such intense rains appear to be characterized by rather depleted isotopic values (Levin et al., 1980) and the regional runoff in the Negev desert was indeed depleted by as much as 3% in $\delta^{18}O$ compared to the mean isotopic value of the relevant precipitation events.

Delayed isotope effects in the transition from surface to the storage reservoirs

Among the delayed effects, evapotranspiration is by far the most influential, not only because of the large isotope fractionation associated with evaporation but also as an important vehicle for the seasonal selection of water.

Evaporation from open water surfaces leaves behind waters which are enriched in the heavy isotopes, $^{18}O$ and deuterium. In $\delta^{2}D$ vs $\delta^{18}O$ space, the enriched waters fall on a line (Lake Evaporation Line, LEL) whose slope is less than that of the Meteoric Water Line (MWL), imprinting a characteristic isotope signature on these waters. They are to be recognized, obviously, when the hydrological pathway features surface waters.

Evaporation from within the soil also leaves behind enriched soil waters, alas on a soil evaporation line (SEL) of even lower slope in the $\delta$ space (Allison et al., 1983). In contrast, the transpired waters are not fractionated to any marked degree relative to their source waters under steady state flux conditions, and their effect on the remaining waters in the soil column is only that of a seasonal selection of the waters removed from the soil water reservoir. One should note that the seasonal change in the magnitude of the evaporation flux from an open water body (such as a lake) also introduces a seasonality of its
own, which is superimposed on that of the seasonal change of the isotopic composition at the input and is additional to the evaporative enrichment of the heavy isotopes due to the isotope fractionation process.

As a rule the effects of selection (based on either amount or seasonal effects in the precipitation input) impose an opposite sense on the isotope composition of the hydrological system than that of the isotope fractionation which accompanies the evaporation. Were it not for different correlation between the changes in the isotope changes for the two isotopic tracers ($^{18}O$ and D) for the case of evaporative fractionation and selection, one often would not be able to distinguish these processes.

Figure 1 schematizes the changes in isotopic composition in the transition from precipitation to groundwater or surface water reservoirs for various landscapes.

THE ISOTOPE TRANSFER FUNCTION FOR MEDITERRANEAN SEMIARID AND ARID ZONES

The semiarid region

A typical semiarid catchment in the Mediterranean area would be a rather sparsely vegetated limestone hill or a permeable sandy soil covered by grasses and bushes, especially during the rainy season. Direct runoff is a relatively minor component of the water balance and most surface flows are generated by perennial springs. The exposure of waters on the surface prior to infiltration is usually quite negligible and canopy losses much smaller than from tropical bush vegetation. Direct evaporation loss from the soil is also minimal due to the shielding vegetation cover. Thus the infiltration flux rather closely follows the precipitation input in its isotopic composition (Gat & Tzur, 1967). The major component of water loss is that of evapotranspiration which typically accounts for more than 60% of the water. This flux however does not result in isotope fractionation, but can be selective on a seasonal basis. For example, rain of the last part of the rainy season, which resides in the upper part of the soil column, is lost selectively. Since these waters are typically more enriched in $^{18}O$, by about 1‰ compared to the midwinter waters (Gat et al., 1994), one notes a shift to more negative $\delta$-values in the recharge flux. Further, the relatively larger utilization of the rain in rain-deficient years by evapotranspiration has a similar effect due to an inter-annual amount effect.

Evidently the transition from precipitation to groundwater by natural processes in the semiarid environment is accompanied by rather small change in the isotope composition. Gat & Tzur (1967) estimated a shift of about 0.5‰ in $\delta^{18}O$, and this estimate was confirmed by later studies (Gat, 1974). However, nowadays, "un-natural" water sources are playing an ever increasing role. These are irrigation waters, often imported from considerable distances, or reclaimed sewage or diverted flood waters. The role of evaporation is thus enhanced. Above and beyond this effect one may encounter a completely extraneous isotope composition, which cannot be accommodated in a simple scheme or set of rules. However, an advantage of having large isotope contrasts is that it opens up the possibility of tracing the admixture of such extraneous waters into the groundwater system.
The arid zone

In the arid zone, in direct contrast to the semiarid zone, direct local recharge to groundwater is rare. The water depth of a single precipitation event is insufficient to escape subsequent evaporation from within the soil column, with the possible exception of open-pore sandy areas (Dincer et al., 1974) or when a number of more closely spaced precipitation events follow one another. In that case the late rain may flush down the residue of the previous event, thus imprinting an evaporative signature on the recharge flux. In most cases, however, some degree of surface flow (which results in
the confluence of water) precedes infiltration (Gat, 1988). Thus the waters are exposed to some degree of enrichment of the heavy isotopic species due to their partial evaporation. Such an enrichment is indeed a characteristic attribute of most arid zone waters.

