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Estimating the snowmelt runoff volume through hydrograph separation

Kar erimesi hacminin hidrograf ayrımı yöntemi ile tahmini

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Abstract

The development of predictive tools that enable synchronization of rain and snowmelt times is desired for efficient water supply management in the snowmelt-dominant basins. This study aims to separate the streamflow hydrograph into its components, such as base flow, rainwater, and snowmelt, to be used for the snowmelt simulation studies of the Upper Karasu Basin, Erzurum, Turkey. The region covers an area of 242 km², where snow cover prevails for about 150 days in a year. The surface water flow component of the total runoff has been determined by using the chloride contents of surface water and groundwater end-members. The volumes of the rain and snowmelt water components in the surface water have been identified from the oxygen-18 contents of the rain, accumulated snow, and surface water. The hydrograph separation calculations have been performed daily by using the end-member contents of the total runoff during the snowmelt period between March 6, 2008, and June 15, 2008. The results show that the total runoff in the river during this period was composed of 9% groundwater, 73% snowmelt water, and 18% rain. The stream water's oxygen-18 isotope content indicates an effective mixing of snowmelt water and rainwater components during the surface flow process. This study also suggests that isotopic exchange is an important process that determines the snowmelt water's isotope content.

Keywords: Snowmelt runoff model, Upper Euphrates basin, Hydrograph separation, Stable isotopes.

Öz

Kar erimesinin baskın olduğu havzalarda verimli su temini yönetimi için yağmur ve kar erime sürelerinin senkronizasyonunu sağlayan tahmin araçlarının geliştirilmesi istenmektedir. Bu çalışma, Yukarı Karasu Havzası'ndaki (Erzurum) kar erimesi simülasyon çalışmalarında kullanılmak üzere akarsu hidrografını taban akışı, yağmur suyu ve kar erimesi gibi bileşenlerine ayırmayı amaçlamaktadır. Bölge, yılda yaklaşık 150 gün kar örtüsünün hâkim olduğu 242 km²'lik bir alanı kaplamaktadır. Toplam akışın yüzey suyu akış bileşeni, yüzey suyu ve yeraltı suyu uç elemanlarının klorür içerikleri kullanılarak belirlenmiştir. Yüzey suyundaki yağmur ve eriyen kar suyu bileşenlerinin hacimleri, yağmurun, birikmiş karın ve yüzey suyunun oksijen-18 içeriklerinden belirlenmiştir. Hidrograf ayırma hesaplamaları, 6 Mart 2008 ile 15 Haziran 2008 tarihleri arasındaki kar erimesi döneminde toplam akışın uç bileşenlerinin izleyici içerikleri kullanılarak günlük bazda yapılmıştır. Sonuçlar, nehirdeki toplam akışın %9'unun yeraltı suyu, %73'ünün eriyen kar suyu ve %18'inin yağmur suyundan oluştuğunu göstermektedir. Akarsuyun oksijen-18 izotop içeriği akarsu akışı sırasında eriyen kar suyu ve yağmur suyu bileşenlerinin etkili bir şekilde karıştığını göstermektedir. Bu çalışma aynı zamanda izotop takasının kar erimesi suyunun izotop içeriğini belirleyen önemli süreç olduğuna işaret etmektedir.

Anahtar kelimeler: Kar erimesi akış modeli, Yukarı Fırat havzası, Hidrograf ayırma, Kararlı izotoplar.

1 Introduction

The snow type precipitation in the high mountain basins of Eastern Anatolia constitutes a significant water potential, particularly in the Euphrates and Tigris basins. Water is stored in snow for about half of the year, and the snow melt governs the water supply dynamics of the dams, which serve as important hydropower production and irrigation water storage facilities. Efficient water supply management in snow-dominated basins requires a reliable understanding of the snowmelt process and its contribution to total runoff. The volume of the snowmelt water can be estimated by various methods, like degree-day, which requires information on snow water equivalent and snow-covered area. However, unlike rainfall, the collection of spatio-temporal snow cover data from the field is extremely difficult due to the inaccessibility of observation sites under winter conditions at high elevations. Secondary methods based on satellite data require ground-based information regarding the volume of snowmelt water in the total runoff.

