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Is there a geomorphic expression of interbasin groundwater flow in watersheds? Interactions between interbasin groundwater flow, springs, streams, and geomorphology

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Key Points:

- Exchanges of IGF in complex geology can affect landscape/watershed geomorphic evolution
- IGF is expressed as preferred orientations of springs and flow directions of channels
- IGF is expressed by unique spatial trends in radiocarbon residence times

Supporting Information:

- Table S1

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Abstract Interbasin groundwater flow (IGF) can play a significant role in the generation and geochemical evolution of streamflow. However, it is exceedingly difficult to identify IGF and to determine the location and quantity of water that is exchanged between watersheds. How does IGF affect landscape/watershed geomorphic evolution? Can geomorphic metrics be used to identify the presence of IGF? We examine these questions in two adjacent sedimentary watersheds in northern New Mexico using a combination of geomorphic/landscape metrics, springflow residence times, and spatial geochemical patterns. IGF is expressed geomorphically in the landscape placement of springs and flow direction and shape of stream channels. Springs emerge preferentially on one side of stream valleys where landscape incision has intercepted IGF flow paths. Stream channels grow toward the IGF source and show little bifurcation. In addition, radiocarbon residence times of springs decrease and the geochemical composition of springs changes as the connection to IGF is lost.

1. Introduction

Groundwater supports perennial springflow and stream base flow which is critical to aquatic ecosystem functioning. Thus, it is imperative to quantify the impacts of climate and land use/land cover change on groundwater and its role in perennial springflow and base flow [*Ophori and Tóth*, 1990; *Rademacher et al.*, 2005; *Tague et al.*, 2008; *Ferguson and Maxwell*, 2010; *Singleton and Moran*, 2010; *Stewart et al.*, 2010; *Frisbee et al.*, 2011; *Gardner et al.*, 2011; *Cook*, 2012; *Frisbee et al.*, 2012; *Manning et al.*, 2012; *Smerdon et al.*, 2012; *Harrington et al.*, 2014]. However, it remains uncertain how perturbations propagate through the groundwater system and impact the surface water system. Conceptual models describing groundwater and surface water interactions typically assume that groundwater flow paths develop within boundaries defined by the surface water drainage divide. This assumption is not always true. In the case of interbasin groundwater flow (IGF), water recharges in one watershed, flows beneath the surface water divide, and discharges in an adjacent watershed. This complicates our ability to quantify impacts to perennial springflow and base flow.

Interbasin groundwater flow is not a new concept. *Hursh* [1946] hinted that the Coweeta Experimental Forest in North Carolina was suitable for hydrological studies in part due to the absence of stratification common in sedimentary rocks that could allow rainfall from outside the watershed to affect streamflow within the watershed. Sedimentary watersheds may be especially conducive for IGF because stratigraphic layers may cross beneath several surface water divides. However, IGF is not limited to sedimentary rocks; it has been identified in volcanic bedrock in Costa Rica [*Genereux et al.*, 2002; *Genereux and Jordan*, 2006; *Genereux et al.*, 2013] and in igneous, metasedimentary, and carbonate bedrock in Death Valley [*Anderson et al.*, 2006; *Gillespie et al.*, 2012; *Gardner and Heilweil*, 2014; *Nelson and Mayo*, 2014]. IGF is not excluded from Tóthian flow models as regional-scale groundwater flow paths can flow beneath local- and intermediate-scale discharge points [*Tóth*, 1995]. Despite the potential for IGF to occur in many different geologic settings, it is seldom considered as a competing hypothesis for field-based research and rarely incorporated into watershed-scale hydrological models (*Zanon et al.* [2014] is a notable exception). This is due to the following: (1) the lack of metrics that can be used to inform the location and magnitude of water exchanges within

