Isotope tracing of hydrological processes in large river basins: Danube study

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Introduction

River discharge consists mainly of surface runoff and groundwater seepage and is an important continent-to-ocean linkage in the global hydrological cycle. Isotope signals in river discharge can potentially contribute to better understanding of the continental portion of the hydrological cycle including information such as water origin, mixing history, water balance, water residence times, surface-groundwater exchange and renewal rates, and evaporation-transpiration partitioning. Coupled measurement of isotope fluxes and volumetric discharge is also useful for tracing progressive changes in basin hydrology related to climate or land use changes, and can be applied as a diagnostic variable for constraining atmospheric circulation models and hydrological models. A CRP (Coordinated Research Project) launched by the IAEA is expected to provide groundwork and a scientific rationale for development of an operational "Global Network of Isotopes in Rivers" (GNIR) to enhance understanding of the water cycle of river basins and to assess impacts of environmental and climatic changes on the water cycle.

Catchment area

The catchment area of the Danube at Vienna (Upper Danube Basin) is about 103 000 km^2 (Danube total 817 000 km^2). The mean annual flow rate is around 1900 m^3/s (Danube total about 6500 m^3/s) with a seasonal variation typical of alpine rivers - a minimum of 1300 m^3/s in November and a maximum of 2700 m^3/s in July.

The catchment upstream of Vienna can be divided into three sectors:

- The sector upstream of Passau: This sector lies almost entirely in German territory and represents about one half of the study area. The mean annual flow rate at Passau is around 670 m^3/s (35 % of the flow rate at Vienna), with a maximum in March (880 m^3/s) and a minimum in October (520 m^3/s). The mean altitude of this sector is relatively low compared to the Alpine regions. Groundwater discharge is the main mechanism forming base flow in this part of the river. The period of high water is mainly controlled by precipitation and melting during late winter and early spring.
- The catchment area of River Inn: The Inn, which enters the Danube at Passau, has a hydrological regime typical of alpine rivers. It is the most important tributary in this sector, contributing 725 m^3/s (38 % of the flow rate at Vienna) and thus doubling the flow rate when it merges in the Danube. Maximum flow rates are observed in June/July (1200 m^3/s) and a minimum in January (400 m^3/s).
- The sector between Passau and Vienna. Along this stretch other alpine rivers, with a mean annual flow rate of about 505 m^3/s (27 % of the flow rate at Vienna), enter the Danube. These rivers are characterized by a hydrological regime similar to that of the

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Inn, with maximum flow rates in May/June (800 m^3/s) and a minimum in January (270 m^3/s).

The amount of precipitation in the Upper Danube Basin shows a distinct gradient with the altitude. It rises from 650-900 mm/a in the lowland areas to more than 3000 mm/a in the high mountain ranges exposed to the west and north. For the stations located in the lowland areas, summer precipitation represents more than 60 % of annual precipitation. For high-altitude stations, winter precipitation is more important, although it is stored on the surface as snow cover until spring and summer, when melting takes place.

Results and conclusions

The ^3H and ^{18}O high-resolution time series of the Danube at Vienna is one of the worldwide longest of a large river (Rank and Papesch 1996, Rank et al. 1998, Fig. 1 and 2, Tab. 1). It demonstrates that not only short-term signals (e. g. seasonal $\delta^{18}O$ variations, Fig. 3, or ^3H releases from nuclear facilities, Rank et al. 2000) but also long-term changes of isotope ratios in precipitation are transmitted through the catchment and can be detected in the river water. Thus also stable isotopes - ^2H, ^{18}O - can be used as independent tracer to simulate transport processes in river systems. Because of the relatively low amplitude of long-term changes of $\delta^{18}O$ (δ^2H) in precipitation and in river water, this approach is useful to assess the mean transit time of the fast component of the flow. For the Danube River, the mean transit time derived from comparisons of $\delta^{18}O$ trend curves for precipitation and river water at Vienna is around 1 (Rank et al. 1998).

