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Editor's Choice Synthesis Article

Incorporating Hydrologic Data and Ecohydrologic Relationships into Ecological Site Descriptions☆,☆☆,★

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ABSTRACT

The purpose of this paper is to recommend a framework and methodology for incorporating hydrologic data and ecohydrologic relationships in Ecological Site Descriptions (ESDs) and thereby enhance the utility of ESDs for assessing rangelands and guiding resilience-based management strategies. Resilience-based strategies assess and manage ecological state dynamics that affect state vulnerability and, therefore, provide opportunities to adapt management. Many rangelands are spatially heterogeneous or sparsely vegetated where the vegetation structure strongly influences infiltration and soil retention. Infiltration and soil retention further influence soil water recharge, nutrient availability, and overall plant productivity. These key ecohydrologic relationships govern the ecologic resilience of the various states and community phases on many rangeland ecological sites (ESs) and are strongly affected by management practices, land use, and disturbances. However, ecohydrologic data and relationships are often missing in ESDs and state-and-transition models (STMs). To address this void, we used literature to determine the data required for inclusion of key ecohydrologic feedbacks into ESDs, developed a framework and methodology for data integration within the current ESD structure, and applied the framework to a select ES for demonstrative purposes. We also evaluated the utility of the Rangeland Hydrology and Erosion Model (RHEM) for assessment and enhancement of ESDs based in part on hydrologic function. We present the framework as a broadly applicable methodology for integrating ecohydrologic relationships and feedbacks into ESDs and resilience-based management strategies. Our proposed framework increases the utility of ESDs to assess rangelands, target conservation and restoration practices, and predict ecosystem responses to

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management. The integration of RHEM technology and our suggested framework on ecohydrologic relations expands the ecological foundation of the overall ESD concept for rangeland management and is well aligned with resilience-based, adaptive management of US rangelands. The proposed enhancement of ESDs will improve communication between private land owners and resource managers and researchers across multiple disciplines in the field of rangeland management.

Introduction

Ecological sites (ESs) are the primary means of evaluating ecosystem health, developing land management objectives, selecting conservation practices, and communicating ecosystem responses to management for US rangelands (USDA, 2013). An ES is a conceptual division of the landscape based on unique physical attributes (climate, soils, landscape position, and topography) that govern the ability to produce characteristic vegetation and to respond to management and disturbances. Individual ecological sites for US rangelands are described through a federal interagency program overseen by the Natural Resources Conservation Service (NRCS) (NRCS, 2013a). The characteristics of each ES are documented in an ecological site description (ESD) containing defining biophysical features, community scale dynamics, and interpretations for land use and management (Table 1).

Plant community dynamics in response to management and disturbances are conceptualized within each ESD by a state-and-transition model (STM) (USDA, 2013). An STM typically contains descriptions of multiple discrete soil-vegetation stable states (ecological states), transitions between the states, and identification of important ecological processes and events that maintain states or drive state transitions (Westoby et al., 1989; Briske et al., 2005, 2008; Bestelmeyer et al., 2009; USDA, 2013; Fig. 1). STMs may also include descriptions of 1) multiple within-state plant community phases and pathways; 2) at-risk pretransition community phases; 3) thresholds and feedback mechanisms that initiate or sustain state transitions; 4) ecological restoration pathways from one state to another, and 5) indicators of ecological resilience for each state. STMs identify one ecological state as the reference state that represents the ecological potential and natural/historical range of variability for the respective ES (USDA, 2013). The reference state generally exhibits vegetation composition/structure and ecological processes that act to self-sustain (negative feedback mechanisms) ecological resilience of the state and produce the largest array of potential ecosystem services (Bestelmeyer et al., 2009). Ecological resilience refers to the degree of alteration necessary to shift a system from one stable state of reinforcing structure–function feedback mechanisms to a new stable state sustained by different structure–function feedback mechanisms (Peterson et al., 1998; Briske et al., 2008). STMs may also identify alternative states that differ from the reference state in terms of one or more ecological processes (e.g., hydrology, nutrient cycling, energy capture and transformation) (USDA, 2013). Each ecological state contains one or more plant community phase(s) that collectively represent(s) the within-state variability in biotic structure, ecological function, and dynamic soil properties (USDA, 2013). An at-risk community phase exhibits conditions near biotic and/or abiotic structural-functional thresholds, beyond which shifts in processes (positive feedback mechanisms) facilitate state transition. Structural thresholds are typically identified (structural indicators) on the basis of changes in vegetation (composition, growth form, and distribution) and bare ground connectivity, whereas functional thresholds are identified (functional indicators) by shifts in processes (e.g., wildfire, infiltration, runoff, soil retention/erosion) that promote ecological function and resilience of an alternative state (Briske et al., 2005, 2008). Transitions are drivers or the mechanism by which state shifts occur and are commonly initiated by triggers (e.g., shifts in biotic or abiotic conditions, wildfire, drought, and flood) occurring independently or jointly (Briske et al., 2006, 2008). State transitions are generally regarded as irreversible without intensive management or restoration action, whereas within-state shifts between community phases represent reversible successional trajectories. Restoration pathways are transition reversal trajectories by which active restoration treatments re-establish and sustain prethreshold states through reinforcing resilience (negative feedback) of a desired state and reducing resilience (positive feedback) of an undesired state (Briske et al., 2006, 2008). Detailed STMs are an invaluable tool in assessment of current conditions, prediction of site responses to conservation practices, and assessment of the impact of management actions (Bestelmeyer et al., 2004; Petersen et al., 2009; Evers et al., 2013).

