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The Variability of the Snow and Ice Melt in Alpine Rivers in Northwestern China

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Abstract: The study of snow and ice melt (SIM) is important in water-scarce arid regions for the assessment of water supply and quality. These studies involve unique difficulties, especially in the calibration of hydro-models because there is no direct way to continuously measure the SIM at hydro-stations. The recursive digital filter (RDF) and the isotopic hydro-geochemical method (IHM) were coupled to separate the SIM from eight observed series of alpine streamflows in northwestern China. Validation of the calibrated methods suggested a good capture of the SIM characteristics with fair accuracy in both space and time. Applications of the coupled methods in the upper reaches of the Hei River Basin (HRB) suggested a double peak curve of the SIM fraction to streamflow for the multi-component recharged (MCR) rivers, while a single peak curve was suggested for the rainfall-dominant recharged (RDR) rivers. Given inter-annual statistics of the separation, both types of the alpine rivers have experienced an obvious decrease of SIM since 1960s. In the past 10 years, the SIM in the two types of rivers has risen to the levels of the 1970s, but has remained lower than the level of the 1960s. The study provided a considerable evidence to quantify the alpine SIM based on the separation of observed data series at gauge stations. Application of the coupled method could be helpful in the calibration and validation of SIM-related hydro-models in alpine regions.

Keywords: Recursive digital filter (RDF); Isotopic hydro-geochemical method (IHM); Snow and ice melt; Separation; the Hei River Basin

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Introduction

It is estimated that 140 million people live in river basins where snow and ice melt (SIM) fraction contributes 25% of river discharge on a seasonal basis (Schaner et al. 2012). Quantification of SIM is of great significance for water management and supply, hydro-power generation, reservoir regulation, irrigation management, and other purposes. This is an especially important issue in water scarce and arid regions, where climate change has further complicated the hydrologic regime (Schultz 1988; Masuda et al. 1993; Ferguson 1999; Singh and Jain 2002; Mark et al. 2005; Akiyama et al. 2007; Xu et al. 2009;

Zhang et al. 2009; Wang et al. 2010; Liu et al. 2012; Vaibhav et al. 2012).

Regional climate plays a key role in the accumulation of snow and ice and in melt patterns (Ferguson 1999; Zhao et al. 2010). Changes in temperature and precipitation affect melt characteristics (Immerzeel et al. 2010). In the northern hemisphere, increases in air temperature have caused redistribution and variation in the mid-latitude mountains snow cover at watershed scales (McCabe and Wolock 2009). The SIM response to temperature change is the most sensitive in snowmelt-dominated river systems (Rauscher et al. 2008; Adam et al. 2009). The SIM is considered a sensitive indicator in studies of regional climate change. It has been found that the first occurrence of snowmelt runoff begins shortly after a rise in temperature (Wang et al. 2010).

Because of the complexity of the SIM process in changeable environments, it is necessary to integrate multiple methods and approaches, especially with respect to the utilization of hydro-models for the simulation of SIM hydrology (Rutter et al. 2009). There have been famous SIM models, such as the concept-based HBV (Bergström 1975) and SRM (Martinec 1975), the physics-based SNOWPACK, (Bartelt and Lehning, 2002) and its offshoot, ALPINE3D (Lehning et al. 2006). There have also been land surface process models with SIM modules embedded, such as SIB2 (Sellers 1996a), VIC (Wood et al. 1992), and its offshoot, VIC-2C (Liang et al. 1994). These models have facilitated the study of SIM in many parts of the world and have developed very well in terms of forming an explanation and determination for the statistical and physical SIM.

Preconditions like calibration and validation are necessary for use of all of the hydro-models listed above (Ferguson 1999). Commonly, the observed series at gauging stations near the outlets of rivers provides the basis for this performance (Li et al. 2010a). Most of the hydro-models simulate the basin processes using the averaged variables at certain time scales as inputs. This results in averages of hydrological responses as the models' outputs (Rutter et al. 2009). To illustrate the SIM process by using models, accurate tests of the models must be performed so that the quantity of the SIM can be determined. However, the measured series at gauging stations are a mixture of all components from the upper reaches. There is no direct way to continuously monitor the SIM at the outlet of a basin, and tests for models face unique difficulties (Sellers 1996b). From this point, the componential separation of streamflow for the SIM is of great importance to the calibration and validation of the melts related to hydrological models (Eckhardt 2008).

Classic separation methods can be used to determine the flow components. According to the response speed, the measured monthly streamflow at mountain outlets can be conceptually divided into two components. The first is the relatively quick portion defined as surface flow (Li et al. 2010b). The other is the flow component, which reacts slowly and usually comes from groundwater, which is defined as base flow (Hall 1968; Tallaksen 1995; Eckhardt 2008). The separation for base flow is necessary to studies of water supply and quality. Methods of calculation fall into two types, manual and automatic (Aksoy et al. 2009). Both are based on the definition of the recession curve (Tallaksen 1995; Eckhardt 2008).

The automated approaches are often more objective relative to the graph-based manual separation methods. They are also easier and faster to implement. Various famous methods and tools suitable for automated separation of base flow have been reported in literature. Most of these methods have been used in many countries for studies of groundwater discharge, water quality, resource assessment, and other applications (e.g., *HYSEP*, Sloto and Crouse 1996; *PART*, Rutledge 1998; *BFLOW*, Arnold and Allen 1999; *UKIH*, Piggott et al. 2005; *Eckhardt*, Eckhardt 2008; *SARR*, Koskelo et al. 2012). The efficiency of different methods and approaches to base flow separation have been compared by several hydrologists (e.g., Nathan and McMahon 1990; Chapman 1999; Furey and Gupta 2001; Eckhardt 2008). Of these, the automatic recursive digit filter (RDF) approach is the most frequently recommended. For this reason it was used in the present attempt to determine the alpine SIM. Although, this automatic approach lacks physical determination, it is often used and is efficient in long-term series separation and can be conducted more than one time (Arnold and Allen 1999). This offers a conceptual possibility for more than two components whose separation can occur according to the different flow responses in rivers.

