A River Runs Underneath It: Geological Control of Spring and Channel Systems and Management Implications, Cascade Range, Oregon

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Long-term sustainable management of Cascade Range watersheds requires an understanding of water sources and discharge patterns from tributary streams, particularly those sourced in large-volume cold springs of the High Cascades geologic province. Focusing on the McKenzie River watershed, measurements of discharge and stream temperature combined with laboratory analysis of spring water isotopes improve our understanding of spatial and temporal recharge and discharge patterns. Summer streamflow in the McKenzie is dominated by water from approximately ten spring-fed streams, which maintain 4 to 7°C spring water temperatures and relatively steady flow throughout the summer. In winter months, streams in the Western Cascades geologic province respond rapidly to rain and rain-on-snow events and become the major water source to the McKenzie River. Spring-fed streams also respond to precipitation events, but show muted and delayed hydrograph peaks. Summer flow behavior varies among springs, even between those that are located near each other. Isotopic data reveal that recharge to large springs occurs between 1300-1800 m in elevation, which is coincident with geologically young lava between McKenzie and Santiam Passes. Recharge elevations also suggest some disagreement between recharge areas and topographic watersheds of the springs. Because of their importance to summer streamflow, water quality, and habitat in the McKenzie River basin, water resources decision-making must differentiate between spring-fed and runoff-dominated streams.

Keywords: *streamflow, groundwater processes, geology/geomorphology, springs, water temperature, Oregon Cascades*

Introduction

The Willamette River basin is home to 70% of Oregon's population, and while the McKenzie River watershed covers less than 12% of the basin's area, it provides almost 25% of the Willamette River's water during low flow periods (PNWERC 2002). The McKenzie watershed includes threatened and endangered fish runs, a complex system of federal and private dams for flood control and hydroelectric power generation, and Oregon's second largest city (Eugene), which draws 10 billion gallons (37.8 billion L) of drinking water per year directly from the river.

Recent analyses show that the Cascade Range is particularly sensitive to current and projected climate warming trends, specifically reduced snow accumulation and earlier spring melt, leading to a decline in summer streamflow (Service 2004). By 2050, Cascade snowpacks are projected to be less than half of what they are today (Leung et al. 2004), potentially leading to major water shortages during the low-flow summer season. Although not yet as contentious as the Klamath River to the south, the stage is set in the Willamette basin for significant future conflicts and demands for water.

Despite the importance of the McKenzie River's water to the region's quality of life, geologic and climatic controls on patterns of streamflow have been poorly understood. The watershed of the McKenzie River lies primarily within two distinct geologic provinces: the High and Western Cascades (Figure 1). The High Cascades are known for their active composite volcanoes and extensive Quaternary basaltic lavas, while the Western Cascades are the products

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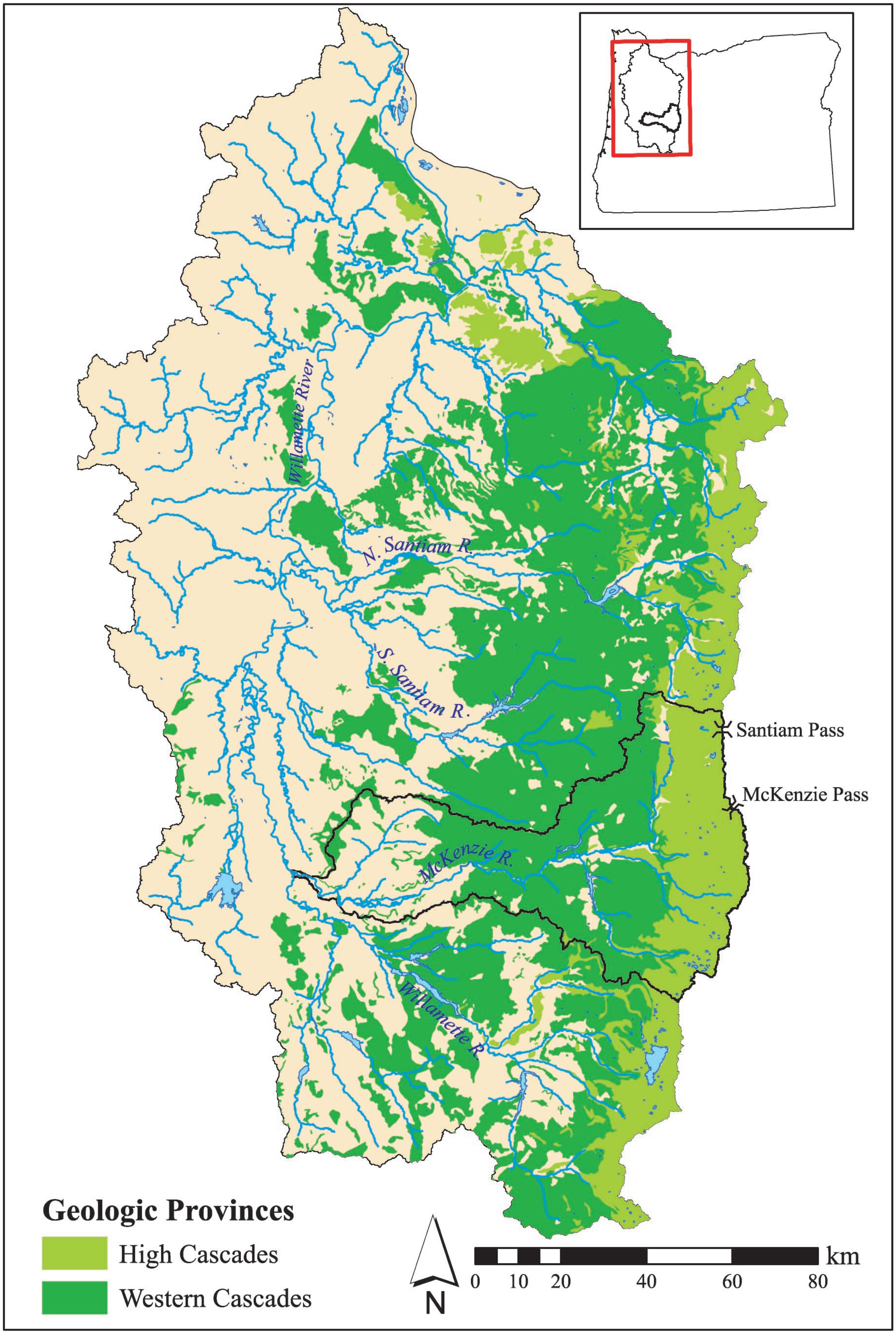
Figure 1. Forty-two percent of the McKenzie River watershed lies within the High Cascades geologic province, the most of any major Willamette River tributary. Geologic classification is based on mapping by Sherrod and Smith (2000).