The resilience of ecological states on rangelands is strongly influenced by vegetation and hydrology interactions (Wilcox et al., 2003; Ludwig et al., 2005; Turnbull et al., 2008, 2012; Petersen et al., 2009; Williams et al., 2014a). Vegetation, litter, and ground cover on well-vegetated rangelands delay and reduce runoff and erosion by trapping water input, stabilizing sediment, promoting infiltration, and reducing the erosive energy of rainfall and overland flow (Pierson et al., 1994, 2008a, 2009, 2010, 2013; Abrahams et al., 1994, 1995; Parsons et al., 1996; Wainwright et al., 2000; Wilcox et al., 2003; Petersen and Stringham, 2008; Al-Hamdan et al., 2013; Williams et al., 2014a). Retention of soil water and nutrients stimulates below-ground biological activity and plant growth and reproduction that further sustain the vegetative community structure and the stable hydrologic function (Schlesinger et al., 1990, 1996; Wilcox et al., 2003; Belnap et al., 2005; Ludwig et al., 2005; Puigdefábregas, 2005). Alteration of vegetation structure through plant community shifts, fire, or other disturbances can increase the susceptibility of the ground surface to runoff and sediment detachment and transport (Fig. 2). Sparsely vegetated or bare soil locations promote runoff and soil loss (Blackburn, 1975; Abrahams et al., 1994, 1995; Parsons et al., 1996; Wilcox et al., 1996; Turnbull et al., 2008; Pierson et al., 2010, 2011, 2013, 2014; Williams et al., 2014a,b) and exhibit high evaporative losses and low soil water storage (Huxman et al., 2005; Newman et al., 2010; Royer et al., 2012). Water and soil losses from bare patches can further inhibit herbaceous productivity and propagate bare ground connectivity (Bhark and Small, 2003). Runoff and soil loss increase where susceptible bare conditions and erosion processes become well-connected at the hillslope scale (Fig. 2; Wilcox et al., 1996; Davenport et al., 1998; Pierson et al., 2008a; Turnbull et al., 2008; Petersen et al., 2009; Pierson et al., 2009, 2010, 2013; Williams et al., 2014a), potentially irreversibly degrading a site beyond a resource conservation threshold (Schlesinger et al., 1990; Whitford et al., 1995; Bestelmeyer et al., 2003; Chartier and Rostagno, 2006; Peters et al., 2006, 2007; Turnbull et al., 2012; Williams et al., 2014a). Inclusion of these ecohydrologic (vegetation and hydrology interactions) relationships in ESDs potentially improves the utility of ESDs for assessing ecological state dynamics and predicting ecological responses to management actions.