Although the RDF can be used to quantify the surface flow and base flow of the channel streamflow, it cannot be used to indicate the source of the water, how much comes from the SIM versus how much from rainfall (Freeze 1972; Nathan and McMahon 1990; Arnold et al. 1995; Koskelo et al. 2012). In such cases, the isotopic hydrogeochemical method (IHM) helps (Feng et al. 2004; Wang et al. 2009; Ma et al. 2010). However, the isotopic fraction of snowmelt may cause large and systematic variations. Nevertheless, most of the IHM have tended to focus on rainfall-driven episodes (Taylor et al. 2001, 2002). The earlier the snow and ice melt, the lower the isotopic tracer values ($\delta^{18}O$), and vice versa. From this point, if the SIM in the streamflow can be quantified by IHM, the rest would be equal to the determinaiton of quotients of the SIM in surface flow and base flow, according to RDF filtering. Applications of IHM using environmental isotopic tracers like $\delta^{18}O$, $\delta^{3}H$, or S_iO_2 have resulted in relatively satisfactory results for separation of rainfall and SIM components in channel streamflow (Hinton et al. 1994; Ren 1999; Nie et al. 2005; Zhang et al. 2009). For a better understanding of the composition in the channel streamflow, it is necessary to divide the gauging total into portions by coupling RDF and IHM methods and to describe not only the relative proportions of rainfall versus SIM in surface flow, but also the relative proportions in base flow (Laudon et al. 2002).

The present paper has two objectives. Firstly, the RDF was passed over the observed series of monthly streamflow two times for determination of surface flow and base flow. The quickest responses in river channel empirically include surface flow and subsurface flow. In this paper, these two components have been combined and are called “surface flow” at a time scale of one month. In alpine area of northwestern China, the surface SIM process responds quicker than the base flow, which will be determined by the second pass of RDF. Coupled with the IHM, ratios of flow component sourced from rainfall and SIM in baseflow was quantified, such as surface flow. Secondly, the coupled methods will be applied to the upper reaches of the Hei River Basin (HRB) over the past several decades. The outcome of the application will be used to analyze the monthly and inter-annual characteristics of the SIM in the alpine area.

1 Study Area

The Hei River Basin (HRB) is the second-largest inland river basin in northwestern China (Zhu et al. 2010). It is geographically located between 97.5°–102° E and 37.8°–42.5° N, in western Gansu Province. It features a zonal differentiation in geomorphology from south to north, includes a mountainous water conservation area in its upper reaches, an arable irrigation-dominated oasis area and cities in its middle, and river terminals and a desertification area in its lower reaches (Figure 1a). Eight of the twelve observed basins in upper reaches of the HRB (Figure 1b) were used to determine the SIM by coupling the RDF and IHM methods. The elevation in the basins ranges from 1670 m in the northeast to 5570 m in the southwest. Accordingly, the mean annual temperature varies from -7.5°C to -3.3°C and the mean annual precipitation ranges from over 650 mm in the southwest to less than 500 mm in the northeast (Table 1).

According to the multi-year average of the selected basins, the annual air temperature is higher in east and north, but precipitation presents an opposite trend. Land surface coverage of forest and grassland varies from 40.89%–79.73%, but only 20% of the LIYU, HEIH, and HSHH basins are covered by forest. There are no obvious zonal characteristics of the grassland, which make up over 50% of the TLAI, LIYU, YNIU, and HEIH basins.

The soil zonality was strong in the HRB and the common soil types in the upper reaches included felty soils, brown calcic soil, and irrigated desert soils, among others.

Glacier storage is not the same throughout these basins. There is much more glacial coverage in the western area than that in the eastern area. The only zone with a glacial coverage of more than 10% is in the HSHB, but in the other basins, coverage is less than 3%. It is especially low in the TLAI, where it is only 0.08%. This is partially due to the large total area of the basin.

There are several types of groundwater in the upper reaches of the HRB (GPGS 2003). The bedrock fissure water and the clastic rock class pore fissure water are the two main types of groundwater discharged into river channels. The carbonate fissure cavern water also affects the