of Tertiary volcanism, and have been extensively faulted, weathered, and dissected (Conrey et al. 2002). The Western Cascades have well-developed drainage networks and watersheds dominated by shallow-subsurface, runoff-dominated flow (Harr 1977), while in the High Cascades large areas lack drainage networks and many of the streams are fed by springs. Preliminary hydrograph analyses indicate that High Cascades streams show much more uniform flow and temperature through time compared to Western Cascades streams (Tague and Grant 2004). These differences have significant implications for water quantity and quality in headwater streams and for larger rivers, such as the McKenzie and Willamette, where both High and Western Cascades streams contribute to flow.

This research represents a systematic attempt to quantify volumes and sources of discharge in the McKenzie River basin. The overall goal of the project was to provide a more complete picture of flow contributions to the McKenzie River, for use in planning the sustainable long-term water management of the basin. Our objectives were to identify sources of summer streamflow to the upper McKenzie River, obtain continuous discharge records for large spring-fed streams, and use isotopic information to characterize groundwater recharge patterns.

Our field campaign focused on the upper McKenzie River basin, defined as the 2409 km^2 watershed upstream of the USGS gage at Vida. This area encompasses all of the High Cascades geology in the basin, as well as two Western Cascades tributaries with Corps of Engineers flood control reservoirs. USGS stream gages operate at four locations on the mainstem of the McKenzie River and on the tributaries Blue River, Separation Creek, Smith River, and the South Fork of the McKenzie. The USGS gages for the McKenzie River at Clear Lake and Separation Creek include a substantial spring-fed component, but do not represent a pure spring signal.

Methods

In summer 2003, discharge was measured at all McKenzie River tributaries flowing from areas of High Cascades geology. These data, combined with knowledge of some spring locations, allowed us to identify all of the major sources of summer streamflow to the upper McKenzie River. Fourteen streams were selected for continuous gaging (Figure 2), and Trutrack[1] capacitance rod water stage and temperature recorders were installed during July 2003. These streams included nine spring-fed streams, four runoff-dominated streams, and one ephemeral spring-fed stream. Selected spring-fed streams included all of the major ungaged springs that are tributary to the McKenzie River. Runoff-dominated streams were selected because they were tributary to or provided a reference site in close proximity to spring-fed streams.

Discharge measurements were made at a variety of stages in order to develop rating curves for each site, following standard USGS procedures. These curves allow interpolation from stage to discharge and result in daily hydrographs for the streams. Discharge was directly measured between four and 18 times at each site, depending on flow variability. Despite repeated measurements, peak flows had to be extrapolated from the rating curve for each site. Where there is not sufficient confidence in such extrapolations, hydrographs are truncated in high flow periods.

In mountainous regions, the isotopic composition of precipitation varies in a systematic way with elevation (Dansgaard 1964). The isotopic composition of spring water can be projected to the elevation at which precipitation has a comparable composition. Recharge elevations estimated by this method represent precipitation-weighted averages and have an error of ±60 m due to analytical uncertainty, plus some uncertainty associated with the altitude-isotope relationship. Spring water samples were analyzed for hydrogen and oxygen isotope ratios (δD and $\delta^{18}O$, respectively) at Lawrence Livermore National Laboratory. Isotopic composition of the water was compared to a published altitude-isotope relationship for the Oregon Cascades (Ingebritsen et al. 1994).