Clearly, hydrologic function is well recognized as an indicator of ecosystem health and ecological state resilience on rangelands (Wilcox et al., 2003; Ludwig et al., 2005; Turnbull et al., 2008; Petersen et al., 2009; Williams et al., 2014a), but hydrologic information is commonly missing in ESDs and STMs. The current recommended framework for constructing ESDs (see Table 1) provides for inclusion

Table 1
Fundamental contents of an ecological site description (ESD) as prescribed in the Interagency ESD Handbook for Rangelands (USDA, 2013). See USDA (2013) for greater specificity on each feature, key element, and utility

Feature	Key elements	Utility
Ecological site characteristics	Site name; ID#; hierarchical classification	General information on soil type, plant community, and precipitation regime based on naming convention
Physiographic features	Description of position on landscape, landform, geology, aspect, slope, elevation, water table, flooding, ponding, runoff class	General topographic, geologic and hydrologic description, potential for runoff generation
Climatic features	Mean annual precipitation; monthly moisture/temperature distribution; frost- and freeze-free periods; storm frequency/intensity/duration characterization; frequency of catastrophic storms; drought trends	Interpretation of production potential and general climatic regime
Influencing water features	Description of water features (streams, springs, wetlands, depressions, etc.) that influence vegetation or management of site	General hydrologic features of importance to vegetation management
Representative soil features	Parent materials; surface/subsurface soil texture, surface/subsurface fragments; drainage class; hydrologic conductivity; depth; electrical conductivity; sodium adsorption ratio; calcium carbonate equivalent; soil reaction (pH); and available water capacity; soil and hydrologic rangeland health indicators that characterize the reference community phase	Distinction, based on soil properties, from other ecological sites; interpretation of key soil properties that affect ecohydrology
States and community phases	Ecological site dynamics (describe successional stages and disturbance dynamics); state-and-transition diagram (description of states, community phases and pathways, transitions, restoration pathways, and ecological mechanisms causing transitions and precluding recovery of references and other states); photos (each state and community phase); narrative (description of each community phase and state, rational for phase and state separations, causes or triggers of community pathways and state transitions, thresholds between states, details on water cycle/nutrient cycle/energy flow, hydrologic and erosion characteristics associated with phases/states/transitions, and changes in key drivers of runoff/erosion behavior); supporting community phase documentation (citations to empirical data); community phase composition (species list, constancy table, and description for phases); range of annual production; total annual production by growth form; canopy or foliar cover; structure (horizontal [canopy and basal gaps, canopy/foliar cover] and vertical); ground surface cover; community phase growth curves[1]	Description of ecological dynamics of the site
Ecological site interpretations[1]	Animal community; hydrology functions (changes in hydrologic functions that may occur with shifts in community phases within states); recreational uses; wood products; other products	Potential alteration of goods and services associated with ecosystem dynamics
Supporting information	Associated or similar ecological sites; inventory data references; agency/state correlation; type locality; relationship to other established systems[1]; other references; rangeland health reference sheet (data on 17 rangeland health indicators for the reference state condition)	Description of similar, related, and easily confused sites; data comparisons; phase relationships to potential natural vegetation; hydrologic function of reference state
Site description approval	Authorship; site approval by appropriate authorized agency representative; name of approving official	Reference for original author(s) and description development

[1] Feature or element is recommended, but not required.

of hydrologic data and key ecohydrologic relationships. However, current guidance for ESD and STM development provides little to no direction regarding what hydrologic or ecohydrologic information should be included therein and provides limited information on how to integrate such information within the ESD concept (USDA, 2013). Inclusion of hydrologic data in ESDs and STMs is also limited by data availability. Although data on vegetation and soils are vast, quantitative hydrologic data are unavailable for many rangeland ecological sites. Currently, hydrologic function is indirectly represented in ESDs through a suite of rangeland health attributes and indicators (e.g., percent bare ground, surface soil stability, water flow patterns) for the reference state (see Pellant et al., 2005). Although rangeland health attributes provide some standards for comparison of the reference state to alternative states, they provide a limited basis for evaluating and quantifying hydrologic and erosional repercussions of disturbances and state transitions and the benefits of conservation practices (e.g., Pierson et al., 2014).