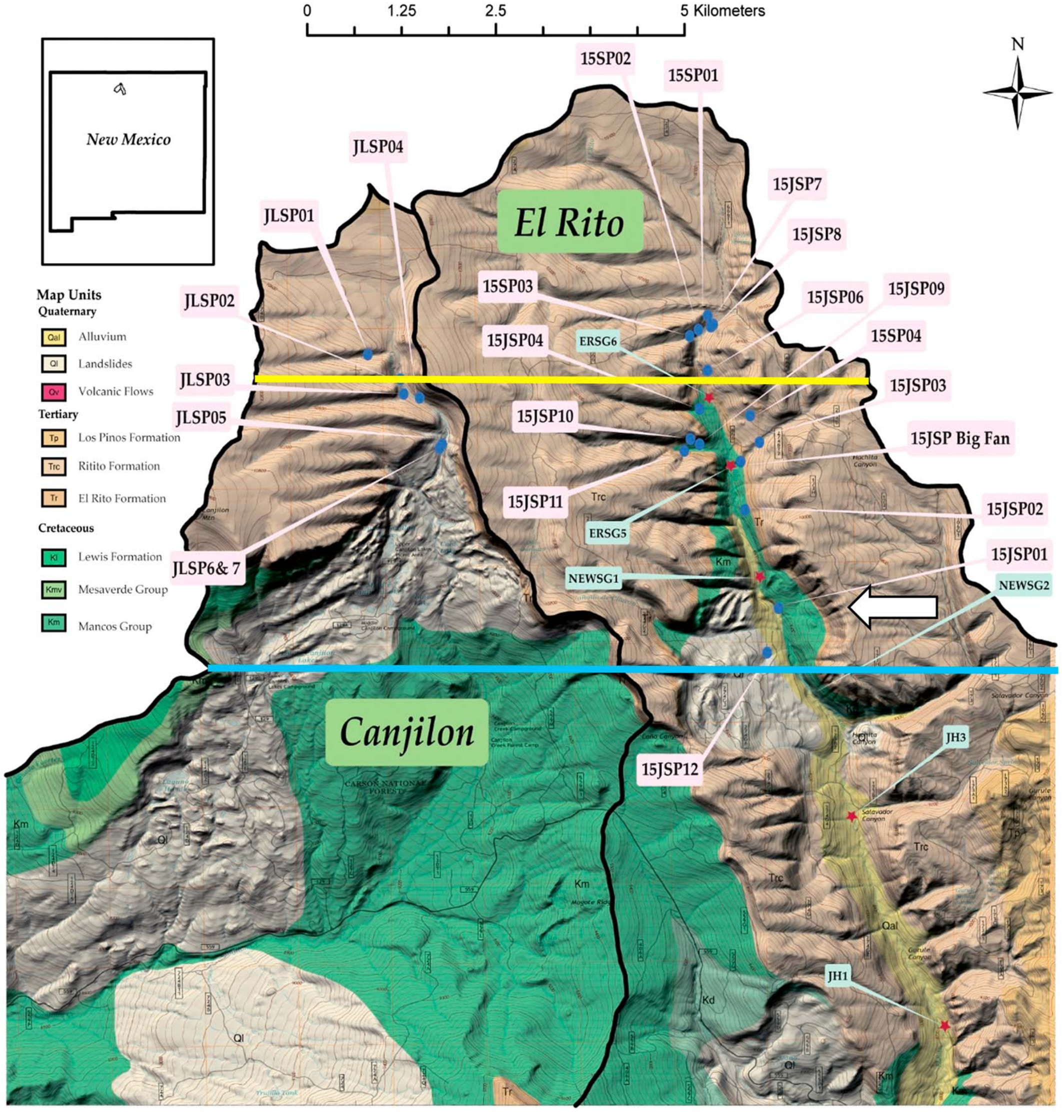

Figure 1. Map of the Canjilon and El Rito headwaters. Spring sampling locations are marked in pink boxes, and stream sampling locations are marked in light green. The transition from gaining to losing conditions is shown by the white arrow.

hydraulically connected watersheds, (2) the lack of observational data defining the conditions in which IGF is most likely to occur, and (3) the increased model complexity required to accurately simulate IGF.