The present study has been conducted in the Kırkgöze Basin, a sub-basin of the Upper Euphrates Basin in Turkey, where large dams are located (Figure 1). Four research-grade flow monitoring stations, have been established to collect continuous flow rate data on the main river (Karasu River, station ID 21-01) and its tributaries, Büyükçay stream (21-161), Yeşildere stream (21-168), and Köşk stream (21-152). The station 21-01 is located at the outlet of Kırkgöze Basin (Figure 1). The 16-year monthly average flow rates of these stations are presented in Figure 2, which indicates that a significant flow occurs during April through June, the snowmelt period (Figure 2). Several hydrological modeling studies to estimate the flowrate according to the change in temperature and the snow-covered area [1]-[7] have been performed in the Karasu Basin to estimate the snowmelt runoff in the area.

However, the contemporary snowmelt simulation studies need to be improved. For example, the runoff coefficients for snow and rain still require modifications, representing the ratios of snow or rain in the total runoff [6]. Besides, it is seen that the values of some other parameters of the snowmelt models are

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determined by subjective decisions. A better understanding of the components of stream flow during the snowmelt period may help reduce the uncertainty in estimating the snowmelt volume through various approaches.

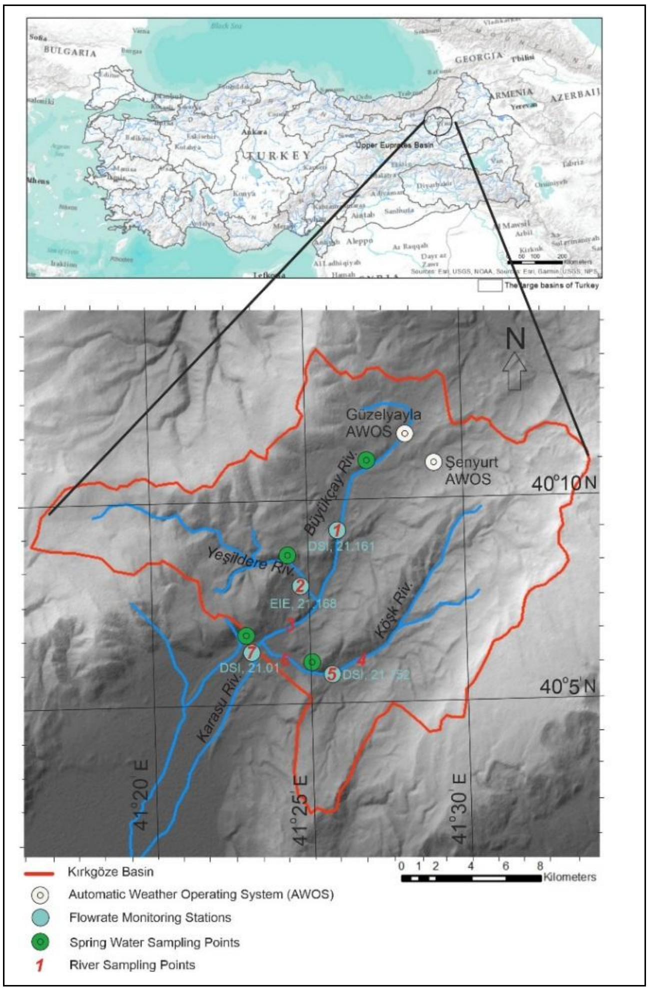

Figure 1. Location map of Kırkgöze Basin, which constitutes the northeast part of Upper Euphrates Basin.