Recent advances in ecohydrology, monitoring techniques, and process-based hydrology models provide a foundation to enhance utility of ESDs for rangeland management by providing more robust and relevant ecohydrologic information. Ecohydrologic studies over the past 2 decades have advanced understanding of the linkages among vegetation structure, hydrologic and erosion processes, ecosystem health, and identification of critical thresholds in ecological succession (Davenport et al., 1998; Wainwright et al., 2000; Ludwig et al., 2005; Peters et al., 2007; Turnbull et al., 2008, 2012; Petersen et al., 2009; Pierson et al., 2010, 2013; Wilcox et al., 2012a; Williams et al., 2014a). Knowledge has also increased regarding rangeland ecohydrologic and erosion responses to disturbances and conservation practices (Pierson et al., 2007, 2008a, 2009; Cline et al., 2010; Weltz and Spaeth, 2012; Bestelmeyer et al., 2013; Pierson et al., 2013, 2014, 2015; Roundy et al., 2014; Williams et al., 2014a,b, 2015). The increased availability of integrated vegetation, hydrology, and erosion datasets from regional and national field experiments has facilitated development of quantitative tools for incorporating hydrology and erosion data into rangeland ESDs and STMs (Wei et al., 2009; Nearing et al., 2011; Al-Hamdan et al., 2012a,b, 2015; Hernandez et al., 2013; Weltz et al., 2014). For example, the Rangeland Hydrology and Erosion Model (RHEM) was developed from diverse rangeland datasets for predicting runoff and erosion responses on rangelands (Wei et al., 2009; Nearing et al., 2011; Al-Hamdan et al., 2012a,b). The RHEM model provides a new tool for integrating vegetation, soils, hydrology, and erosion predictions in the development of ESDs and STMs (Weltz and Spaeth, 2012; Hernandez et al., 2013; Weltz et al., 2014). RHEM was recently paired with USDA-NRCS National Resources Inventory (NRI; NRCS, 2013b) rangeland data to determine areas of vulnerability to accelerated soil loss on non–federally owned rangelands across the western United