Unfortunately, the presence of IGF may be obscured in most of the commonly employed field techniques [*Genereux et al*., 2002]. Recent research indicates that the contributions of water, solute, and age-mass from IGF can outweigh the sources derived from within the surface water boundary [*Genereux et al*., 2013]. Therefore, if IGF contributes water and solute mass from one watershed to another and is not accounted for in mass-balance models, then the modeled water and geochemical flux will be too low from the "receiving" watershed [*Anderson et al*., 2006; *Belcher et al*., 2009; *Genereux et al*., 2013] and too high from the "contributing" watershed. These are not easy problems to address since IGF, like groundwater flow paths in general, is "hidden" from direct observation. It is important to develop methodologies to reliably identify IGF and provide information on the location and magnitude of exchanges.

We address these questions in the geologically complex El Rito and Canjilon watersheds located in the Tusas Mountains of northern New Mexico (36°20.61′N and 106°11.34′W; Figure 1). The headwaters of the El Rito watershed are characterized by two distinct, persistent hydrogeological zones: (1) gaining conditions in the upper headwaters supported by direct groundwater discharge and flow from perennial springs and (2) losing

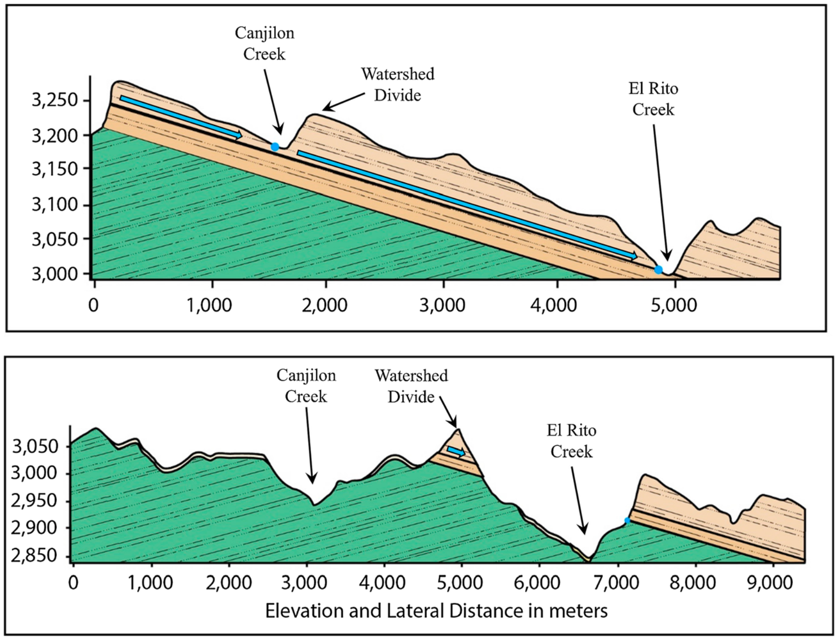

Figure 2. Geologic cross sections through (top) the upper Canjilon headwaters and Northern 15 Springs (see yellow line in Figure 1) and (bottom) the lower Canjilon headwaters and Southern 15 Springs (see blue line in Figure 1). The upper east dipping, light tan layer is the Ritito conglomerate. The lower east dipping, sandy brown layer is the El Rito conglomerate. The underlying west dipping, green layer is the Mancos Shale. The blue dots represent approximate spring locations. The blue arrows show groundwater flow paths through the Ritito conglomerate.

conditions immediately downstream of the headwaters and present to the midreaches of the watershed. The headwaters encompass an area known as “15 Springs,” where east dipping Cenozoic conglomerates unconformably overlie west dipping Mesozoic sedimentary units (Figure 2). We test two hypotheses: (1) the gaining reach (zone 1) is sustained by IGF from the Canjilon watershed located to the west, and the losing reach (zone 2) occurs where that hydraulic connection is lost; and (2) geomorphic relationships (e.g., preferential landscape placement of springs and preferential flow directions of stream channels) are present in the gaining reach where IGF is present, and those relationships are absent in the losing reach where IGF is lost.