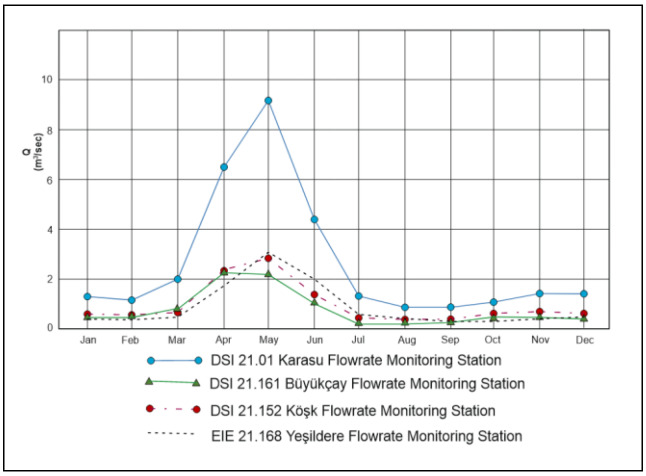

Figure 2. Average flow rates of flowrate monitoring stations in the Kırkgöze Basin.

The present study's objective is to separate the total runoff into its components (i.e. rain-fed surface water, snowmelt-fed surface water, and groundwater) by using the isotopic and chemical tracer contents of these end members. The chloride (Cl^-) concentration and stable isotope (i.e. oxygen-18 (18O)) content of water were commonly used for the separation of the components of runoff. Stable isotopes have been widely used to consider the source of streams and groundwater recharge [8]-[11]. Chemical tracers like Ca^+, Mg^{2+}, SO_4^{2-}, and Cl^- are also used for the separation of hydrograph components [12]-[16]. Cl^- and $\delta^{18}O$ are preferred in such studies as both tracer species behave conservatively upon mixing. In other words, the tracer mass is conserved, and there is neither a sink nor a source of tracer other than the end-members contributing to the mixture.

Chloride is very stable in geochemical processes and cannot be absorbed by clay minerals under the usual conditions of near-surface environments. Chloride ions don't precipitate unless the chloride concentration exceeds 200 g/l. Chloride minerals dissolve very easily by surface, subsurface, and transport processes and leave the system with water, so most groundwater systems have low chloride concentrations. The geologic formations of the study area are poor in chloride minerals (e.g. chlorapatite). Rain and snow have a very low chloride concentration, which does not change remarkably over annual periods. Because of the evaporation of water in the soil zone and the dissolution of the chloride minerals, groundwater always has a higher concentration than precipitation water. The effect of the evaporation of the chloride concentration in stream water in the study area is negligible because of the cool climate. Several studies [17]-[20] used both isotope and chemical tracers for hydrograph separation. For a successful hydrography component separation, the snowmelt water and groundwater end-members do not have to have similar tracer compositions, and each end-member should have a temporally homogeneous composition over the timescale of the hydrograph. The stream water can be separated into its two contributing components using mass balance calculations [21].

This paper is organized as follows: the protocols and data acquisition are presented in the Materials and Methods section, highlighting the stability of the chloride tracer and the mathematical model. The Results and Discussion section includes our predictions and findings about the study area.

2 Materials and methods

In this study, a two-stage hydrograph separation calculation approach was performed to determine the surface water and groundwater contributions to the total runoff. The first hydrograph separation has been used to separate the groundwater and surface water components. Then, the second hydrograph separation has been used to separate the snowmelt water and rain water contributions to the surface water component. The chloride. Cl^- and $\delta^{18}O$ tracers have been used in the first and second hydrograph separation calculations, respectively (Figure 3).

A two-stage hydrograph separation mass balance can be derived using the following equations (1-3). These equations have been employed earlier in several applications (e.g., [22]-[24]).

$$Q_T = Q_1 + Q_2 \quad (1)$$

$$C_T Q_T = C_1 Q_1 + C_2 Q_2 \quad (2)$$

$$Q_1 = Q_T \left(\frac{C_T - C_2}{C_1 - C_2} \right) \quad (3)$$

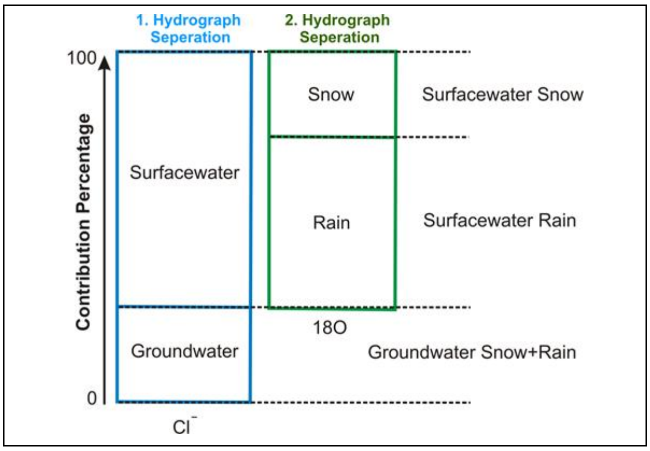

Figure 3. Two-stage hydrograph separation model.