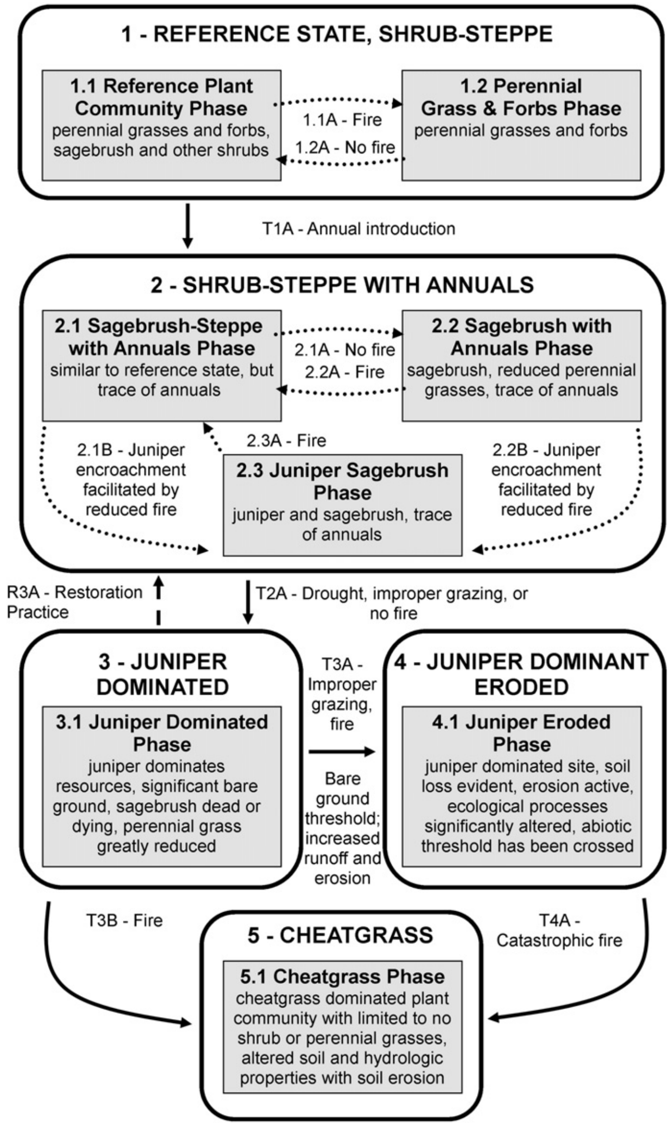

Figure 1. Example state-and-transition model (STM) showing fundamental components for the "South Slopes 12-16 PZ" Ecological Site (NRCS, 2014) located in Malheur High Plateau Mountain Land Resource Area (MLRA 23, USDA, 2006). The site includes a reference state with bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve ssp. *spicata*), Idaho fescue (*Festuca idahoensis* Elmer), Sandberg bluegrass (*Poa secunda* J. Presl), and Thurber's needlegrass (*Achnatherum thurberianum* [Piper] Barkworth) understory and a mountain big sagebrush (*Artemisia tridentata* Nutt. subsp. *vaseyana* [Rydb.] Beetle), basin big sagebrush (*A. tridentata* Nutt. subsp. *tridentata*), and antelope bitterbrush (*Purshia tridentata* [Pursh] DC.) shrub component. The site also includes alternative stable states associated with conifer encroachment by native western juniper (*Juniperus occidentalis* Hook.) and invasion by the exotic annual cheatgrass (*Bromus tectorum* L.) (NRCS, 2014). Individual ecological states are delineated by bold black rectangles, each with one or more within-state plant community phases (shaded rectangles). State transitions are indicated by solid black arrows. Within-state community pathways are indicated by dotted black arrows. Restoration pathways are indicated by dashed black arrows. An STM typically includes an accompanying table with text descriptions of the plant community composition, community pathway/transition dynamics, and key structural and functional indicators. See USDA (2013) and Briske et al. (2008) for detailed descriptions of components of STMs.