We test these hypotheses by first determining if IGF is present (hypothesis 1). Where springs are supported by IGF along a stratigraphic unit, we expect to see similar geochemical characteristics, perhaps even a continuous geochemical evolutionary pathway that extends across the surface water divide. In contrast, springs that are not hydraulically connected to the same IGF source will be geochemically distinct. In addition, the mean radiocarbon residence times of springs will be longer where IGF is present due to longer flow paths originating outside the divide. Second, we determine if there is a geomorphic expression of IGF (hypothesis 2). We expect to see a preferential orientation in spring emergences especially where the stratigraphic layer supporting IGF has been incised by a stream channel. In this case, springs should emerge in a systematic fashion on the upstream location where the groundwater flow has been intercepted. Likewise, we expect to see a topographic response in the form of preferred landscape orientations (placement) of streams where a strong groundwater connection is present.

2. Site Description and Methods

The watershed-scale geomorphology is strongly influenced by stratigraphy and structure. The upper reaches of the El Rito and Canjilon watersheds are on east dipping Cenozoic conglomerates. These include the Oligocene Ritito conglomerate, which is poorly lithified, iron poor, silica cemented, and comprised predominantly of Proterozoic plutonic and metamorphic clasts. It overlies the Eocene El Rito conglomerate, which is well lithified, iron rich, silica cemented, and comprised of primarily Proterozoic quartzite clasts eroded from the Tusas Mountains [*Smith et al*., 1961; *Doney*, 1968; *Smith*, 1995; *Maldonado*, 2008]. In the upper reaches of the headwaters of both watersheds, the streams are developed and flow within the Ritito conglomerate.

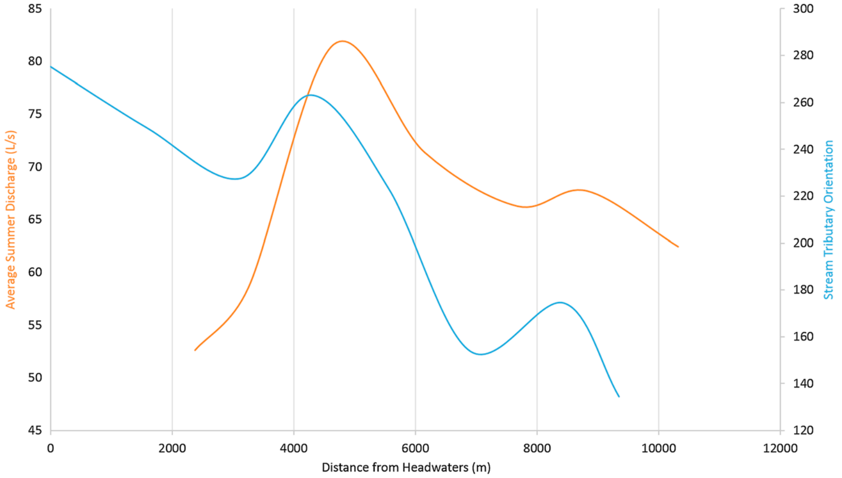

Figure 3. Average summer discharge and flow direction of tributary channels in the El Rito headwaters.

Tributary streams on the dip slope tend to be well developed and linear, while tributaries on the obsequent slope are shorter and steeper compared to the gently sloping relief of the dip slopes. Since the overlying Cenozoic layers dip to the east, the dip slope is located on the western side of the valley formed by the main stream channels and the obsequent slopes are located on the eastern side of the valley (Figure 1). The character of the landscape changes dramatically where the main channels downcut into the west dipping Mesozoic Mancos Shale, a dark grey, fine grained, calcareous unit (Figures 1 and 2). The slopes are dominated by chaotic mass wasting deposits and deep-seated rotational slumps with arcuate head scarps developed in the conglomerates. The main channels are visibly displaced opposite the mass movements (see white arrow in Figure 1).