As shown in Fig. 2, three recharge pathways have been recognized, which differ somewhat in their ITF. The first, already mentioned above, entails evaporation from within the soil column; this is marked by a low-slope evaporation line, as described by Allison et al. (1983). The second pathway is activated by some surface flow into depression storage, where infiltration through cracks or fissures can take place. This mechanism is typical for rocky terrain. In the first phase of this process, namely the

![Diagram of major recharge pathways.](image)

**Fig. 2** The groundwater recharge pathways in the desert environment and their isotopic signatures (from Gat, 1988).
inception of surface flows, a negative bias will be introduced through exclusion of smaller rains to be followed by evaporative enrichment, as is typical for surface waters. A third pathway is that involving large-scale regional flash floods which recharge shallow alluvial aquifers along their flow path and deep aquifers through intersecting fault lines. It was found that these regional flood flows are quite depleted in the heavy isotopes compared to the average isotope composition of precipitation (Levin et al., 1980).

As was noted (Gat, 1992), the arid zone hydrological system is very sensitive to changes in land use whenever these affect the surface flow paths and thus the recharge mechanisms. Allison et al. (1984) also discussed the change in the isotopic enrichment in the soil profile in the arid zone as a function of the vegetation cover.

THE EFFECT OF CHANGING ENVIRONMENTAL AND CLIMATIC CONDITIONS

In the case of an open water body (e.g. a lake) an averaged value of the isotopic composition of precipitation and inflow serves as input to the isotopic budget of the lake; the period of averaging is obviously determined by the turnover rate of water in the system. Gat & Lister (in press) have discussed the (usually) small distortion of the isotopic composition of the inflow relative to the precipitation which is the consequence of processes in the drainage basin. The ITF for the lake water is dictated by the evaporative component of the water balance, and its result can be recognized by virtue of the deviation of the isotopic composition of the lake water from the Meteoric Water Line (i.e. by a decreasing value of the d-excess parameter). Selective discrimination may operate on a seasonal or inter-annual time scale (especially noticeable in seasonally stratified systems), but the higher frequency modes can be neglected except for the case where a river flows "through" the lake. The value of $\Delta = (\delta_{\text{system}} - \delta_{\text{in}})$ can be an appreciably positive number, but with very little noise associated with it.

The situation is evidently quite different in a case of a terrestrial drainage basin. Here the higher frequency responses (on the time scale of single rain events) assume greater importance and become dominant for arid zone processes. Delayed effects due to evapotranspiration then further modify the isotopic composition. As stated above, under semiarid conditions the values of $\Delta$ are small but can be related unequivocally to the ecological make up of the system, as exemplified in a study of the spatial variability of the phreatic coastal aquifer of Israel (Gat, 1974). In the arid zone, however, $\Delta$ is changeable both spatially and temporally and very sensitive to both meteorological and surface structure details.

How will the isotope composition of a system under review respond to a change in climate (rain pattern), to a change in the environment, or to both? The answer to this question will obviously determine the possibility of the isotopic record serving as a monitor of the environmental condition and its changes, and as a tool for reconstructing past (hydrological) conditions.

For a given (and unchanged) input, the isotopic response of the hydrological system to a (manmade?) change of the environment — or in other words, the value of $\Delta$ imposed by the ITF — will depend on the climate zone and structure of the basin. Destruction of the plant cover, urbanization, etc., should manifest itself by a marked
shift in the isotope composition of the aquifers and their discharge. The converse change from a barren to a less arid landscape can be expected to be as significant, yet it might not be as easy to recognize on the background of the large noise inherent in the isotope data of the arid region.

When a change of the meteorological parameters occurs (climate change?), affecting both the pattern of precipitation and the ecology of the basin, then clearly under semi-arid conditions (where the high frequency effect can be neglected), the isotope composition in the water resources can be expected to be a fair measure of the averaged isotopic composition of the precipitation. Only a major excursion in the isotopic compositions with lowering of the d-excess values could be interpreted as showing increasing aridity. In that case a sizable distortion of the isotope composition by the basin processes has to be taken into account. Under arid conditions, and since the detailed intra-storm isotopic pattern will not be known, all interpretations need to be cautious and limited.

REFERENCES


