Journal of Arid Environments 122 (2015) 169–179

Contents lists available at ScienceDirect

Journal of Arid Environments

journal homepage: www.elsevier.com/locate/jaridenv

Chemistry and evolution of desert ephemeral stream runoff

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ARTICLE INFO

Article history:
Received 28 May 2014
Received in revised form
1 June 2015
Accepted 15 June 2015
Available online xxx

Keywords:
Amargosa desert
Ephemeral arroyos
Solute transport
Lysimeter
Redundancy analysis

ABSTRACT

The study investigates how water chemistry evolves as ephemeral stream runoff is formed through the interaction of sediments and precipitation in the Amargosa Desert region and by analogy other desert regions. In this study, thirty lysimeters were installed in the major arroyos in the Amargosa Desert to capture runoff water. The sampling process included sediment, precipitation, and runoff water chemistry. Innovative and low cost methods were used to measure the chemical composition of the resulting runoff and examined some of the important processes affecting the runoff chemistry. Results of the analytical and statistical analyses indicate that runoff salinity is low as a result of net salt accumulation in sediments. Chemical behavior between precipitation and runoff is classified as leached (TDS, alkalinity, Ca, Mg, K, Na, Ba, Cs, Li, Sr, Fe, Ni), nutrient (Br, As, SO_4^{2-}, PO_4^{3-}, NO_3^-, Rb, B, Cu, Zn, V), scavenged (U, F), and conservative (Al, Mo, Mn). Bromide behaves as a nutrient meaning the chloride/bromide ratio, a common tracer of groundwater sources, is not conservative. Runoff chloride, sulfate, and sodium are predominantly associated with concentrations of the same ions in sediment. Trace elements are more closely associated with precipitation chemistry.

1. Introduction

Climate change models predict that future precipitation will be more episodic, leading potentially to larger geographic areas being dominated by ephemeral streams. Surface runoff from ephemeral streams in desert regions could be an important water resource if increasingly captured for beneficial use by dams and engineered recharge facilities with rising future water demand. Relatively little information is available about the chemistry of ephemeral streams runoff in desert regions and how it relates to precipitation and sediment chemistry.

Many models have been developed to study the transport of chemical constituents from soil into runoff, and the most used approaches were: the lumped, mixing layer approach and the diffusion approach. The mixing layer approach suggests that rainfall, soil water, and runoff water mix instantaneously and produce a thin mixing film just below the soil surface, and that there is no transport toward this layer from deeper soil (Ahuja, 1990; Steenhuis et al., 1994; Zhang et al., 1999). The diffusion approach assumes that chemical constituents are transferred from soil into runoff in a diffusion mechanism, and ignoring the effect of rainfall (Wallach and van Genuchten, 1990; Wallach, 1991). In general, these approaches can be fitted to experimental data by calibrating one or more unknown parameters so it remains unclear how multiple processes interact to facilitate chemical transport between soil and runoff (Barry et al., 2013). A recently developed approach (Gao et al., 2004, 2005; Walter et al., 2007) produced from merging the two previous approaches as the rainfall-driven transport of chemical constituents from the mixing layer into runoff, and the diffusion-driven transport from deeper soil layers into the mixing layer and infiltration. However, these models present theoretical approaches based upon laboratory experiments without supporting field data.

The scarcity of data and the lack of high quality observations as well as the potentially discontinuous occurrence of flow in both space and time are the major characteristics of the ephemeral streams in arid regions (Al-Qudah et al., 2015, Al-Qudah et al., 2010). Some authors (e.g., Fisher and Minckley, 1978; and Nativ et al., 1997) have studied desert flash floods (runoff) as a dilution phenomenon in terms of dissolved substances, in which low conductivity rainwater dilutes salts accumulated by evaporative

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http://dx.doi.org/10.1016/j.jaridenv.2015.06.010
0140-1963/

concentration of precipitation. Fisher and Minckley (1978) described the changes in selected chemical parameters during a single flash flooding event on Sycamore Creek, Arizona, an intermittent stream. Their results showed that the major anion, bicarbonate, and conductivity followed a dilution pattern; whereas nitrate, phosphate and iron varied widely through the cycle. Nativ et al. (1997) used major ion chemistry and water stable isotopes to evaluate the processes affecting salinization of precipitation and runoff in the Negev Desert, Israel, and their results showed that, a) calcium and bicarbonate are the dominant ions in both precipitation and runoff water; b) runoff salinity (expressed as total dissolved solids) is higher than that of the precipitation by almost one order of magnitude; c) variability in the relative salt enrichment by a factor of three to five in the runoff with respect to precipitation; and, d) the ranges and mean values of the isotopic composition of runoff water are light with respect to those observed in precipitation. Their results indicate that the dilution phenomena of floods are partially offset by runoff and increased leaching from the ephemeral stream beds and surrounding lands and dissolution of solutes from newly exposed rock and soil minerals as well as from suspended particles.