Discharge was measured longitudinally down the El Rito stream using salt dilution [*U.S. Geological Survey*, 1977; *Payn et al.*, 2009]. Average summer discharge is shown in Figure 3. Grab samples of water were collected from six springs in the headwaters of the Canjilon watershed and 24 springs in the headwaters of the El Rito watershed (Figure 1). Water samples were promptly filtered and analyzed for standard cations, anions, silica, and selected metals including strontium, iron, aluminum, manganese, and selenium. Metals were chosen to assist in the delineation of flow paths through the underlying Mesozoic sedimentary units since the Mancos Shale is a known source of selenium [*Mast et al.*, 2014; *Tuttle et al.*, 2014a, 2014b].

The weighted mean residence time of each spring was estimated using radiocarbon (t_{14C})

$$t_{14C} = -\left[t_{1/2}/ln(2)\right]\ ln(a_m/a_0) \tag{1}$$

where $t_{1/2}$ is the half-life of ^{14}C (5730 years) and a_m is the measured radiocarbon activity of each spring in percent modern carbon (pmC). Radiocarbon residence times for springs with δ^{13}C values less than -20.0‰ and carbon activities (a_m) less than 0.8500 were corrected by assuming that the radiocarbon activity of the recharging water (a_0) was 85 ± 5 pmC [*Vogel and Ehhalt*, 1963; *Plummer and Glynn*, 2013]; four decimal places were reported by the analytical lab and are reproduced here. Springs with these characteristics likely have not experienced significant exchange with soil CO_2 or calcite in the bedrock.

The landscape orientations of springs were measured in the field, and the tributary flow directions were measured using geographic information system tools. The upper Cenozoic layers in the headwaters dip to the east and strike roughly north (0°) to south (180°). The main channels of the Canjilon and El Rito headwater streams are both subsequent streams, i.e., flowing parallel to the strike. Springs are point features in the landscape; however, we define the landscape orientation of a spring as its cardinal location relative to the main channel. Since the main headwater streams are flowing north to south, springs that emerge west of the main channels have an orientation of 270°, east of the main channels have an orientation of 90°, northwest of the main channels have an orientation of 315°, etc. This allows us to describe the spatial distribution of all springs relative to the stream channels. All spring orientations were projected into rose diagrams. Tributary flow directions were converted to unit vector representations, which were averaged

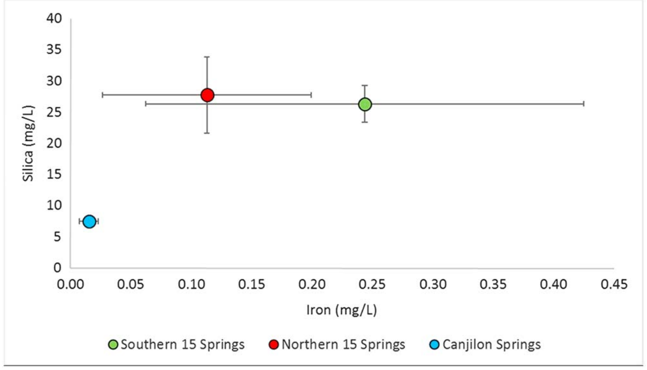

Figure 4. Average silica and iron concentrations of springs.

along the stream networks giving an average flow direction of the tributary stream. These flow directions were then binned using the stream length as a weighting function. These bins were finally converted to degree representations where, for example, a stream that flows from west to east has a flow direction of 270° (i.e., the flow direction describes where it originates and which direction it flows). Likewise, a stream that flows from east to west has a flow direction of 90°.