Q_T is the total runoff of the river (m^3/s), Q_1 is the contribution from surface water (m^3/s), Q_2 is the contribution from groundwater, C_T is the Cl^- concentration of the total runoff of the river, C_1 is the Cl^- concentration of the surface runoff, and C_2 is the Cl^- concentration of the groundwater contribution for the 1st hydrograph separation.

For the 2nd hydrograph separation, Q_T is the surface flow contribution of the runoff (m^3/s), Q_1 is the contribution from snowmelt water (m^3/s), Q_2 is the contribution from rain water, C_T is the $\delta^{18}O$ content of the surface flow, C_1 is the $\delta^{18}O$ content of the snowmelt water, and C_2 is the $\delta^{18}O$ content of the rain water.

The contribution from the subsurface flow, which is the rapid flow toward the stream channel that occurs below the surface, has been assumed to be negligible, and snow's isotopic content is equal to snowmelt's isotopic composition. Further assumptions are discussed in [23], [25], and [26]. The hydrograph separation calculations were performed daily during the snowmelt period of 2008 (i.e. 6 March 2008 -15 June 2008).

Flow rate and tracer concentrations were observed from May 24, 2007, to June 15, 2008, to determine the end member contents required for the hydrograph separation calculations. The chemical analyses have been undertaken at Hacettepe University's Water Chemistry Laboratory. The isotope samples have been stored under cool conditions and sent to the Ehleringer Isotope Laboratory of the University of Utah for analysis.

2.1 River samples

Samples were collected at 15-day intervals at Flowrate Monitoring Stations (FMS) 21.01, 21.161, 21.152, and 21.168, which are located on the rivers Karasu Çıpak, Karagöbek, Köskdere, and Yeşildere, respectively (Figure 1). November 2007 samples are missing because of the road blockage after a heavy snow fall on November 22, 2007. The measurements have not been conducted between December 20, 2007, and March 10, 2008 due to the potential measurement error resulting from the icing of stream water.

2.2 Groundwater samples

To determine the tracer composition of the groundwater end-member, we utilized samples collected from seasonal springs since there are no accessible wells to be sampled. The seasonal springs' sampling was performed monthly from May through August 2007 (Figure 1). Since seasonal springs have no or very low flow rates during arid period, their discharges directly represent the annual recharge of the sampling year.

2.3 Precipitation samples

During the entire observation period, the precipitation samples were collected monthly in cooperation with the Erzurum Office of the State Meteorological Affairs (i.e., DMİ) Daily snow precipitation collected in sampling containers located on top of the stations has been let to melt in a closed container under low-temperature conditions. This approach prevented the evaporation of the sample. Some of these samples are a mixture of rain and snow. Separating the daily precipitation of snow and rain was not possible because of technical setbacks. However, the air temperature records show that when the samples were taken, the temperature of the air was very low. For this reason, the precipitation that occurred between the months of December 2007 and February 2008 has been assumed to consist only of snow.

2.4 Accumulated snow samples

Accumulated snow samples have been collected from different parts of the basin where the snow does not receive direct sunlight, which can change the isotope composition. The individual snow samples are assumed to be an ideal, mass-weighted average mixture of different snow fall events. The entire snowpack has been sampled by an auger, and the sample has been left to melt in a closed container at a low temperature.

3 Results and discussion

3.1 Predicting the end-member contents of the total runoff

For the first hydrograph separation, 0.20 and 0.69 ppm were used, as representative chloride concentrations of the groundwater and the surface water end-members, respectively. In general, groundwater should have a higher chloride concentration than river water, and precipitation is expected to be observed. The chloride contents of the end-members through the entire observation period showed that the chloride content of the river, which was sampled on the FMS 21.01, was lower during the wet period and higher during the dry period (Figure 4).