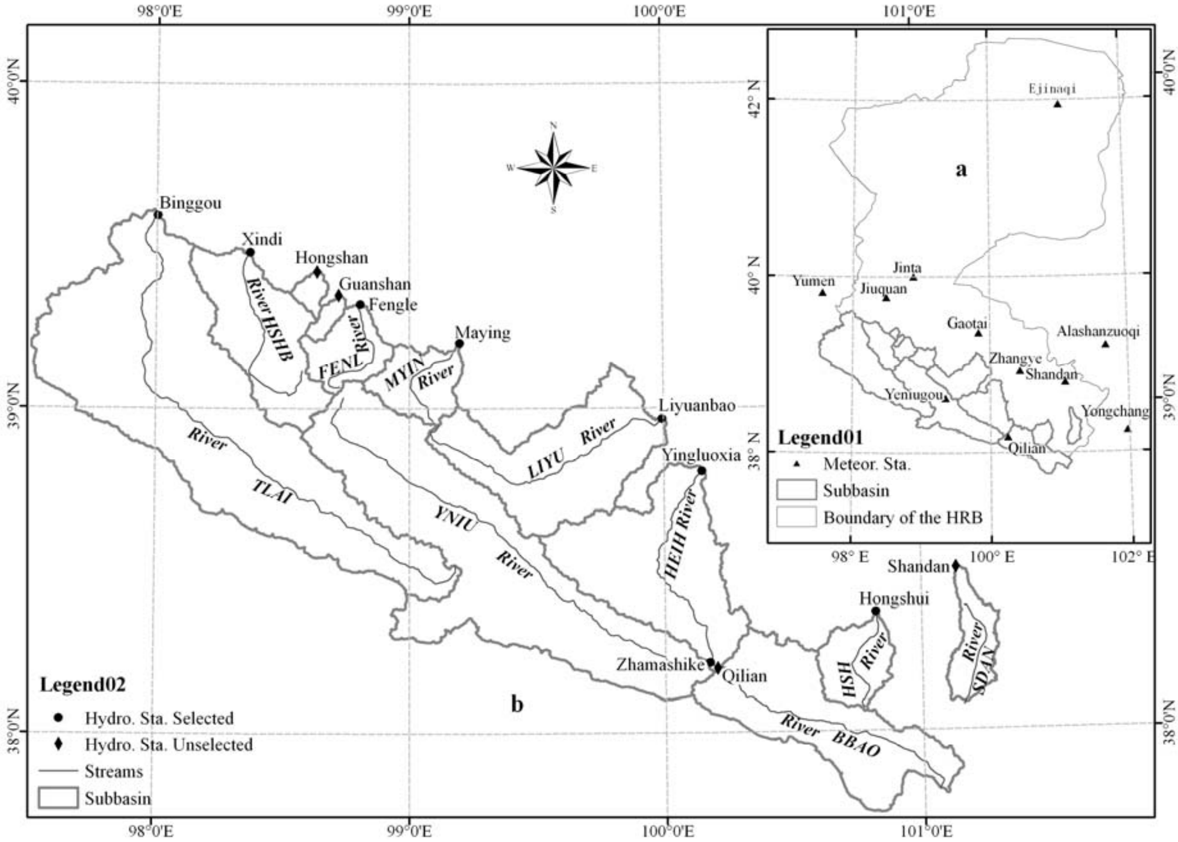

Figure 1 Location of the study area with the nationally basic hydrometeorologic stations (a) and the selected hydrologic stations (b) in the upper reaches of the Hei River Basin (HRB). The independent basins in the upper reaches of HRB with their main channel are also showed (b).

high-altitude parts of the TLAI and the suprapermafrost water affects the very alpine and cold regions. There is also a relatively large quantity of loose rock class pore water that has developed in the broad mountain valleys of large river basins like TLAI and HEIH. All these kinds of groundwater together are the main source of the base flow in the area.

The observed series of streamflow recorded since the hydrologic gauge stations built were selected and organized (Table 2). Some of the measures were abolished but the observed data series were still used for analysis. Statistics regarding information collected in time periods during which no observations were adjusted to the same length for separation.

2 Materials and Methods

Inland alpine rivers are mostly supplied by rainfall and SIM (Kang et al. 1999). The two original water sources can redistribute and transfer water into surface flow (overland flow), subsurface flow and base flow. According to a pilot study of the alpine hydrology of northwestern China, the series observed at gauging stations was a mixture of all types of flow components. Even after separation, rainfall and SIM appear to contribute water to the base flow and surface flow. In the study area, SIM in surface flow was often observed in the rainless days in late April when the melt begins.

In the present study, the RDF and IHM methods were coupled to quantify the SIM in surface flow and base flow. The IHM was implemented to divide the streamflow into the flow components of rainfall or SIM sources while the RDF was passed twice for the separation of the surface flow, the surface SIM flow, and the base flow (Figure 2).

Lyne and Hollick have suggested that the time domain-based RDF method to separate base flow from the observed series. The streamflow was conceptually assumed to include surface flow and

Table 1 Characteristics of the selected 8 sub-basins in the Hei River Basin, northwestern China

Items	**TLAI**	**HSHB**	**FENL**	**MYIN**	**LIYU**	**HEIH**	**YNIU**	**HSHH**
Gauge Stations	Binggou	Xindi	Fengle	Maying	Liyuanbao	Yingluoxia	Yeniugou	Hongshui
Catchment area (km^2)	6265	1520	559	614	2234	9446	4760	586
Mean annual T (°C)	-6.40	-7.10	-7.10	-7.20	-4.20	-5.70	-7.50	-3.30
Mean annual P (mm)	577	604	648	676	567	669	588	472
Average elev. (m a.s.l.)	3842	3952	3816	3724	3112	3657	3875	3479
Land use (%)*								
Arable	0.00	0.00	0.00	0.11	0.65	0.33	0.29	2.66
Forest	1.44	2.30	6.81	14.75	21.76	21.36	8.73	56.39
Grassland	57.34	38.59	45.96	43.04	57.97	51.29	59.61	18.44
Water area	0.22	0.01	0.01	0.11	0.06	1.80	1.53	0.56
Developed	0.02	0.00	0.00	0.00	0.06	0.10	0.07	0.18
Unused	40.91	58.29	45.79	39.51	18.62	22.90	28.43	11.63
Glacier	0.08	0.81	1.44	2.47	0.89	2.22	1.34	10.14
Soil types (%)**								
Felty soils	39.43					25.68	50.33	27.04
Gray-brown desert soils	21.55							
Brown calcic soil	18.10	14.78	17.10		47.96		23.36	72.96
Ash brown soil		71.84						
Irrigated desert soils		13.22	53.28	30.22	20.98	20.71	11.30	
Saline soil			26.61	58.22				
Desert sand soil				11.56	20.58			
Sierozem								
Chestnut soil						19.19		

