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Soil disturbance as a driver of increased stream salinity in a semiarid watershed undergoing energy development

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SUMMARY

Salinization is a global threat to the quality of streams and rivers, but it can have many causes. Oil and gas development were investigated as one of several potential causes of changes in the salinity of Muddy Creek, which drains 2470 km^2 of mostly public land in Wyoming, U.S.A. Stream discharge and salinity vary with seasonal snowmelt and define a primary salinity–discharge relationship. Salinity, measured by specific conductance, increased substantially in 2009 and was 53–71% higher at low discharge and 33–34% higher at high discharge for the years 2009–2012 compared to 2005–2008. Short-term processes (e.g., flushing of efflorescent salts) cause within-year deviations from the primary relation but do not obscure the overall increase in salinity. Dissolved elements associated with increased salinity include calcium, magnesium, and sulfate, a composition that points to native soil salts derived from marine shales as a likely source. Potential causes of the salinity increase were evaluated for consistency by using measured patterns in stream chemistry, slope of the salinity–discharge relationship, and inter-annual timing of the salinity increase. Potential causes that were inconsistent with one or more of those criteria included effects from precipitation, evapotranspiration, reservoirs, grazing, irrigation return flow, groundwater discharge, discharge of energy co-produced waters, and stream habitat restoration. In contrast, surface disturbance of naturally salt-rich soil by oil and gas development activities, such as pipeline, road, and well pad construction, is a reasonable candidate for explaining the salinity increase. As development continues to expand in semiarid lands worldwide, the potential for soil disturbance to increase stream salinity should be considered, particularly where soils host substantial quantities of native salts.

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1. Introduction

Salinity, the sum of dissolved salts or solutes in water, is a global challenge to water-quality management and a wide variety of human activities can increase the salinity of streams and rivers (Cañedo-Argüelles et al., 2013). Excessive salinity can make water unsuitable for domestic use (DeZuane, 1997) and negatively impact irrigated agriculture (Ayers and Westcot, 1985) and wildlife (Chapman et al., 2000; Hart et al., 1991). Water and energy development have always been intertwined as energy development can impact water quality and availability (Entrekin et al., 2011; Olmstead et al., 2013) and vice versa (Nicot and Scanlon, 2012). Such interactions are part of the water-energy nexus that will increasingly influence how both of those resources are used worldwide (Healy et al., in press; Schnoor, 2011; Voinov and Cardwell, 2009). In the western United States, new energy development technologies are spurring the development of unconventional oil and gas resources including shale gas, oil recovered by hydraulic fracturing and coalbed methane (CBM) (Breyer, 2012; Kerr, 2010). In western Wyoming, the Wyoming Landscapes Conservation Initiative (WLCI) has been organized to ensure wildlife and habitat viability in southwest Wyoming as the region undergoes significant energy development (http://www.wlci.gov/). One component of that work has been monitoring of streams for water quality changes. In this paper, an upward shift in salinity for a given discharge rate is documented for Muddy Creek, a semiarid watershed in the development area. The goal of the study is to determine the cause of that increase in salinity to the extent possible with available data. Globally, surface water quality faces a variety of threats, but for a given watershed it is rare to have sufficient data to link changes to causes.

Establishing cause and effect can be difficult in large and complex natural systems. Stream water composition, particularly from

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a large watershed, reflects multiple sources and processes that mobilize solutes and modify solute concentrations. A strategy was followed of first identifying all processes with the potential to increase stream salinity and then comparing those to patterns in available data. This approach is similar to the Stressor Identification process from the Causal Analysis/Diagnosis Decision Information System (http://www.epa.gov/caddis). Processes that increase salinity can be divided into those that concentrate salts and those that mobilize salts that would not have entered stream water under other conditions (Anning et al., 2007). In the Muddy Creek watershed, processes in each category were identified, some related to anthropogenic disturbance and others reflecting natural environmental fluctuations (Table 1).

Three processes that could concentrate salts in waters reaching streams were identified. Warmer temperatures could boost evapotranspiration. Increases in open water surface area and wetland and riparian vegetation generated by reservoir construction could do the same. In contrast, the diluting effects of runoff could be diminished by a decrease in precipitation inputs.