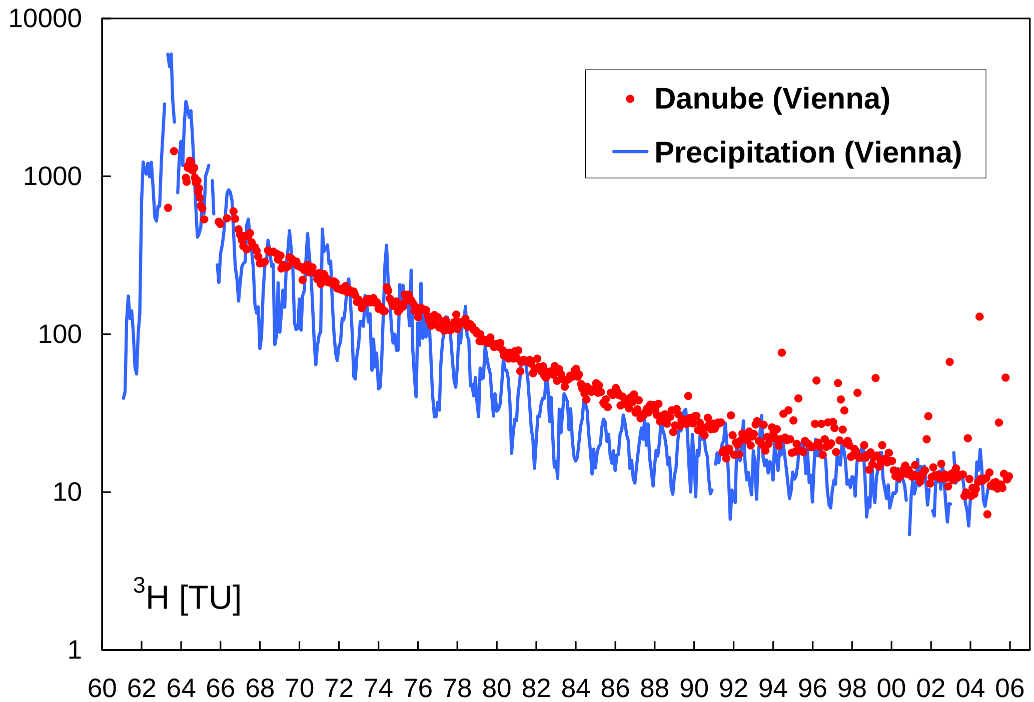

Fig. 1: ^3H-time series of precipitation (monthly mean values) and Danube (monthly grab samples) at Vienna. The sometimes higher ^3H content in the Danube water during the last years is due to releases from a nuclear power plant some 400 km upstream of Vienna.

The different isotopic behaviour of tributaries from different parts of the catchment area (Fig. 4) reflects differences in the geographical and hydro-meteorological parameters, like altitude of the drainage areas, spatial and temporal precipitation distribution, source of air moisture, infiltration characteristics, residence times of ground or lake waters in the drainage areas, evaporation processes and others. The long-term changes in the isotopic records (e.g. increase of $\delta^{18}O$ during the eighties) may help to trace hydro-climatic changes in these areas, which otherwise would be difficult to detect. The main reason for the increase of $\delta^{18}O$ during the eighties is probably an increase of the environmental temperature (Rank & Papesch 2001). But also poor snow covers in the drainage areas during some winters and changes in the winter/summer distribution of precipitation play a certain role for the long-term changes of isotope records.