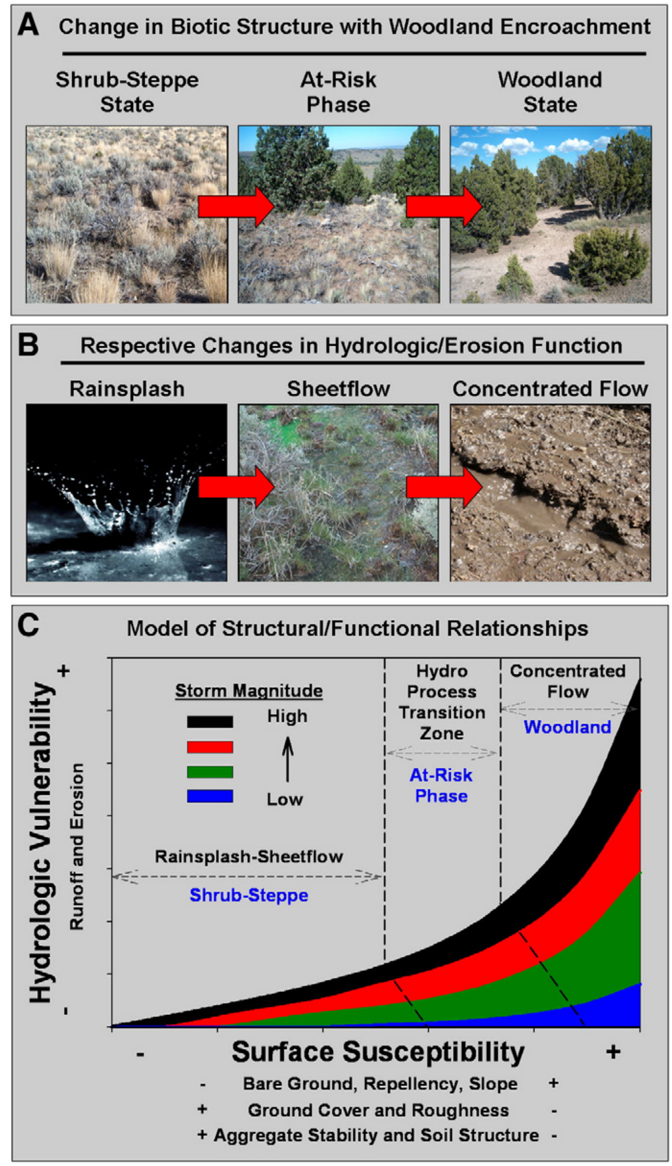

Figure 2. Common biotic structural (**A**) and hydrologic/erosion functional (process) shifts (**B**) following woodland encroachment into Great Basin, USA, shrub-steppe, and the conceptual increase in hydrologic vulnerability (runoff and erosion response) associated with the respective changes in surface susceptibility (**C**). Surface susceptibility (**C**) is dictated by the amount, type, and distribution of vegetation and ground cover (biotic structure), inherent soil properties (e.g., bulk density, erodibility, texture, and water repellency), surface roughness, and topography/slope steepness. Runoff and erosion from a well-vegetated shrub-steppe state (**A**) occurs primarily by rainsplash and sheetflow processes (**B**) and is typically low. Hydrologic vulnerability (**C**) increases exponentially with site and ground surface degradation through the at-risk phase (**A**), particularly where bare soil increases beyond 50–60% (structural threshold). High rates of erosion typically occur where Great Basin shrub-steppe communities transition from the at-risk phase to the woodland state (**A**). The exponential increase in soil loss (**C**) following the transition results from a shift (functional threshold) to concentrated flow (**B**) as the dominant runoff/erosion process in the woodland state. Concentrated flow has higher velocity than sheetflow and thereby exhibits greater sediment detachment and transport capacity than the combined effects of rainsplash and sheetflow. Overall hydrologic vulnerability for a particular surface susceptibility is strongly influenced by storm magnitude (**C**). Long-term hydrologic vulnerability is dictated by the spatial and temporal variability in surface susceptibility and climate regime (e.g., monsoonal vs. continental storm regimes). In this context, ecohydrologic resilience is considered the degree of alteration of biotic structure and the associated hydrologic/erosion function required to shift the ecosystem from one state to the other state, essentially from one side of graph **C** to the other side. Figure modified from Williams et al. (2014a,b) and Miller et al. (2013). Rainsplash photograph (**B**) courtesy of U.S. Department of Agriculture, Natural Resources Conservation Service.

States (USDA, 2011; Weltz et al., 2014), as part of the multiagency Conservation Effects Assessment Project (CEAP) (Spaeth et al., 2013). RHEM was also recently paired with NRI data from more than 100 sites to evaluate the influence of vegetation, ground cover, soils, and topography on soil erosion rates from rangelands in the southwestern United States (Hernandez et al., 2013).

In this paper, we explain a methodology for incorporating hydrologic data and key ecohydrologic relationships into ESDs. The goal is to provide a framework for populating ecohydrologic information in ESDs and for enhancing the utility of ESDs for assessing rangelands, identifying threats/opportunities, and guiding resilience-based management (e.g., Briske et al., 2008). We begin with identification of key data and information required for ecohydrologic enhancement of ESDs. Second, we identify an ES for development and demonstration of our proposed framework. Third, we describe and demonstrate application of the RHEM tool for predicting runoff and erosion data needed in ESDs. We conclude with demonstration of the recommended framework incorporating hydrologic data and ecohydrologic relationships into the ESD concept and evaluation of the RHEM tool for refinement and development of ESDs.