Notes: * Sourced from the Institute of Geographic Sciences and Natural Resources Research, CAS, 2000; ** Sourced from the Institute of Soil Science, CAS, 1996; Soil types with a percentage < 10% are ignored.

base flow (Lyne and Hollick 1979). To better illustrate the streamflow separation in the area, the RDF was modified so that it was composed of three components:

$$Q_t = d_t + O_t = d_t + s_t + b_t \qquad (1)$$

where the subscript t denotes time; Q_t is the measured streamflow (mm); d_t represents the monthly quickest corresponding of rainfall-sourced surface flow (mm); O_t is the remaining flow components after the first separation for surface flow (mm); s_t is the surface SIM flow (mm), which is slower than the rainfall-derived surface flow but higher and faster than the base flow. d_t and s_t were filtered by the RDF method as follows:

$$d_t = \beta_d d_{t-1} + (1+\beta_d)/2 \times (Q_t - Q_{t-1}) \qquad (2)$$

$$s_t = \beta_s s_{t-1} + (1+\beta_s)/2 \times (O_t - O_{t-1}) \qquad (3)$$

where β_d is the filter constant for d_t and β_s is the filter constant for s_t.

Table 2 Observed series in the gauge stations of the the selected 8 sub-basins

Stations	**Time period**	**Series length**
Binggou	1956-2009	54
Xindi	1956-2004	49
Fengle	1966-2007	42
Maying	1970-2003	34
Liyuanbao	1984-1999	16
Yingluoxia	1956-2009	54
Yeniugou	1979-2000	22
Hongshui	1978-1987	10

Source: Gansu Bureau of Hydrology and Water Resources Survey

The RDF-separated base flow includes rainfall and SIM as sources of water. The two-component IHM can be combined to determine the relative proportions of water from different sources. The ratio of the SIM in the total streamflow was defined as (Pearce et al. 1986; Zhang et al. 2009):

$$r_s = \left[(C_Q - C_P)/(C_s - C_P)\right] \times 100\% \qquad (4)$$

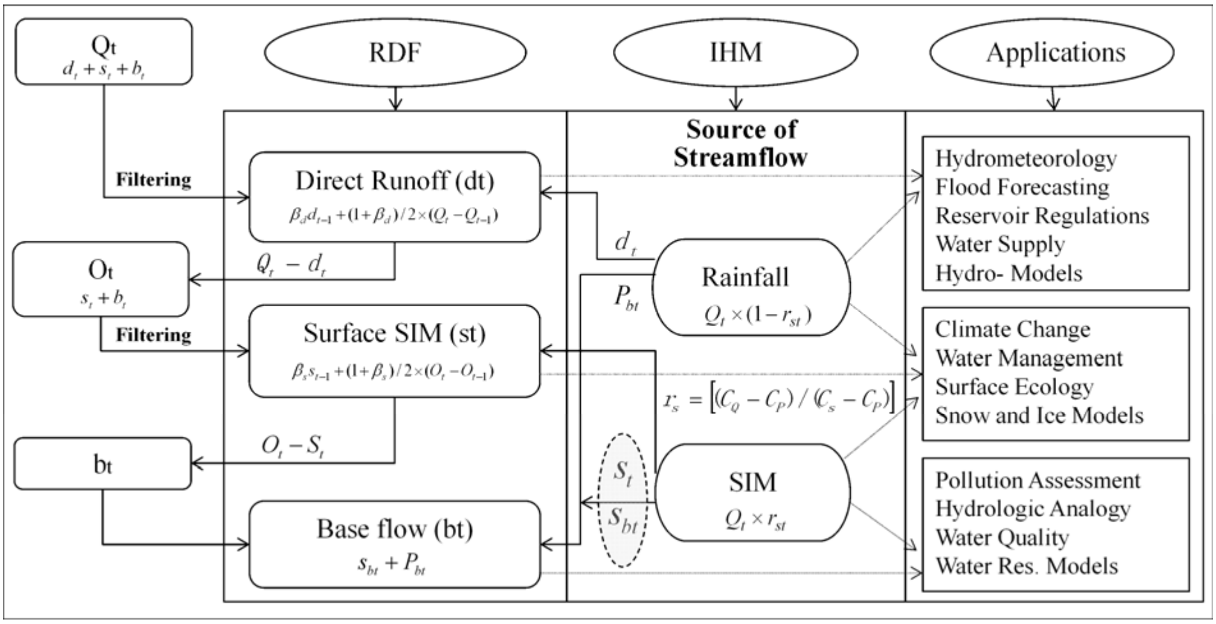

Figure 2 Flow chart of the coupled recursive digital filter (RDF) and the isotopic hydrogeochemical method (IHM) for monthly snow and ice melt (SIM) separation. Potential applications of the approach are also shown.

where r_s is the relative amount of SIM in the total streamflow (%) and C_Q, C_P, and C_s are the concentrations of the corresponding tracers (δ¹⁸O) (‰) in the streamflow, rainfall, and snow and ice, respectively.

Flows sourced from SIM and precipitation were then calculated as follows:

$$Q_{st} = Q_t \times r_{st} = s_t + s_{bt} \tag{5}$$

$$Q_{Pt} = Q_t \times (1 - r_{st}) = d_t + P_{bt} \tag{6}$$

where Q_{st} and Q_{Pt} are flow components in the streamflow sourced from the SIM and rainfall (mm), respectively, and s_{bt} and P_{bt} are flow components in the base flow from the two sources, respectively. Base flow was then described as follows:

$$b_t = s_{bt} + P_{bt} \tag{7}$$

According to the above, recharges from SIM and rainfall to the surface flow and base flow could be determined using the measured series as relative volume (%) or runoff depth (mm).