Several processes can increase stream salinity through salt mobilization. Groundwater can contribute to salinity through discharge from springs and in gaining reaches of the streambed. Increased contributions from either source could boost stream salinity (Salama et al., 1999). A distinct Na-HCO_3-type groundwater in the region likely reflects SO_4^{2-} reduction, indicative of sourcing from coalbed aquifers (Brinck et al., 2008; Van Voast, 2003). CBM development co-produces these waters in relatively large volumes (Rice and Nuccio, 2000). Environmental concerns regarding the disposal of CBM waters in other parts of Wyoming have spurred efforts to track their influence on surface water (Clark, 2012) and groundwater (Healy et al., 2011) or put the waters to beneficial use (Bern et al., 2013). However, oil and gas development has thus far generated little surface discharge in the Muddy Creek watershed because co-produced water generally is reinjected into the Haystack Mountains Formation of the Mesaverde Group, below the coal seams being dewatered for CBM development, or evaporated in ponds lined with plastic to prevent infiltration (Bureau of Land Management, 2007). Well construction failure is rare (King and King, 2013) but could create a situation where CBM water contaminates groundwater and then reaches streams. Larger contributions of Na-HCO_3-type waters likely enter Muddy Creek from springs (McLaughlin et al., 2011), dispersed discharge through the streambed, and at least two failed wells under artesian pressure (Anderson, 2010). Groundwater in the region has widely varying salinities and compositions that complicate grouping (Bartos et al., 2006). However, groundwater with a Ca–Mg–SO_4-type composition that generally reflects weathering is relatively common and has been documented issuing from springs in the Muddy Creek watershed (McLaughlin et al., 2011).

Various land use practices can mobilize additional salts into Muddy Creek (Table 1). Irrigation return flow, in which waters applied to fields gain or displace salts as they percolate through soil toward streams, is a common process increasing stream salinity in the region (Gardner and Young, 1988; Goff et al., 1998). Reservoir construction also can mobilize salts, through the increased interaction between water and potentially salt-laden sediments in their beds (Lieberman et al., 1989; Ponce and Lindquist, 1990; Williams, 2001). Similarly, manipulation of stream morphology as part of habitat restoration can place waters in contact with previously dry sediments. Soil disturbance and removal of vegetative cover caused by livestock grazing, particularly in riparian zones, has been the cause of water quality declines in many areas of the western U.S. (Belsky et al., 1999).

Perturbations in hydrologic regimes are commonly associated with increased salinity (Williams, 2001) and natural fluctuations, such as an increase in annual precipitation and water availability, might function in a similar manner. In a semiarid region, greater than normal percolation of waters into salt-rich soils could mobilize native salts. Rising water tables have the potential to mobilize salts accumulated in the unsaturated zone during drier periods. High runoff events generate erosion, both in channels and in the overland flow portion of the landscape that have the potential to expose salt-rich soil to water. Anecdotal evidence suggests that above-normal precipitation in 2011 mobilized salts to the surface at seeps and along gaining reaches of streams in the Muddy Creek watershed.

The final potential process for increasing stream salinity considered here is substantial recent disturbance related to oil and gas development. In a semiarid landscape, surface soils often contain little salt, but substantial concentrations of salts may occur at relatively shallow depths (Szabolcs, 1989). Construction of dirt roads, well pads, and pipelines necessarily disturb soils, exposing or bringing subsurface salts closer to the surface. Runoff can carry those salts to streams, and the wicking process that produces efflorescent salts can successively bring more salt to the surface. Where water is allowed to pond and infiltrate in new locations, flow-through can mobilize salts to streams. Construction of roads and underground pipelines across perennial or ephemeral tributaries would have an even greater chance of increasing contact between waters and native salts in sediments by altering the hyporheic zone. A study of well pad construction effects in east Texas found significant increases in sediment yield (McBroom et al., 2012). A study in Pennsylvania found significant positive correlations between the number of shale gas wells and associated pads and total suspended solids in surface waters (Olmstead et al., 2013). The wetter climates in these states and resultant soil leaching make shallow salt accumulations unlikely, and no significant increases in water salinity were documented in relation

Table 1
Candidate causes for increased salinity in Muddy Creek considered in this paper along with evaluations of consistency with measured patterns and overall plausibility.

Category	Candidate cause of increased salinity	Consistent with measured patterns?			
		Stream chemistry	Salinity–discharge relationship slope	Inter-annual timing	Plausible overall?
Salt concentration	• Warmer temperatures, evapotranspiration concentration	No	No	No	No
	• Reservoirs, evapotranspiration concentration	No	No	Maybe	No
	• Decreased precipitation, less dilution of salinity	No	No	No	No
Salt mobilization	• Na-HCO_3-type groundwater from natural discharge/gas wells	No	Unknown/no	No	No
	• Ca–Mg–SO_4-type groundwater from natural discharge	Yes	No	Unknown	No
	• Irrigation return flow	No	No	No	No
	• Reservoir bed salt mobilization	No	Yes	Maybe	No
	• Disturbance from stream morphology manipulation	Yes	Yes	No	No
	• Disturbance from livestock grazing	Yes	Yes	No	No
	• Fluctuations in precipitation causing increased erosion, deep percolation through soil, and/or rising water tables	Yes	Yes	No	No
	• Soil disturbance from oil and gas development	Yes	Yes	Maybe	Yes