Spring water samples were also analyzed at the University of Waterloo (Waterloo, Ontario, Canada) for tritium, a radioactive hydrogen isotope with a half life of 12.43 years. Tritium in the groundwater system indicates that it has been recharged within the last ~50 years (Clark and Fritz 1997). Tritium concentrations were greatly increased in the atmosphere as a result of nuclear weapons testing in the 1950s and 1960s, but by the 1990s atmospheric tritium activities had approximately returned to pre-bomb levels.

Results

During 5-7 August 2003, discharge measurements were made on High Cascades tributaries to the McKenzie River (Figure 3). Discharge of the McKenzie River at Vida was 50.7 m^3/s on 7 August 2003. According to our measurements, 83% (42.3 m^3/s) of this flow came from spring-fed streams. By combining locations from this project and the USGS, over 97% (49.4 m^3/s) of the flow in the McKenzie River was measured, despite neglecting most tributaries flowing from Western Cascades geology.

[1]The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Figure 2. Gaging sites are located on spring-fed and runoff-dominated streams in the upper McKenzie River watershed. Indicated big springs have more than 0.85 cms average annual discharge.

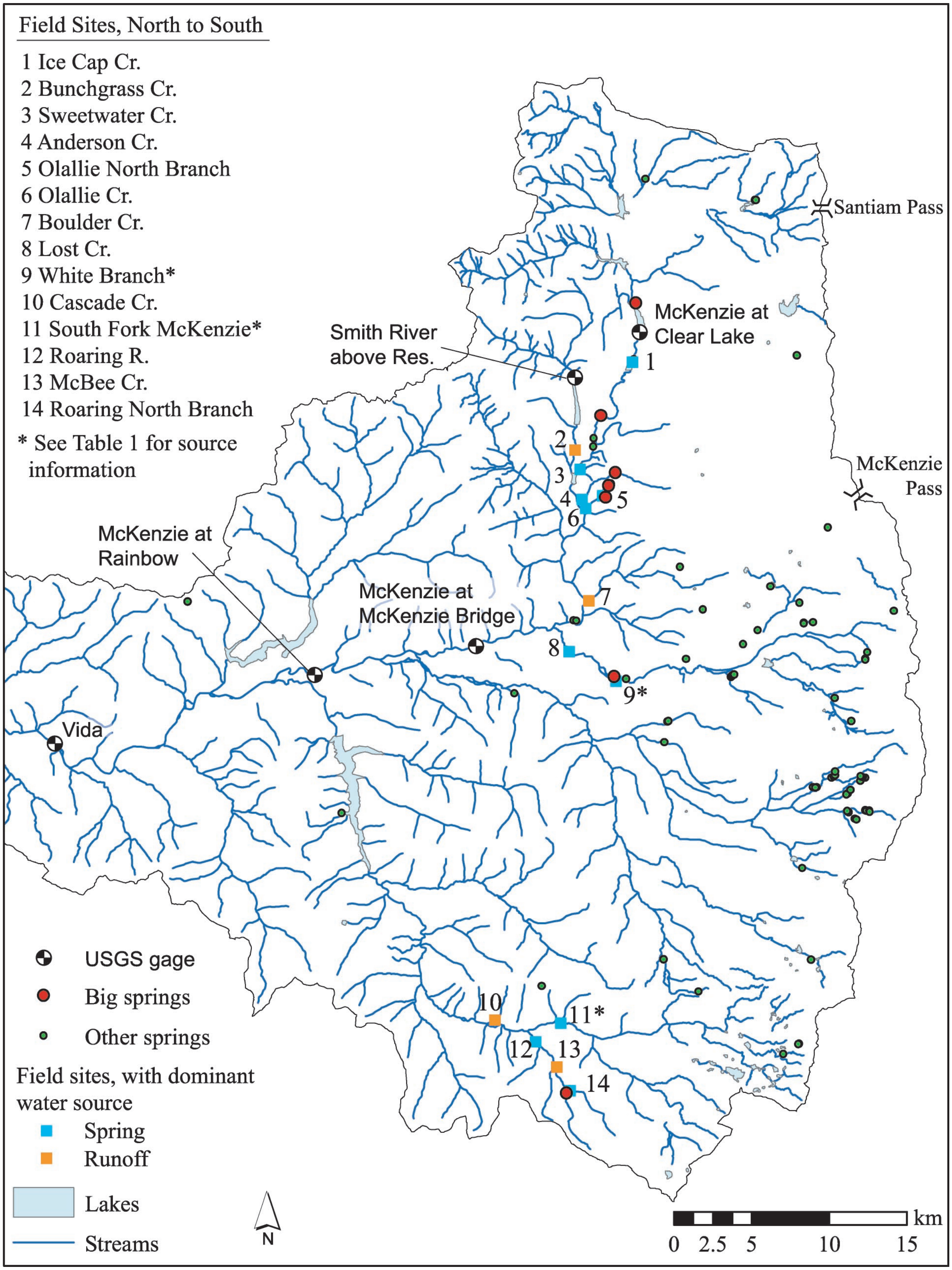


Table 1. Summary of characteristics of discharge measurement sites. For more detailed information on groundwater patterns, see Jefferson et al. (2006).