The correlation coefficient and Nash-Sutcliffe efficiency index (*NSE*) (Nash and Sutcliffe 1970; Li et al. 2010b; Sridhar and Nayak 2010; Nayak et al. 2012) were used to assess the accuracy assessments of the separated SIM with those have been published in literature.

$$NSE = 1 - \frac{\sum_{t=1}^{n} (Q_{st} - Q'_{st})^2}{\sum_{t=1}^{n} (Q_{st} - \overline{Q_{st}})^2} \tag{8}$$

where Q_{st} and Q'_{st} are the separated and published SIMs (mm), respectively, $\overline{Q_{st}}$ (mm) is the mean value of the reported SIM, and n is the length of the validation period.

3 Pilot Study

3.1 Characteristics of the monthly streamflow

Primary analysis of the monthly series for the characteristics of the channel streamflow was conducted. Diagrams of the selected eight basin rivers were divided into two types of hydrographic curves. The first type included those generated from higher altitude with more glacier storage. Groundwater discharge had a pronounced role in the regulation of rivers in these areas. Channel runoff in these rivers occurred always with a multi-yearly stable base flow (Figure 3a). Rivers in TLAI, YNIU, HEIH, and HSHH belonged to this type. Rivers in these areas are here conceptually said to be recharged by multiple components (MCR). The others were recharged mainly by the rainfall during the rainy season and featured a very low base flow during the dry season (Figure 3b). Rivers in HSHB, FENL, MYIN, and LIYU belonged to this type, which was here defined as rainfall-dominant recharged (RDR) rivers.

The slope of the runoff trend lines for both types of rivers were very close to 0 (Figure 3), which indicated an imperceptible change of the total streamflow in the area over the past half century.

3.2 Manual separation of the streamflow

The pilot study of the manual graphic separation empirically suggested that the base flow represents a large proportion of the annual total in the multi-component recharged (MCR)rivers. This observation holds true for the TLAI (Figure 4a) where the discharge of groundwater to the channel was widespread. In the RDR rivers, however, the proportions of the base flow to the annual totals were correspondingly low (Figure 4b). The land surface SIM made a smaller contribution to the MCR rivers than to RDR rivers (Figure 4).

4 Results and Discussion

4.1 Calibration and validation of the coupled methods

The coupled methods were implemented on all eight of the selected alpine rivers. Surface flow components at the beginning of the filtering (always in January when the dry season produced the lowest base flow in the channels) were set as zero, as in Equation (2). Multi-year averaged ratios

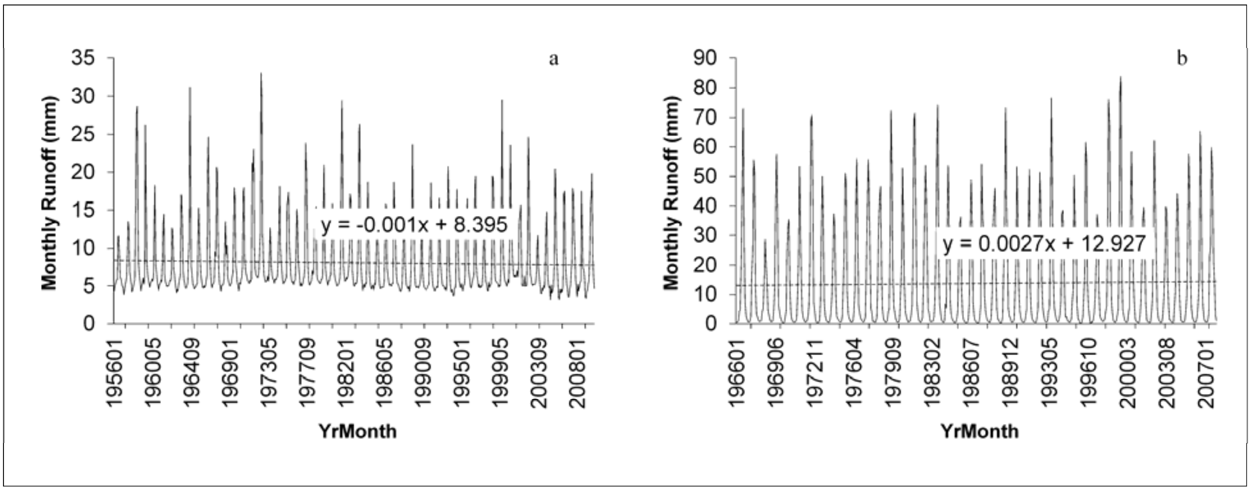

Figure 3 Monthly characteristics of the two types of mountainous runoff in the upper reaches of the HRB. (a: the TLAI River; b: the FENL River). YrMonth indicates the certain month in a corresponding year.