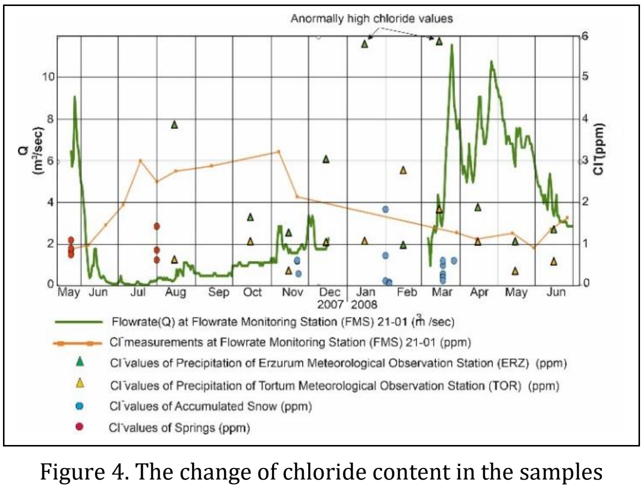

Figure 4. The change of chloride content in the samples through sampling period.

This situation shows an increase in groundwater and surface water contribution ratios in river flow during the dry period

(November). For this reason, the highest chloride content of the river is accepted as the representative end-member value of the groundwater. The river water does not have neither rain water nor snowmelt water contributions during the arid period, during which the river flow is sustained only by groundwater contributions. However, the spring samples have a lower chloride concentration (average 0.921 ppm) than the surface water component (Tables 1 and Table 2). This situation shows that the seasonal springs have shorter residence times than the regional groundwater flow system, which feeds the river. In other words, the chloride contents of the seasonal spring samples do not represent the groundwater end-member.

Table 1. Observed chloride contents of the springs.

Sampling Date	Sample ID	Cl^- (ppm)
24.05.2007	Spring 1	0.876
24.05.2007	Spring 2	0.788
24.05.2007	Spring 4	0.905
24.05.2007	Spring 5	0.751
24.05.2007	Spring 6	1.102
01.08.2007	Spring 2	0.870
01.08.2007	Spring 7	0.635
01.08.2007	Spring 6	1.441
Mean		0.921
Standard Deviation		0.250

Table 2. Observed chloride contents of accumulated snow (Acc. Snow) samples and precipitation samples from Tortum Meteorology Observation Station (TOR).

Type	Sampling Date	Cl- (ppm)	Location
Precipitation	August 2007	0.655	TOR
Precipitation	October 2007	1.085	TOR
Precipitation	November 2007	0.389	TOR
Precipitation	December 2007	1.071	TOR
Precipitation	January 2008	1.100	TOR
Precipitation	February 2008	2.813	TOR
Precipitation	March 2008	1.853	TOR
Precipitation	April 2008	1.075	TOR
Precipitation	May 2008	0.386	TOR
Precipitation	June 2008	0.375	TOR
Acc. Snow	22.11.2007	0.599	Snow Sample
Acc. Snow	22.11.2007	0.625	Snow Sample
Acc. Snow	23.11.2007	0.300	Snow Sample
Acc. Snow	01.02.2008	0.124	Snow Sample
Acc. Snow	04.02.2008	0.091	Snow Sample
Acc. Snow	01.02.2008	0.739	Snow Sample
Acc. Snow	12.02.2008	1.844	Snow Sample
Acc. Snow	04.02.2008	0.060	Snow Sample
Acc. Snow	18.03.2008	0.267	Snow Sample
Acc. Snow	18.03.2008	0.499	Snow Sample
Acc. Snow	18.03.2008	0.224	Snow Sample
Acc. Snow	18.03.2008	0.295	Snow Sample
Acc. Snow	18.03.2008	0.216	Snow Sample
Acc. Snow	18.03.2008	0.611	Snow Sample
Acc. Snow	18.03.2008	0.134	Snow Sample
Acc. Snow	27.03.2008	0.610	Snow Sample
Mean		0.694	