Site Name	Dominant Water Source	Mean Water Temperature (°C)†	Std Dev. (°C) †	Daily Discharge (m^3/s) 5 August 2003
Anderson Cr.	Spring	4.7	0.9	0.61
Boulder Cr.	Runoff	8.3	3.7	0.0061
Bunchgrass Cr.	Runoff	6.6	3.6	N/A
Cascade Cr.	Runoff	7.0	3.1	N/A
Ice Cap Cr.	Spring	4.5	0.2	N/A
Lost Cr.	Spring	6.9	0.3	5.8
McBee Cr.	Runoff	6.4	3.0	0.021
Olallie Cr.	Spring	5.0	0.1	4.7
Olallie North Br.	Spring	4.7	0.0	1.6
Roaring River	Spring	5.4	0.7	2.7
Roaring North Br.	Spring	4.3	0.1	0.79
South Fork McKenzie	Spring likely - location unknown	5.9	1.8	2.3
Sweetwater Cr.	Spring	N/A	N/A	N/A
White Branch	Ephemeral spring	6.1‡	1.9‡	0.11

† For period of record between 10 July 2003 and 31 March 2004.
‡ For period when stream has flowing water.

Reservoir supplementation accounted for ~10% of the flow at Vida. Without this supplementation, spring-fed streams would provide 93% of the flow in the McKenzie River.

This campaign of discharge measurements indicated that all major springs discharging into tributaries of the McKenzie River were accounted for in the gaging scheme described above. There is considerable accretion of groundwater directly into the mainstem of the McKenzie River between Clear Lake and Trail Bridge Reservoir (Stearns 1929), but direct discharge measurements are unattainable. The difference in discharge between the USGS gages at Clear Lake and Trail Bridge Reservoir minus the discharge of Smith River and Bunchgrass Creek can be attributed to this groundwater accretion. During August 2003, 10.3 m^3/s of groundwater were added to the flow of McKenzie River in the Clear Lake to Trail Bridge Reservoir reach. Additionally, there are small springs in the watershed which discharge water to the surface where it quickly infiltrates back into the ground, while other springs discharge into closed-basin lakes, where their water either evaporates or recharges the groundwater system.

Considerable differences were observed between the hydrographs of spring-fed and runoff-dominated streams in the McKenzie River watershed (Figure 4). Peak flows were 1.5 to 2.7 times greater than low flows on spring-fed steams, whereas for runoff-dominated streams peak flows were approximately 30 to 1000 times greater than low flows. Hydrographs of spring-fed streams also showed little recession during the summer, as compared to those of runoff-dominated streams. Comparison of flows from summer 2003 to spot discharge measurements in 2001-2002, and to irregular measurements from the 1910-1926 (Stearns 1929) suggests that springs have less interannual variability than runoff-dominated streams.

Two major peak flow events are represented in the gaging record: 13-14 December 2003 and 29 January 2004. The spring-fed streams exhibit a delayed peak flow compared to runoff-dominated streams, and this cannot be completely explained by elevation or watershed area. For example, all four runoff-dominated streams had their peak flow on 29 January 2004, but the spring-fed streams reached their peak flows on 30-31 January. Anderson Creek showed almost no response to rain events, while the bigger spring-fed streams showed some responsiveness. Some of this responsiveness may be due to gaging location, as the Roaring and South Fork sites are downstream of runoff-dominated tributaries.

Springs feeding the same creek exhibited different dynamics during the summer period, as illustrated by Olallie Creek and Roaring River (Figure 4, Table 1). Olallie North Branch rises through July and August and drops off in September, while downstream on Olallie Creek, below the confluence of the north and south branches, Olallie Creek exhibits a slight recession throughout the summer as well as greater fluctuations. This recession is similar to the stage record at Olallie South Branch (not shown), which contributes most of the flow to Olallie Creek. Thus,

Figure 3. By combining data from USGS gages and sites measured for this research, 97% of discharge in the McKenzie River at Vida can be apportioned. Discharges in the McKenzie River and its tributaries on 5-7 August 2003 are schematically represented by the thickness of each line. Distances are not to scale.