3. Results

All Canjilon springs have a_m greater than 1.0000 pmC and δ^{13}C less than −23.0‰. This indicates that the average residence times of the Canjilon springs are modern (less than 100–150 years old/recharged after 1900) and that the groundwater has experienced little, if any, exchange with CO_2 or calcite in the soil or bedrock. In comparison, a_m increased and average residence times decreased progressing from north to south in the El Rito headwaters. Springs in the upper reaches (northern) of the El Rito headwaters emerge almost exclusively from the Ritito conglomerate. They have δ^{13}C ranging from −19.7 to −24.0‰ and a_m ranging from 0.6909 to 0.9694 pmC. The average residence times of the northern springs range from 1710 ± 30 years (providing additional evidence that old groundwater can discharge in small watersheds) to modern (springs located farther south; see supporting information Table S1 for ^{14}C data). Springs in the lower reaches (southern) of the El Rito headwaters emerge primarily at the contact between the El Rito conglomerate and the Mancos Shale. These springs have δ^{13}C ranging from −15.2 to −21.9‰ and a_m ranging from 0.8840 to 1.0316 pmC implying modern residence times and enhanced exchange with calcite in the soil or shale bedrock.

Spatial trends in the geochemical evolution of groundwater were quantified by dividing the springs into three groups based on the radiocarbon data: Canjilon springs, Northern 15 Springs (El Rito), and Southern 15 Springs (El Rito). Canjilon springs discharge relatively geochemically immature groundwater (Figure 4). In comparison, the Northern 15 Springs have the highest silica concentrations yet relatively low iron concentrations. This contrasts with the Southern 15 Springs which have elevated and highly variable iron concentrations and similar high silica concentrations. Selenium and manganese were present at low concentrations (0.001 to 0.0005 mg/L; $n = 4$) in the Southern 15 Springs, were not detected in the Canjilon springs, and were detected in only 2 of the Northern 15 Springs (0.0005 mg/L). Aluminum was not detected in the Canjilon springs but was detected in 2 of the Northern 15 Springs (averaged 0.018 ± 0.005 mg/L) and in all the Southern 15 Springs and at higher concentrations (averaged 0.034 ± 0.034 mg/L).

Springs and streams in the headwaters of both watersheds show remarkably strong preferred spring orientations and flow directions (Figure 5). Greater than 70% of all springs in the Canjilon and Northern 15 Springs emerge on the western side of the stream valleys in the Ritito conglomerate (Figures 5a and 5b). In comparison, this strong preferential orientation is not present in the Southern 15 Springs (Figure 5c). Instead, these springs primarily emerge from the eastern ($<$50%) and northwestern sides of the valley ($<$35%) from the El Rito/Mancos Shale contact and from within the upper Mancos Shale. The preferential flow directions of tributary stream channels are shown in Figures 5d–5f. The tributary channels of the Canjilon and Northern 15 Springs areas primarily flow from west to east; stream channels grow in the direction of IGF and show little bifurcation (Figures 5d and 5e) [*Marra et al.*, 2015]. In fact, there is little, if any, channel development on the eastern side of the Canjilon or eastern side of the Northern 15 Springs valleys. In comparison, there is large variability in the flow direction of tributary channels in the Southern 15 Springs area (Figure 5f), consistent with the loss of that hydraulic connection to the groundwater flowing along the Ritito. When the flow directions of tributary channels are plotted against the average summer discharge (Figure 3), it is readily apparent that the transition from gaining (zone 1) to losing (zone 2) occurs where the preferential west-to-east flow direction is lost.