The chloride contents of the Surfacewater-Snow and Surfacewater-rain (see Figure 3) end-members have been determined from the mean of the accumulated snow and precipitation samples collected at Tortum Meteorological Observation Station (TOR), respectively. The Surfacewater-Snow and Surfacewater-rain end-members have mean chloride contents of 0.45 ppm and 1.08 ppm, respectively. The precipitation samples that are observed at the Erzurum Meteorological Station (ERZ) were relatively higher than the usual rain concentration (Figure 4). The reason for this situation is probably linked to human activities like flue gases formed by coal burning. Therefore, the data observed at the station in Erzurum is not considered in the assessment.

The stable isotope contents of the rain water and snowmelt water contributions to surface water have been used in the second-stage hydrograph separation. The isotope contents of these end members are presented in Table 3.

Table 3. The $\delta^{18}O$ isotope contents of rain water and snow water end-members.

End-Member	$\delta^{18}O$ (‰, V-SMOW)
Mean March (rain)	-5.98
Mean April (rain)	-6.72
Mean May (rain)	-5.63
Mean June (rain)	-4.22
Mean Accumulated Snow	-16.85

In this separation, the isotope contents of different months are assumed to represent every day of the corresponding month, and the isotope content of the snowmelt water is assumed to be constant throughout the melting period. In order to ensure that the snow samples represent a composite mix of snow-type precipitation, snow sampling was carried out at the beginning of the melting period (March) and in different parts of the catchment from non-sunlit locations. During the year, the isotope content of the river water stayed stable around -12 ‰ (Figure 5).

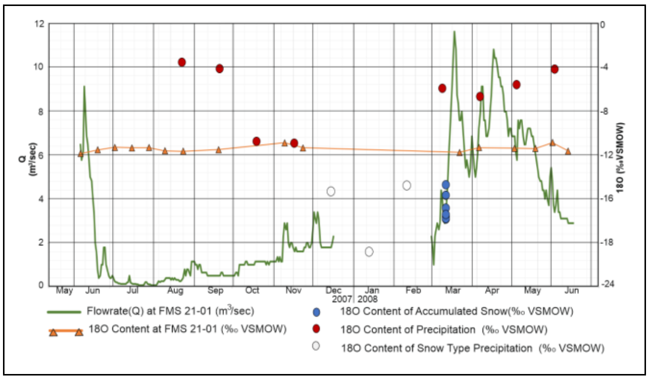

Figure 5. The change of $\delta^{18}O$ content in samples through the sampling period.

On the other hand, the $\delta^{18}O$ contents of the rain have also been stable during the melting period. At the beginning of the melting period, the $\delta^{18}O$ content of accumulated snow samples generally varied between -14‰ and -17‰ (Table 4).

Table 4. The $\delta^{18}O$ isotope contents of accumulated snow used in hydrograph separation.

Snow Sampling Date	$\delta^{18}O$ V-SMOW)
18.03.2008	-14.72
18.03.2008	-17.84
18.03.2008	-16.85
18.03.2008	-17.61
18.03.2008	-17.81
18.03.2008	-17.43
18.03.2008	-15.68
Mean	-16.85

A two-stage method was used to determine the contribution rates of “Surfacewater Snow”, “Surfacewater Rain” and “Groundwater Snow+Rain” to the total runoff in the river during the snow melting period of the basin (see Figure 3). For this purpose, first hydrograph separation calculations have been performed by using the chloride contents of the “Surfacewater” and “Groundwater” end-members to separate the groundwater and surface water components of the total runoff. Then, second hydrograph separation calculations have been performed by using the $\delta^{18}O$ contents of the “Surfacewater Snow” and "Surfacewater Rain” end-members to separate the snowmelt water and surface water subcomponents of the total runoff.

3.2 The 1st hydrograph separation

The total runoff has been separated into groundwater and surface components by the first hydrograph separation. The chloride content of total runoff has been observed at 15-day intervals at the outlet of the basin (i.e., FMS 21-01). The geological and hydrogeological data show that the basin-wide lithological units have low permeability. Hence, the contribution of subsurface flow to the total runoff was assumed to be negligible. According to the results of the first component separation calculations, 9% of the total runoff is composed of groundwater, whereas the surface water component comprises 91% of the total runoff (Figure 6).