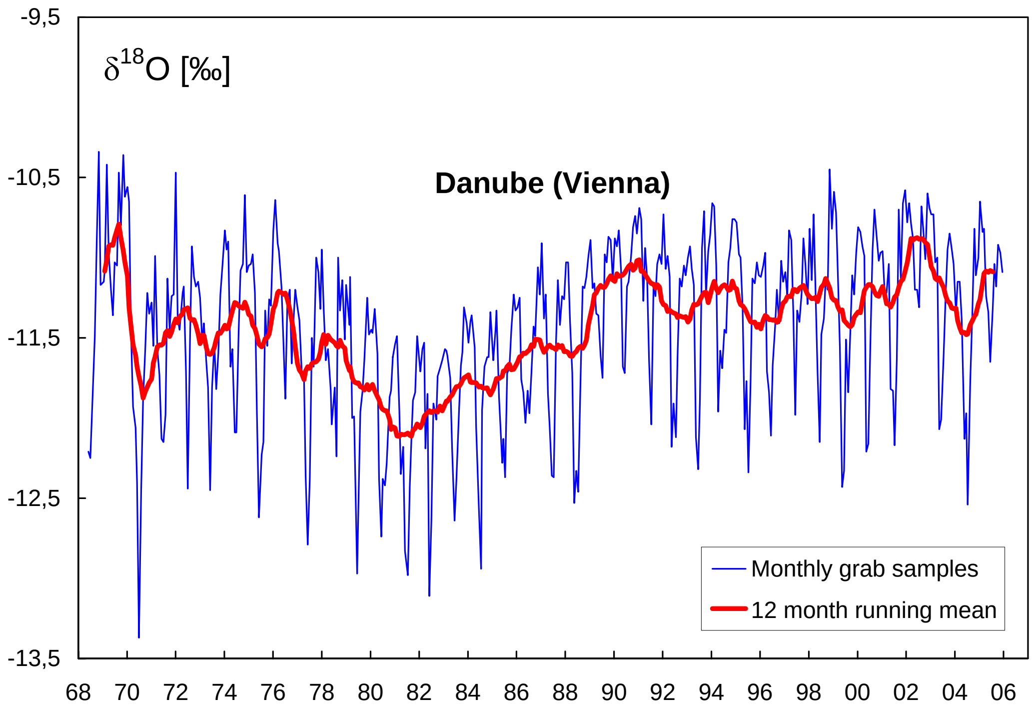

Fig. 2: $\delta^{18}O$ time series of the Danube at Vienna (monthly grab samples and 12 month running mean).

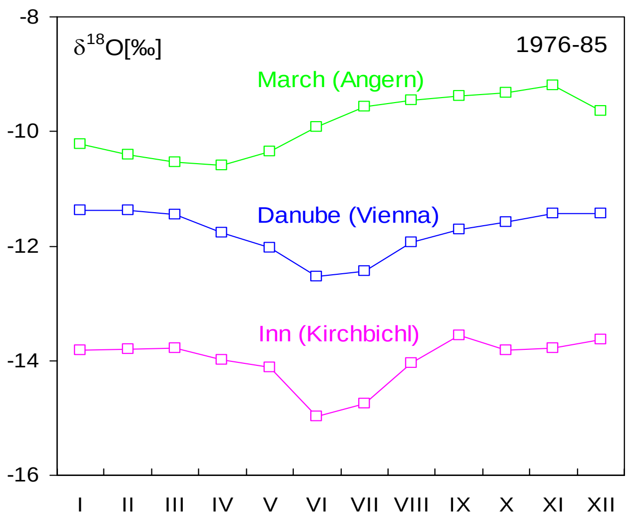

Fig. 3: Seasonal $\delta^{18}O$ variations in Austrian rivers. The observed seasonality of the Danube at Vienna is mainly governed by the melting water contribution of the Alpine tributaries which causes a significant $\delta^{18}O$ minimum in summer.

The time series of tritium in the Danube were modelled using the lumped parameter approach. The comparison of measured and modelled ^{3}H contents in the river revealed that the best fit which could be obtained (mean residence time of 3 a) is still not satisfactory (Rank et al. 1998).