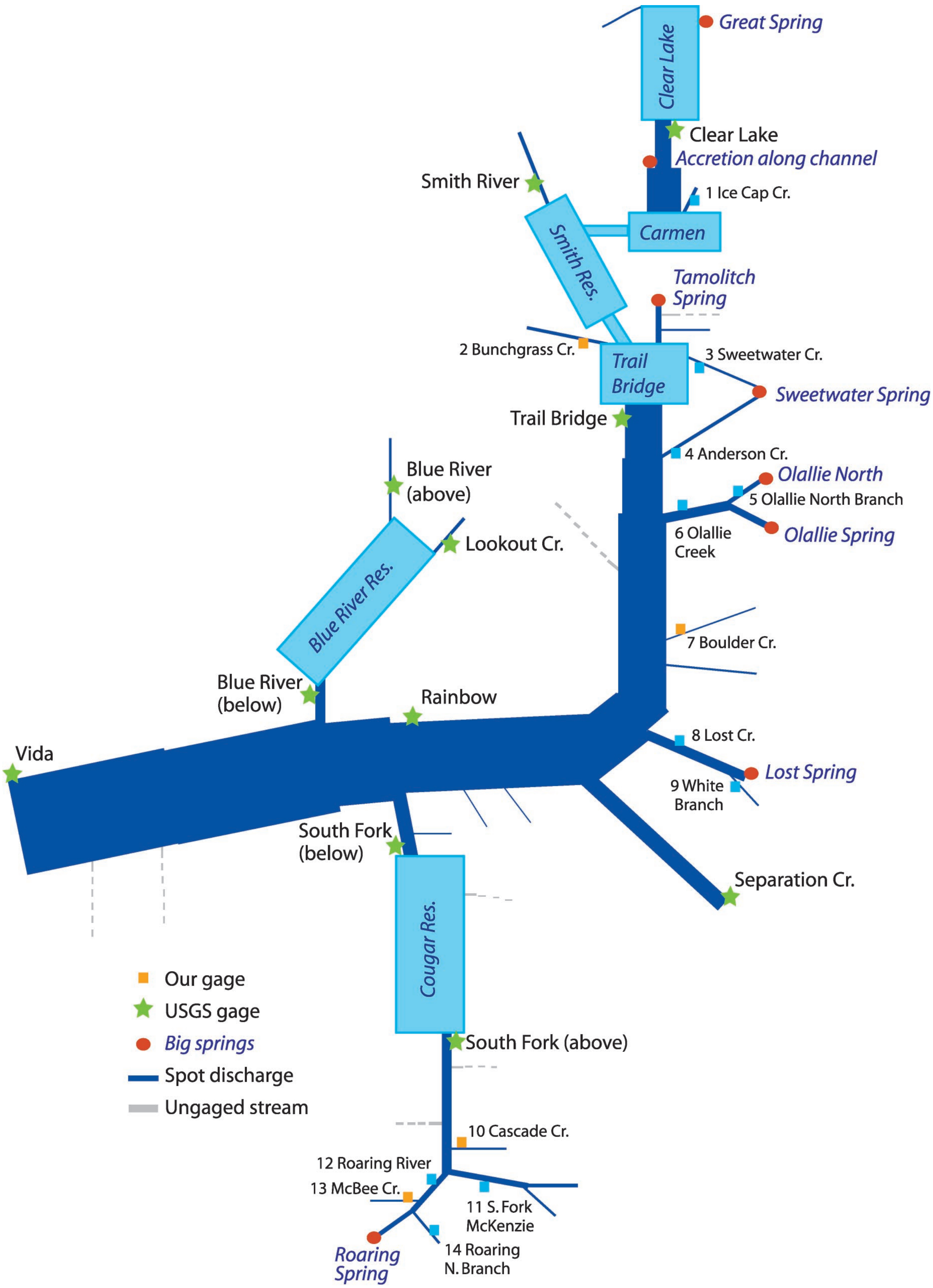
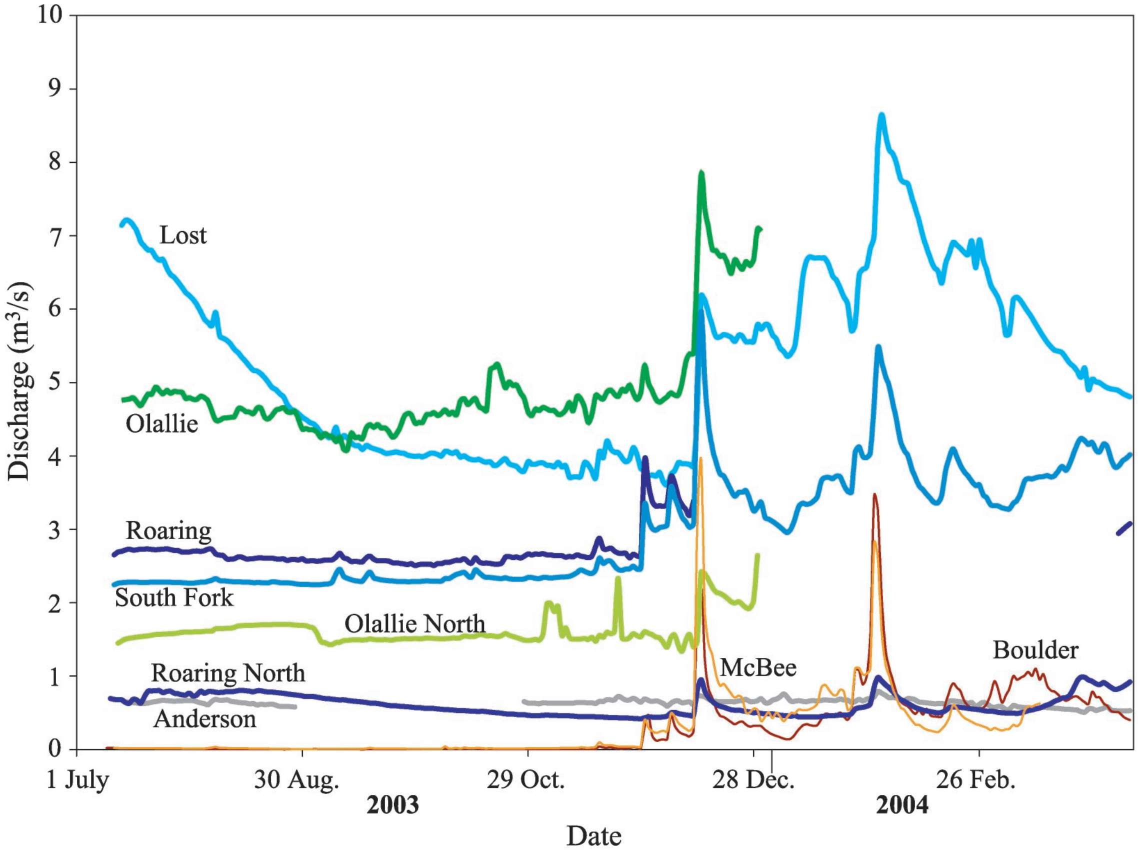