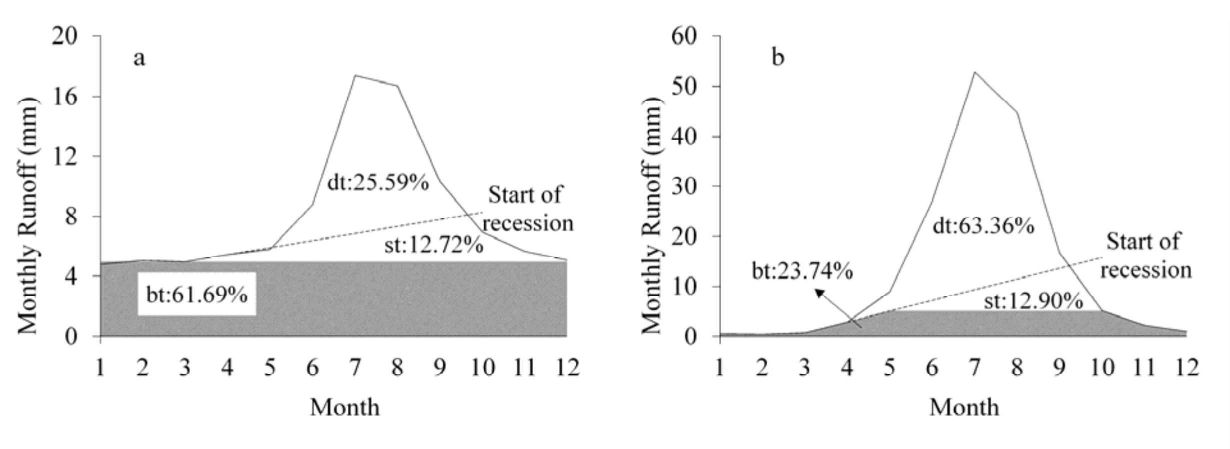

Figure 4 Manual separation of the two representative streamflows (a: the TLAI River; b: the FENL River).

of the SIM to the streamflow were compared to the manually separated ratios, which have been reported in earlier studies. The filter constant was adjusted for a better RDF filtering of d_t . The adjustment was tested by comparison to manual separation values. The rest of the flow was filtered again for the land surface SIM and the base flow. The IHM approach was implemented to determine the s_{bt} in the base flow according to Eq. (4). RDF constants and IHM values used in the study are listed in Table 3. Results from the IHM were calibrated by investigations performed by the Gansu Province Geological Survey (GPGS) in 2003. Analysis of the δ^{18}O samples and calculations of isotopic tracer concentrations were described by Ren (1999), Nie et al. (2005), and Zhang et al. (2009).

Comparison between separated SIMs and the GPGS investigated SIMs in the eight sub-basins showed a correlation coefficient of 0.86 and a NSE value of 0.72, which indicated that the coupled methods of quantifying SIM were reasonably accurate (Figure 5a). The streamflow in RDR rivers was very low during the dry season and the RDF filtering resulted in zeroes during this period. The SIM fractions during the months of April to October were compared to those reported by Zhang et al. (2009) for the year 2000. Comparison between the separated and reported SIMs indicated a fair accuracy rating of 0.71 for the correlation coefficient (Figure 5b) and a NSE value of 0.67. The spatial and temporal comparisons primarily indicated that the coupled RDF and IHM methods were suitable for determination of the monthly SIM in the area.

Table 3 Parameters for the applications of the coupled RDF and ICM methods

Basin	Annual runoff (mm)	RDF		IHM*		
		β_d	β_s	C_P	C_Q	C_s
TLAI	97.00	0.99	0.99	-6.96	-8.44	
HSHB	158.06	0.90	0.97	-6.98	-8.92	
FENL	163.34	0.90	0.92	-6.79	-8.90	
MYIN	14.17	0.95	0.90	-7.01	-9.01	13.09[a]
LIYU	77.71	0.96	0.90	-6.95	-8.08	13.90[b]
YNIU	144.84	0.95	0.95	-6.94	-7.93	
HEIH	165.90	0.96	0.99	-6.46	-7.63	
HSHH	99.95	0.95	0.95	-6.47	-8.20	

Notes: [a] 15 sampling data averaged; [b] 13 sampling data averaged apart from two singular values; * By Zhang et al. 2009.

4.2 SIM in surface flow and base flow

The calibrated methods were implemented to quantify the SIM in base flow and surface flow over the past 50 years. One part of the land surface SIM, s_t , was automatically separated using the RDF filter, and another part, s_{bt} , SIM in base flow, was determined using IHM. These two parts averaged into proportional percentages of 58% and 42% of the total SIM for s_t and s_{bt} , respectively. These results indicated that a considerable fraction of the SIM could be attributed to local infiltration and percolation into the groundwater and then into the streamflow, as shown on the left side of Figure 6. The multi-year averaged SIM in monthly base flow and surface flow is shown on the right side of the figure. It indicates that a great deal of SIM accumulated during the winter in the form of groundwater discharging into the channels, but in

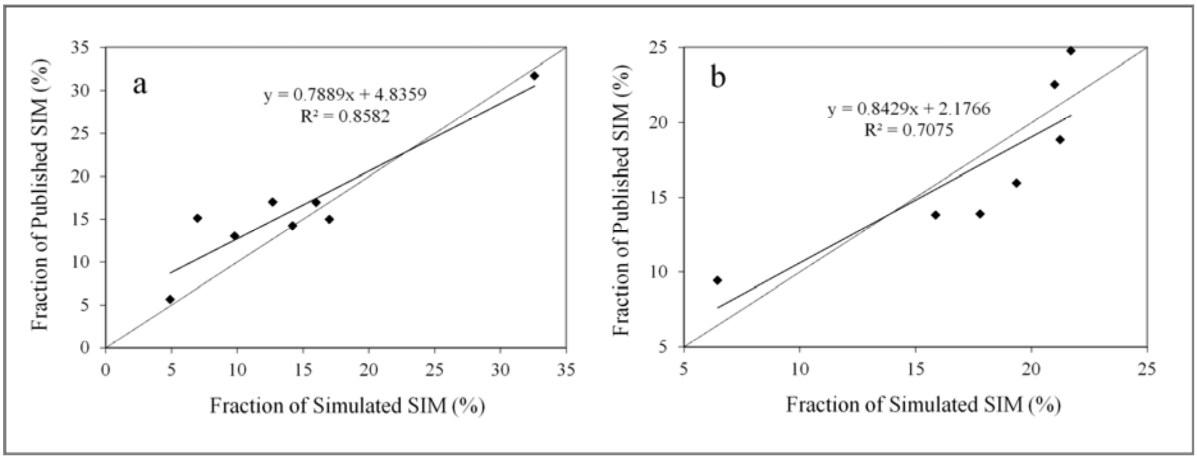

Figure 5 Comparisons of the simulated and reported SIMs (a: spatial comparison of all selected basins; b: temporal comparison of monthly SIMs of the FENL River).

summer, it took place mainly in the form of surface flow.