Table 1: ^{3}H (TU) and $\delta^{18}O$ (‰) values of Danube water at Vienna 1996-2005 (monthly grab samples, day of sampling in brackets)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
1996	19,4 (15) -11,12	27,0 (19) -11,05	50,8 (19) -10,97	20,5 (15) -11,71	19,3 (14) -11,84	27,0 (14) -12,11	17,2 (12) -11,67	21,6 (16) -11,43	19,3 (12) -11,20	27,6 (16) -11,41	19,8 (14) -11,02	20,3 (13) -11,15	24,2 -11,39
1997	27,7 (14) -11,09	25,4 (14) -11,24	17,9 (14) -10,83	48,9 (16) -10,89	21,2 (15) -11,35	38,5 (13) -11,98	24,8 (15) -11,33	32,8 (14) -11,40	20,3 (16) -11,22	21,0 (15) -10,88	19,8 (14) -11,05	16,7 (15) -11,29	26,3 -11,21
1998	17,0 (14) -10,82	18,7 (16) -11,14	18,2 (16) -10,73	42,4 (15) -11,22	16,5 (15) -11,70	16,5 (15) -12,15	16,7 (10) -11,48	19,8 (17) -11,38	16,5 (15) -11,13	17,2 (15) -11,20	13,8 (13) -10,45	17,8 (15) -10,82	19,3 -11,19
1999	15,0 (15) -10,59	16,7 (15) -10,72	52,7 (15) -11,09	17,0 (14) -11,56	14,5 (17) -12,43	15,9 (15) -12,33	19,8 (15) -11,51	15,6 (16) -11,84	16,2 (15) -11,47	15,4 (15) -11,11	17,7 (15) -11,23	15,7 (15) -10,97	19,4 -11,40
2000	15,7 (13) -10,81	13,7 (15) -10,84	12,6 (15) -10,93	13,4 (14) -10,99	12,3 (15) -12,21	12,6 (15) -12,16	13,3 (14) ---	13,9 (15) -10,96	14,7 (14) -10,70	13,0 (16) -10,87	13,8 (15) -11,02	13,1 (14) -10,97	13,5 (-11,13)
2001	12,5 (15) -10,96	12,9 (15) -11,22	14,8 (15) -11,22	12,6 (17) -11,04	12,6 (15) -11,82	11,6 (18) -11,83	12,4 (13) -12,17	13,3 (14) -11,63	13,7 (13) -10,70	21,6 (15) -11,13	30,2 (15) -10,66	11,3 (18) -10,58	15,0 -11,25
2002	12,4 (16) -10,78	14,3 (15) -10,66	12,7 (18) -10,79	12,6 (15) -10,88	12,9 (15) -11,20	12,2 (17) -11,20	15,1 (15) -11,31	12,2 (19) -10,68	12,9 (16) -10,82	12,3 (15) -11,01	10,9 (17) -10,60	66,7 (17) -10,69	17,3 -10,89
2003	13,0 (15) -10,73	11,9 (17) -10,73	13,4 (14) -11,03	14,1 (14) -11,00	12,3 (14) -12,07	12,8 (13) -12,01	--- (18) ---	12,9 (18) -11,24	9,4 (16) -10,95	9,9 (16) -10,85	21,9 (18) ---	12,1 (15) -11,04	(13,1) (-11,17)
2004	9,4 (19) -11,35	10,6 (12) -11,15	9,7 (17) -11,15	10,5 (15) -11,39	11,6 (28) -12,13	129 (22) -11,97	12,1 (13) -12,54	11,8 (20) -11,77	12,1 (21) -11,35	12,2 (22) -10,82	7,2 (12) -11,11	13,3 (21) -11,00	20,8 -11,48
2005	11,0 (14) -10,65	10,9 (23) -10,84	11,4 (15) -10,82	11,5 (15) -11,24	10,5 (20) -11,34	27,5 (15) -11,65	11,2 (25) -11,31	10,6 (17) -11,04	13,0 (15) -11,18	52,9 (14) -10,92	12,0 (14) -10,97	12,6 (15) -11,09	16,3 -11,09

$\delta^{18}O$ data 1969-1995 see Rank & Papesch 1996, ^{3}H data in Rank, Rajner & Lust 1984-1996.

Short-term ^3H peaks on the Danube, probably due to releases from nuclear power plants, offer a possibility to study the travel velocity and the dispersion processes of a pollution pulse along the river.

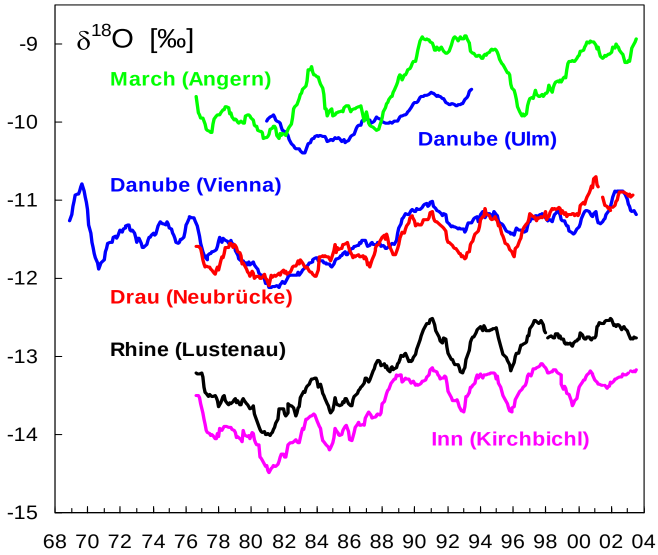

Fig. 4: $\delta^{18}O$ records of the Danube, some tributaries and the alpine part of the Rhine (12 month running mean). All the alpine rivers show a similar long-term pattern (R. Inn, R. Drau and Rhine). This isotopic signal dominates also in the Danube at Vienna. The upper Danube (Ulm, data from Rank et al. 1998) and the R. March show a somewhat different isotopic behaviour.

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