Figure 4. Spring-fed streams (thick lines) display less seasonal fluctuation and muted event response compared to runoff-dominated streams (thin lines), as exhibited by these hydrographs for 9 July 2003 to 7 April 2004. Olallie Creek and Olallie North hydrographs are truncated where there is low confidence in extrapolated discharge values. Other missing data are the result of instrument failure.



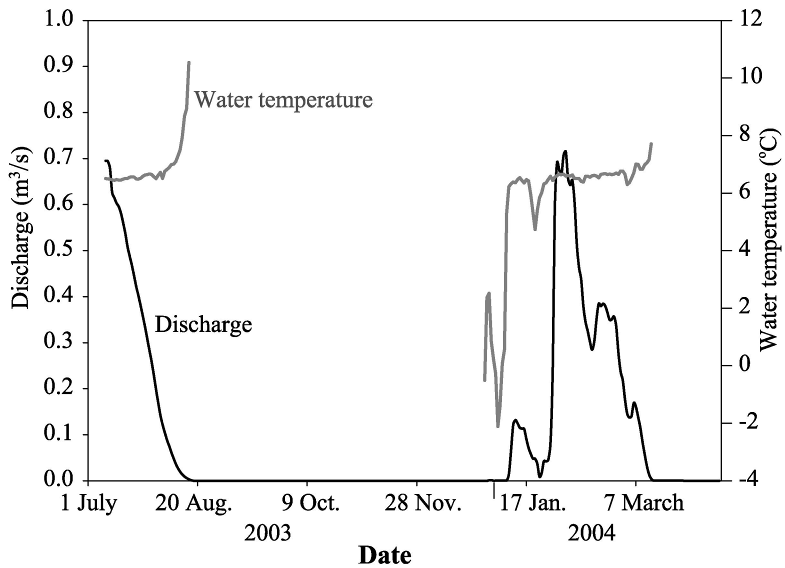
although the two branches are sourced in springs less than one kilometer apart, their summer flow behavior differs. Between 15 August and 15 September 2003, discharge from the north spring on Roaring River declined 0.15 cms, while flow at the downstream gage dropped only 0.04 cms. Increased flow from Roaring Spring (south branch) must account for the discharge measured downstream.

White Branch Creek, as measured near its confluence with Lost Creek, appears to be controlled by an ephemeral spring (Figure 5). It exhibits markedly different discharge dynamics than either spring-fed or runoff-dominated streams, despite its spatial proximity to perennial Lost Spring. The stream had a very steep recession in July-August and again in March, each time resulting in a completely dry channel. The stream did not respond to the 13-14 December peak flow event, and exhibited a five-day delay in peak flow for the end of January event. Throughout the vagaries in discharge, water temperature remained nearly constant between 6.5 and 6.7°C, within the range exhibited by Lost Spring. Only when discharge was below ~0.1 m^3/s did significant temperature fluctuations occur.