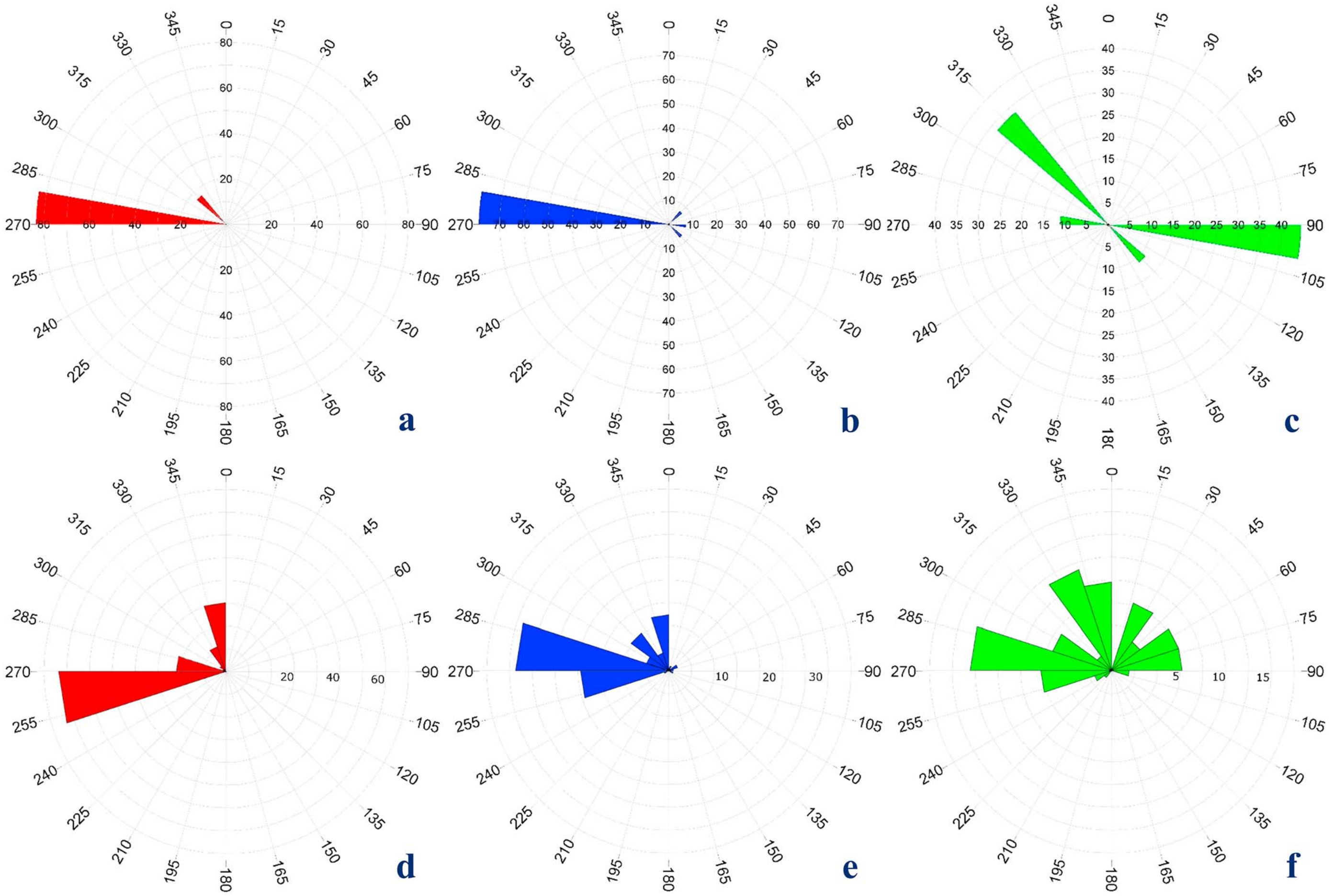

Figure 5. Spring orientations and flow directions of tributary streams. The upper row of rose diagrams shows the orientation of (a) Canjilon springs, (b) Northern 15 Springs, and (c) Southern 15 Springs. The lower row of rose diagrams shows the flow directions of tributary stream channels in (d) Canjilon, (e) Northern 15 Springs, and (f) Southern 15 Springs.