4.3 Characteristics of the monthly SIM

The coupled methods were implemented using all available gauging series for analysis of the monthly characteristics of the SIM flow. Results of the same-type rivers were averaged to illustrate the common attributes of the SIM. Multi-year averages yielded a monthly fractional curve with double peaks (Figure 7a) for the MCR rivers, but curves for RDR rivers yielded a single peak (Figure 7b). In MCR rivers, groundwater regulation of channel streamflow was huge, and the SIM in the base flow was relatively perennial and stable. There was more streamflow during the flood season, and the proportional SIM was relatively low, especially in July and August. For the RDR rivers, the variation of the SIM and the streamflow followed almost same trend along with the precipitation in a year, resulted in a curve with a single peak.

The period from May to October showed the highest relative contribution of SIM to the annual total, especially during the rainy season from June to September, when the proportion of the SIM was about 60% for the MCR rivers and 95% for the RDR rivers (Figure 7).

4.4 Inter-annual characteristics of the SIM

According to the simulations created using the coupled methods, proportions of the annual SIM to the total streamflow for the RDR rivers were holistically higher than those of the MCR rivers, mainly because of the relatively low levels of total streamflow in the RDR rivers. The inter-annual trend of the SIM for the two types of rivers was tested using the statistical methods of Least Square (LS), Sen's Slope (SS) (Sen 1968) and Mann-Kendall (Mann 1945; Kendall 1955). These statistical methods have been well described and compared by Nayak et al. (2010). Comparison between LS and SS for this study resulted in little difference in trend slope values at a time scale of decade (Figure 8). The similarity supports use of either test statistic method for the trend test of the alpine SIM in the study area. The separated SIM series of the two types of river were analyzed for their variable trends by M-K test and variable amplitude in decades by SS, combined with the LS-based trend line of the decadal variability as illustrated in Figure 9. M-K test resulted in a dramatically reductive trend of the SIM in both types of rivers sine 1970s till after middle 2000s, on a basis of the SIM in the 1960s. When analyzed in different decades, the variable amplitudes of

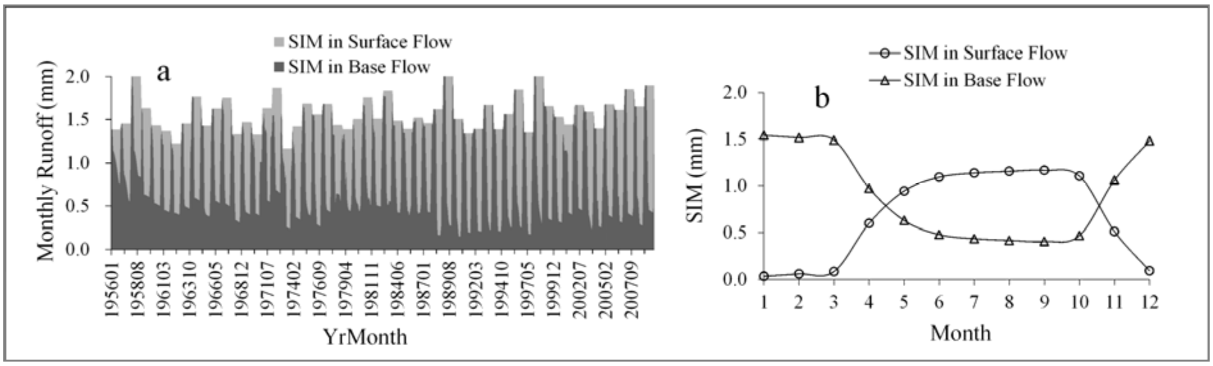

Figure 6 SIM in and out of the base flow (a: monthly SIM over the past 50 years; b: multi-year average).

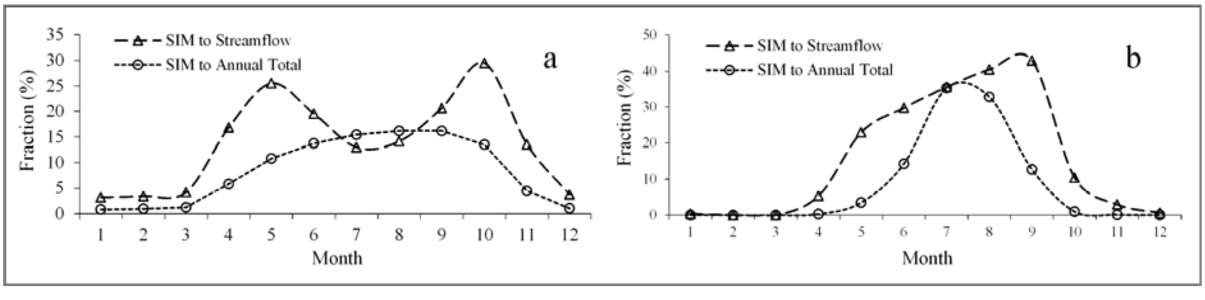

Figure 7 Monthly characteristics of the SIM recharging the two types of channel streamflow (a: the MCR rivers; b: the RD rivers).