Water temperature trends also exhibited differences between spring-fed and runoff-dominated streams (Figure 6, Table 1). Temperature measured directly at springs was nearly constant throughout the year, while streams showed fluctuations likely due to cooling or heating from the surrounding air mass. However, spring-fed streams showed much smaller variation in temperature both seasonally and daily than did runoff-dominated streams.

Water samples for five springs were analyzed for tritium, and results ranged from 2.9 to 6.1 tritium units, indicating that the groundwater had been recharged within the last 50 years (Clark and Fritz 1997). Recharge elevations, based on isotopic composition of spring water samples, are at substantially higher elevations than the springs are discharging (Figure 7). The recharge elevations for the springs are concordant with the elevation of extensive young lava flows between McKenzie and Santiam Passes (Figure 2). Springs providing discharge to tributaries of the South Fork of McKenzie also recharge in this elevation range (1325-1825 m), despite less extensive areas of young lavas. Recharge elevations inferred by isotopic methods

Figure 5. White Branch Creek is fed by an ephemeral spring, and its hydrograph and temperature history are dissimilar to other spring-fed or runoff-dominated streams. White Branch, as measured near Oregon Highway 242, had no water in its channel from 19 August to 25 October 2003 and from 16 March 2004 until the end of the analysis period.



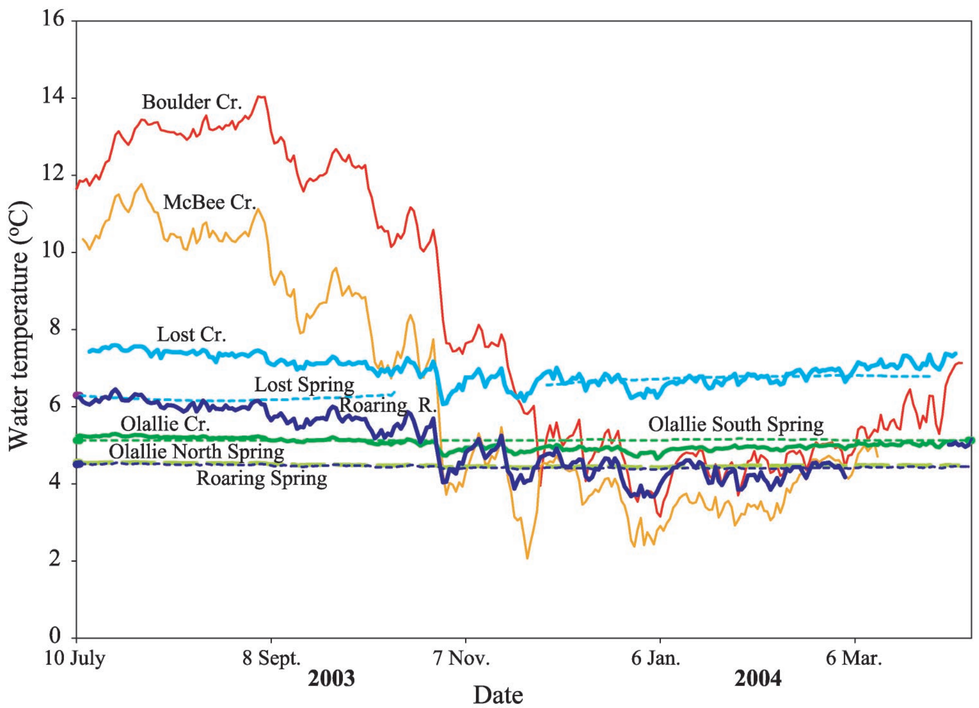


Figure 6. Water temperatures in springs (dashed lines) and spring-fed streams (thick lines) exhibit less variability than temperatures of runoff-dominated streams (thin lines). Water temperature at springs measured by Hobo Water Temp Pro sensors, and in streams, temperature was measured using Hobo or Trutrack sensors.

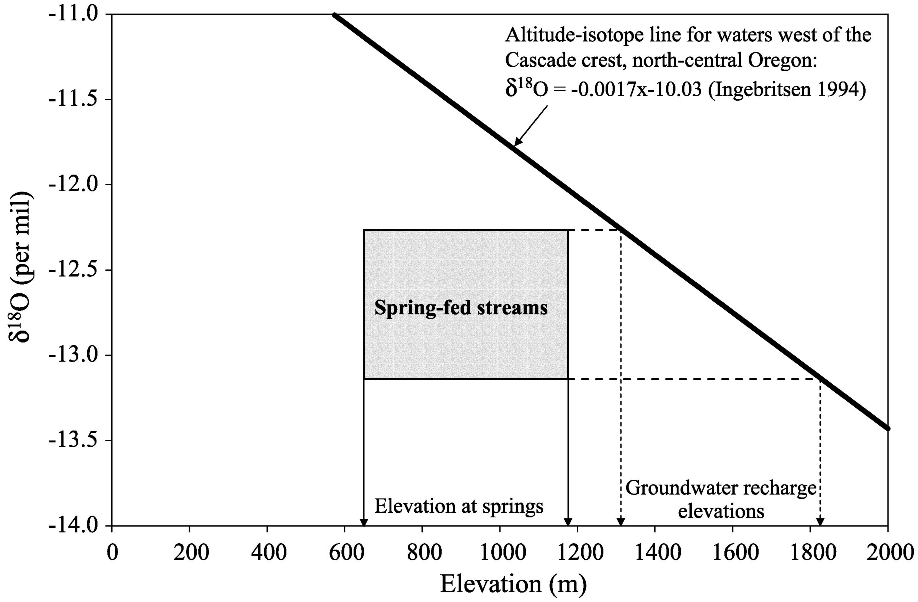
indicate that topographic watersheds may not be providing evenly distributed recharge to the groundwater system. In at least one case, the inferred average recharge elevation is greater than the maximum elevation in the topographic watershed, requiring significant recharge from outside its boundaries.