4. Discussion

The pattern of residence times, geochemistry, and stream discharge all point to interbasin groundwater flow through the Ritito Conglomerate. Where the Canjilon stream flows on the Ritito Conglomerate, the IGF paths are continuous across the divide leading to gaining conditions in the upper reaches of the El Rito creek and long residence times of springs. Where the Canjilon cuts into underlying less permeable units, the hydraulic connection is lost, and groundwater in the southern El Rito springs becomes younger and geochemically distinct. The El Rito becomes a losing stream where the Ritito conglomerate thins to the west, with groundwater flow likely traveling from east to west through the Mancos Shale.

Doney [1968] suggested that the angular unconformity and the associated permeability contrast between the overlying Cenozoic conglomerates and underlying Mesozoic sediments were responsible for the occurrence of springs in the El Rito headwaters. At the time, no connection was made linking the larger hydraulic connection between the Canjilon and El Rito watersheds. We infer that the poorly lithified Ritito conglomerate establishes the hydraulic connection between these watersheds. Its east dipping attitude is critical to the creation of interbasin groundwater flow and more importantly, the maintenance of spring flow and stream base flow in the area. The hydraulic connection is strongest where the Ritito conglomerate is widespread and continuous (Figure 2, top). That hydraulic connection is lost as the areal distribution of the Ritito thins or is incised by streams moving from north to south in the headwaters (Figure 2, bottom). The hydrological expression of IGF is as follows: (1) persistent gaining conditions in the upper reaches of the El Rito watershed, (2) the substantial increase in silica progressing from Canjilon springs to the El Rito springs (west to east), and

(3) the increase in radiocarbon activity and decrease in average radiocarbon residence time progressing from north to south in the headwaters of the El Rito watershed. The geomorphic expression of IGF in the landscape is as follows: (1) the preferential emergence of springs on the western side of the stream valley, (2) the growth of tributary stream channels flowing from west to east upstream of the losing reach (growing in the direction of IGF), and (3) the propagation of mass wasting on the western side of the stream valley. These data indicate that interbasin groundwater flow has influenced watershed-scale geomorphology.

5. Summary and Conclusions

Quantifying groundwater/surface water interactions is often a difficult task because of their hidden nature in catchments, and characterizing the presence and impact of IGF presents an even greater challenge. It is difficult to identify IGF in the field and determine where it occurs and the direction and magnitude of exchanges. We proposed two hypotheses, and the geomorphic metrics and geochemical and age-dating data presented here provide support for these hypotheses. As indicated above, the Ritito conglomerate provides the pathway for groundwater to flow from the Canjilon headwaters to the El Rito headwaters. Without this hydraulic connection, the headwaters of the El Rito watershed would be much drier and perhaps ephemeral. Thus, interbasin groundwater flow plays a critical role in maintaining perennial flow from these springs and base flow in the streams and likely the aquatic ecosystems associated with them. The hydrological characteristics are starkly different in the Southern 15 Springs area where IGF is not present. The number of perennial springs decreases dramatically progressing south of the gaining to losing transition. In fact, we can only find one perennial spring in the lower reaches of the El Rito watershed. Furthermore, the losing reach of the El Rito stream (zone 2) flows within the Mancos Shale and loses between 30 and 80% of all the water that is gained in the upper gaining reach.

Our data indicate that there are geomorphic expressions of IGF in the landscape; utilizing such simple geomorphic metrics may improve our ability to identify IGF components in other watersheds. If we do not consider the effects of geology on groundwater/surface water interactions, then we may fail to recognize these processes in other watersheds. Furthermore, if traditional hillslope-oriented field techniques had been employed or if hydrological data had only been collected from equipment located at the watershed outlet (a common practice), then the IGF complexities present in the watershed would have been missed. IGF has played a critical role in the geomorphic evolution of the watershed. It will also have a vital control on hydrological resilience to any changes in climate and/or land use. The approach presented here may provide a methodology for evaluating IGF in other watersheds and catchments around the world, especially in sedimentary geologic settings.

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