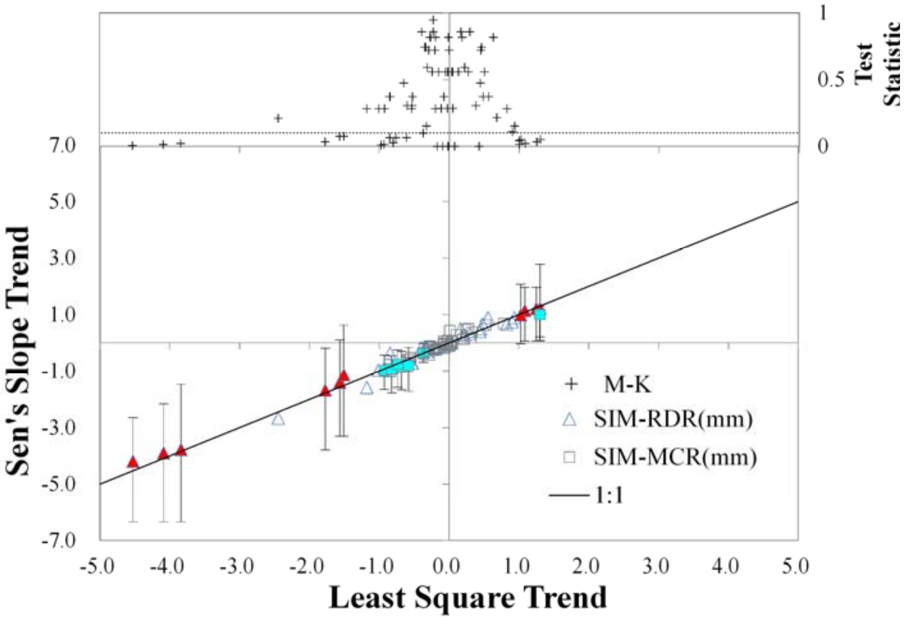

Figure 8 Trend slope values determined by Least Square (LS) and Sen's Slope (SS) methods compared to a 1:1 line for separated SIM series of the two types of rivers. For significant trends (α<0.10), data makers are solid and SS upper and lower limits are shown as error bars. Data with insignificant trends are shown as open data markers. M-K test statistics for all trends are compared to dashed lines at α=0.10 and shown on the top of the chart.

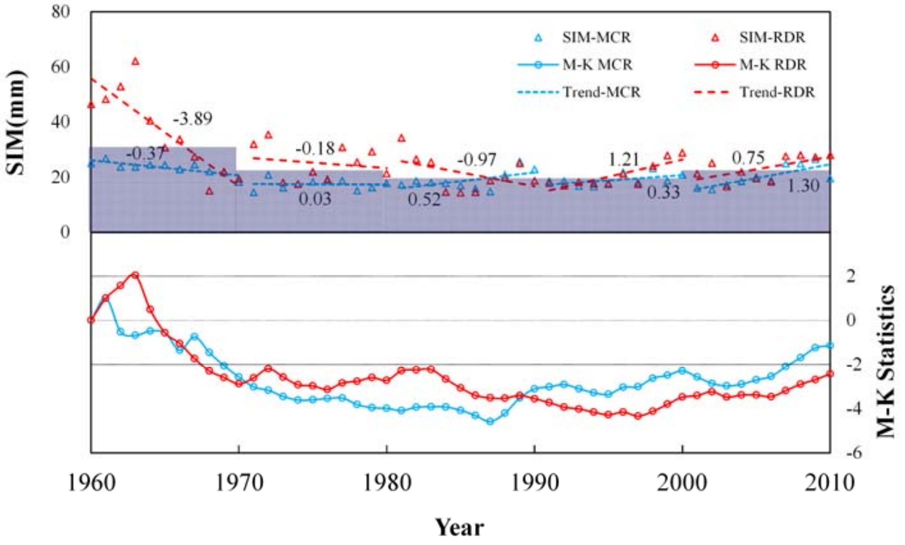

Figure 9 Annual variation of the SIM recharging to channels in the upper reaches of the HRB. General trend tested by M-K; variable amplitude tested by SS; SS trend values marked near LS trend line; decadal average of the SIM of the two types of rivers illustrated as broad blue columns.

SIMs changed with different SS values, indicated a complicated variability of SIMs in study area. For the MCR rivers, the SIM increased in most of decades except in 1960s, while SIM in RDR rivers kept to reduce until 1990s. Decadal average of SIMs in the two types of rivers indicated that SIM in the upper reaches of the HRB has risen to the levels of the 1970s in recent 10 years, but they remain lower than those of the 1960s (Figure 9).

5 Conclusions

Focusing on the determination of the alpine SIM based on the streamflow separation by coupling the RDF and IHM methods, the present study has been conducted on information collected over the past 50 years. Based on these findings, the following conclusions were drawn:

The coupled RDF and IHM methods helped to quantitatively classify the SIM in the surface and base flow. Validation of the coupled methods resulted in fair correlation coefficients in both space and time, suggesting that the RDF and IHM were suitable for the determination of the monthly SIM.

The simulated fractions of SIM to streamflow fell into a double peak curve for MCR rivers, and a single peak curve for RDR rivers. Both types of rivers have experienced an inter-annual decline in SIM since the 1960s. However, during the past 10 years, SIM in the two types of rivers again rose to the levels observed during the 1970s, but it remained below the levels of the 1960s.

The physical regime of the alpine SIM is very complex due to the strong heterogeneity of the environmental factors in both space and time, especially the variability of precipitation and air temperature in the high-altitude, non-gauging area (Rutter et al. 2009; Immerzeel et al. 2010). The coupled methods for SIM quantification described here were found to be helpful for the SIM dataset and the calibration and validation of the SIM related hydro-models.

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