Discussion and Management Implications

Spring-fed streams are the dominant source of summer streamflow in the upper McKenzie River, and this flow is sourced from less than ten discrete areas in the watershed. Most of these springs occur on federal land, requiring local and federal water resources agencies to cooperate in their management and protection. The discrete nature of the source areas of water in the McKenzie suggests a number of implications for management.

Maintaining the high water quality of the springs and spring-fed streams requires consideration of several distinct environments: a) the springs themselves; b) the extensive, but often cryptic or unknown area upstream of the springs contributing flow to the springs; and c) channel and riparian areas bordering spring-fed streams. Each of these environments can potentially have different ownerships (public or private), management allocations, impacts, and consequences for water quality. We are only beginning

Figure 7. Mean recharge elevation for the springs can be determined by projecting their isotopic composition onto the altitude-isotope line. On average, the springs are recharging almost 800 m higher in elevation than they are discharging.



to understand the interplay of these environments and potential impacts of human and land use activities on each. Specifically, the effects of human activities and natural disturbances in recharge areas on spring water quantity and quality are not well understood. For example, most large springs in the McKenzie drainage are located on national forest lands, and are included in riparian reserves under the Northwest Forest Plan (USDA and USDI 1994). This affords a relatively high degree of protection against forest-harvest and road-building activities. However, source areas that contribute to the springs may or may not be included in riparian or other reserve or protection categories, since groundwater systems are not explicitly included in the Northwest Forest Plan. Whether land-use activities, including forest harvest, recreation, fire suppression, and fuels management, affect the flow in springs remains an open question.

Recharge elevations are significantly higher than spring locations and suggest some discordance between recharge areas and topographic watersheds. These findings emphasize the importance of further investigation into recharge area geometry, the question of whether specific portions of the landscape provide a disproportionate share of recharge to the groundwater system, and what effects human activities in source areas may have on streamflow and water quality.

It is not clear whether highlighting the location of springs (i.e., on maps or through media) will contribute to their future protection or degradation. Many springs are quite sensitive ecologically, with extensive wetland vegetation, unique habitats, and undeveloped access, and would probably be degraded by extensive human use. On the other hand, some springs are on well-developed trail systems and appear to have been quite resilient to the effects of nearby recreational uses.

Despite their importance to water supply during low flow seasons, none of the springs and few of the spring-fed streams have established long-term monitoring facilities (i.e., USGS gages). While spring-fed streams provide more consistent flow than runoff-dominated streams, they do experience higher flows in response to rain and rain-on-snow events. Thus, adequate gaging of these systems is still important for reservoir management planning. A small number of discharge measurements might be sufficient to characterize summer streamflows in spring-fed streams, but winter flows cannot be assumed to be static. Furthermore, differences in flow dynamics between spring-fed streams, even those in close proximity to each other, preclude generalizing measurements from one spring system to others.

Stream temperature, an important habitat criteria for bull trout (*Salvelinus confluentus*) and other species, is generally lower and more stable in spring-fed than runoff-dominated streams, suggesting that conservation efforts for some species might be concentrated in spring-fed streams. At a minimum, the relationship between ecosystem structure and function in spring- versus non-spring streams should be investigated, as this may have implications for regulatory standards affecting water quality and forest management.

Post-1950 groundwater recharge dates imply that the groundwater system is being actively recharged, probably in balance with the amount discharged at springs annually. This suggests that spring water may be susceptible to contamination by atmospheric deposition or chemical spills in recharge areas. Contamination of spring water may appear several years after a spill and the effects may last for decades. Finally, a change in the overall amount of precipitation falling on the Cascades would probably have an impact on spring discharge within a few years, but a change in seasonality or form of precipitation may be less significant for spring-fed streams than for runoff-dominated streams.

Because of their importance to summer streamflow, water quality, and habitat in the McKenzie River basin, water resources decision-making must differentiate between spring-fed and runoff-dominated streams. This will require cooperation between local and federal organizations, continued assessment of long-term behavior of spring-fed streams in light of climate variability and change, and more investigation into how human and natural impacts on recharge areas could affect groundwater quantity and quality.

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