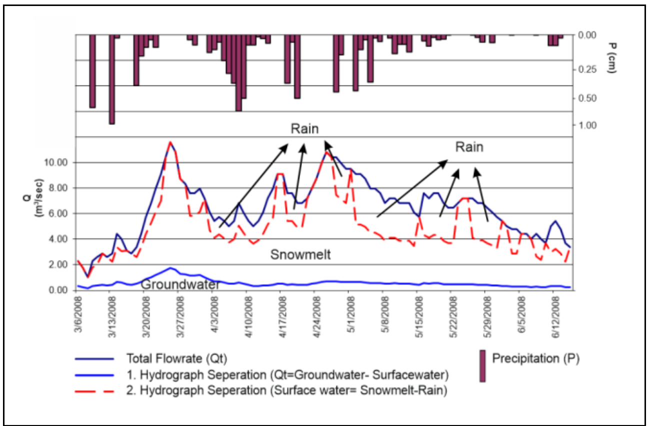

Figure 6. Hydrograph separations.

Results of the first component separation calculations also show that the heavy rain and snowmelt inputs into the groundwater system cause an increase in the groundwater input into the total runoff. The relatively low contribution of groundwater is thought to be associated with the low hydraulic conductivity of aquifer rocks, which are mainly volcanic.

3.3 The 2nd Hydrograph separation

The second hydrograph separation has been used to determine the rain water and snowmelt water contributions to the "surface water” component. The surface flow volume obtained from the first hydrography separation has been separated into its components by using the average isotope content of accumulated snow and monthly collected rain samples. The calculations were made for the days the rain event occurred. It is assumed that on days without rain events, the only source of surface flow is snowmelt (Figure 6). According to the results, the surface flow was composed of 80% snowmelt water and 20% rain water during the snow melting period between March 6, 2008, and June 15, 2008.

In the present study, the isotopic value of the snowmelt water has been obtained from snow core samples, and it has been assumed to be constant throughout the melt season, as stated in [21]. However, field [27] and laboratory [28] experiments show significant differences between meltwater's isotopic composition and the snowpack's average isotopic value and rain-on-snow events used for hydrograph separation [21]. With the data available, there is currently no alternative method to better quantify the contribution rates of rain, snow, and groundwater. For better hydrograph separation, a denser network of rain and snow cover should be established during the snowmelt period. However, the feasibility of such monitoring processes is low because of substantial logistical and financial limitations.

4 Conclusions

The study has been carried out on the Karasu (Kırkgöze) river in the basin, which has a drainage area of 242 km^2, and the basin is covered by snow for about 150 days. The stream flow took place in the spring, mainly due to snow melt in the basin. Calculations performed for the snowmelt period of 2008 (March 6, 2008-June 15, 2008) The first hydrograph separation have been performed by using the chloride contents of the end members to separate groundwater and surface water components of total runoff. Then the second hydrograph separation has been performed by using the $\delta^{18}O$ isotope contents of the end-members to separate surface water subcomponents of snowmelt water and rain water.

Daily calculations using the contents determined from the hydrograph separations during the melting of snow between March 6, 2008, and June 15, 2008 revealed that groundwater, snowmelt water, and rain water comprise 9%, 73% and 18% of the total runoff, respectively. The results of this study are based on various assumptions. For better hydrograph separation, more spatio-temporal data on the tracer content of rain and snow is needed. However, the feasibility of such monitoring processes is low because of substantial logistical and financial limitations.

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6 Author contribution statements

Emrah PEKKAN and Celal Serdar BAYARI conceived of the presented idea. Emrah PEKKAN developed the theory and performed the computations. Celal Serdar BAYARI and Alparslan ARIKAN verified the analytical methods. Celal Serdar BAYARI and Alparslan ARIKAN supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

7 Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared."

"There is no conflict of interest with any person/institution in the article prepared".

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