In the Amargosa Desert, runoff occurs only as a transient response to precipitation events, which can be sudden and intense. The Great Basin desert is known for flash floods that start and end abruptly, carrying objects as large as boulders and cars when they do strike (Beck and Glancy, 1995). Run-on occurs when water from higher areas accumulates in lower areas, which creates the potential for localized increases in infiltration (DOE-OCRWM, 2006). Water-chemicals transportation along the vadose zone has been intensively studied in the vicinity of the Amargosa Desert (Montazer and Wilson, 1984; Claassen, 1985; Savard, 1998; Dettinger, 1989; Fabryka-Martin et al., 1998; Flint et al., 2002, 2001a, b; Hevesi et al., 2003, 2002; Russell et al., 2007; Al-Qudah et al., 2011). However, the chemical evolution of surface runoff in the Amargosa Desert region received little attention. The purpose of this study was to provide insight into chemical transformations (chemical losses and gains) in the precipitation/sediment interaction that creates runoff chemistry in an arid region. A plausible hypothesis was that stormwater from small storms would dissolve and transport the soluble salts that accumulate in the shallow sediments leading to ephemeral water with high total dissolved solids (TDS) and chloride.

2. Description of the study area

The Amargosa Desert lays in southern Nevada, USA north east of Death Valley, between the Mojave Desert and the southern boundary of the Great Basin, and is presented in Fig. 1. The area is drained by the ephemeral Amargosa River drainage basin which is the major stream channel drainage area to Death Valley. Fortymile Wash, an ephemeral stream that originates in the uplands north of Yucca Mountain between Timber Mountain and Shoshone Mountain, flows southward along the east of Yucca Mountain and fans out in the northern part of the Amargosa Desert just north of Highway 95. Near U.S. Highway 95, the Fortymile Wash channel changes from being moderately confined to several distributary channels that are poorly confined. This poorly-defined, distributary pattern persists downstream to its confluence with the Amargosa River. A deep carbonate aquifer, locally up to 4600 m (m) thick (Stetzenbach et al., 2001) and composed mainly of Paleozoic limestones and dolomites (Flint et al., 2001b), underlies most of the tuff volcanic rocks and the desert valley sandy soil alluvial fill (Kwicklis et al., 2003).

The present climate in the Amargosa Desert region is considered arid to semiarid. The distribution of precipitation is related to the altitude and latitude of the land surface; the higher mountains in the northern part of the Amargosa Desert receive the largest amounts of precipitation and the valley the least. The majority of the precipitation falls in the winter, while most of the remaining precipitation occurs in the summer as thunderstorms. The average annual precipitation ranges from less than 130 mm (mm) at lower elevations ($\leq$600 m above mean sea level [amsl]) to more than 280 mm at higher elevations ($\geq$1200 m-amsl), and the annual average precipitation is considered as 170 mm per year (mm/yr) (SNL, 2008; Stetzenbach et al., 2007; Flint et al., 2002). Between 2001 and 2005, the annual average evapotranspiration rate, air temperature, soil temperature, and relative humidity were, respectively, 147.7–232.6 mm/yr, 18.0–18.4 °C (°C), 21.1–21.9 °C, and 21.7–33.3 percent (%) (Johnson et al., 2007). Recharge in the region is generally considered sparse and derived from precipitation infiltrating at high elevations (>1200 m-amsl) and ephemeral streams runoff at low elevations (<1200 m-amsl) (Harrill, 1976; Dettinger, 1989; Flint et al., 2001a, b; Russell and Minor, 2002), and most conceptual models have estimated net infiltration to be <3% of the precipitation with the most prevalent assuming less than 1 mm/yr (Flint et al., 2001a, b).

In the vicinity of the Amargosa Desert, Beck and Glancy (1995) have documented the flow in the Fortymile Wash and Amargosa River during some flash flood events occurring between 1983 and 1995. This documentation confirms that Fortymile Wash and the Amargosa River have the potential, in the present climatic regime, to transport dissolved and particulate materials beyond the confines of the Nevada nuclear test site (NTS) and Yucca Mountain areas during moderate and severe streamflow.

3. Methods

3.1. Runoff, precipitation, and sediment sampling

Fig. 2 portrays the sequence of the lysimeter and sediment methods described here. A simple lysimeter (Fig. 2a and b) was designed to collect runoff that has contacted and leached some of the top sandy soil in order to measure its chemical characteristics and better understand its chemical evolution as the water moved from precipitation to runoff in the Amargosa Desert's ephemeral streams. The lysimeters were placed – in pre-selected arroyos in the Amargosa Desert region (Al-Qudah et al., 2010) – at locations where water is likely to pool and where sufficient depth of sediment facilitates digging a hole for emplacement (Fig. 2c, d). To the extent possible, lysimeters were placed in low gradient (depositional) portions of the arroyo to minimize washing out during storms (Fig. 2e). The top of the lysimeter was 25–50 mm below the undisturbed surface of the arroyo, and this gap was covered with washed silica sand (Fig. 2c and d). At each location, a T-post (fence post) was installed to identify the site and serve as the mount for a rain gauge. The T-post was pounded on a flank of the wash to prevent it from being washed away during storm events (Fig. 2f). In total, thirty lysimeters filled with washed silica sand (Fig. 2b) were installed between January and September 2009 at thirty different locations in the vicinity of the Amargosa Desert with an elevation-range between 600 and 1300 m-amsl as shown in Fig. 1.

Three storm events occurred during the study period, in February, 2009; January, 2010; and December, 2010, with total depth/precipitation rates of, respectively, (23.9; 4.1), (39.9; 3.8), and (47.8; 3.3) (mm/event; mm/hour) (CEMP, 2013). The storm events were local, with runoff only occurring in stretches of the channels rather than being continuous from distant highlands. However, the storm events were enough to produce runoff and lysimeter infiltration in the washes (Fig. 2f, g and 2h).

Samples collected from each site location included runoff