Development of Framework and Methodology

Ecohydrologic Data Required for ESDs

We developed a catalog (Table 2) of key variables and information required for inclusion of ecohydrologic data and feedbacks into the current ESD structure (see Table 1). The catalog separates data into two primary groups: 1) discrete quantitative data and 2) descriptive or qualitative data on ecosystem function and response to management. Discrete quantitative data consists of five subcategories: 1) climate, 2) vegetation and ground cover, 3) soil properties and soil water storage, 4) topography, and 5) hydrology and erosion. Vegetation and ground cover, soil properties, and topography data collectively define the susceptibility of a site to runoff and erosion (Figs. 2 and 3; Pierson et al., 2011; Williams et al., 2014b). Climate data provide insight into potential storm magnitudes and associated recurrence intervals and, when evaluated in context with site-susceptibility variables, provide information for predicting hydrologic vulnerability (Fig. 2C; Pierson et al., 2011; Williams et al., 2014b) and populating runoff and erosion prediction tools. Predicted or measured hydrology (e.g., evapotranspiration, infiltration, runoff) and erosion data provide tangible measures of short- and long-term hydrologic vulnerability for individual plant community phases, disturbances, and conservation practices. The integration of discrete quantitative data with qualitative data on ecosystem dynamics provides an interpretative and management basis for assessing and predicting ecological resilience of states and community phases, structural and functional thresholds, transitions, and responses to disturbance and management (Briske et al., 2008; Petersen et al., 2009). The suggested data in Table 2 are currently required or recommended within various feature areas of ESDs (see Table 1; USDA, 2013). However, many approved ESDs are devoid of the suggested quantitative hydrology and erosion data and its linkage to plant community dynamics and rangeland health. We suggest that the data requirements in Table 2 provide a source for populating the "hydrologic functions" element within the "ecological site interpretations" feature (see Table 1) and that a well-developed "hydrologic functions" section provides the basis for integration of key ecohydrologic data within the STM and community dynamics content of the "states and community phases" feature.

Ecological Site and Associated Ecohydrologic Dynamics

The "South Slopes 12-16 Precipitation Zone (PZ)" (ID: R023XY302OR; Table 3; NRCS, 2014) ES (hereafter referred to as the study site) was

Table 2
Data required for describing and predicting hydrologic function and ecohydrologic feedbacks on rangelands

Data category	Variables or description	Location in current ESD structure[1]
Discrete quantitative data		
Climate[2–4]	Precipitation and soil temperature regime; rainfall intensity/duration/frequency distribution or representative climate station[4]	Climate feature
Vegetation and ground cover[2,4,5]	Percent foliar and basal cover by plant growth form[4]; percent ground cover by cover element (e.g., rock, litter)[4]; percent bare soil; if woodland, percent of site covered by tree canopy and as intercanopy	States and community phases feature (narrative; supporting community phase documentation; community phase composition; canopy or foliar cover; structure; ground surface cover)
Soil properties and soil water storage[2,4,5–7]	Aggregate stability; bulk density; depth to restrictive layer and/or bedrock; erodibility; hydraulic conductivity; proportional area for exhibiting wettable, slight, moderate, and strong soil water repellency; soil texture[4]; water-holding capacity	Representative soil feature
Topography[2,4,5]	Hillslope angle[4], length[4], and shape[4] (concave, convex; linear; S shaped)	Physiographic feature
Hydrology and erosion[2,5,7]	Cumulative runoff and erosion for design storms (e.g., 2-, 5-, 10-, 25-, 50-, 100-yr event) and annual averages	States and community phases feature (narrative); ecological site interpretations feature (hydrology functions); supporting information feature (rangeland health reference sheet)
Descriptive qualitative data		
Structural thresholds[2,5]	Indicators and drivers of structural thresholds separating states and community phases	States and community phases feature (ecological site dynamics; state-and-transition diagram; narrative); ecological site interpretations feature (hydrologic functions)
Functional thresholds[2,5]	Indicators and drivers of functional thresholds separating states and community phases	States and community phases feature (ecological site dynamics; state-and-transition diagram; narrative); ecological site interpretations feature (hydrologic functions)
Response to management[2,5]	Description of plant community dynamics relative to management actions and climate	States and community phases feature (all sections therein); ecological site interpretations feature (hydrology functions); supporting information feature (rangeland health reference sheet)
Rangeland health indicators[2,5,6]	See Pellant et al. (2005) for list of indicators	Supporting information feature (rangeland health reference sheet)

1 See Table 1 for current Ecological Site Description (ESD) structure and feature descriptions.
2 See Bestelmeyer et al. (2009, 2010), Moseley et al. (2010), and USDA (2013) for guidance on and data sources for the development of ESD features and STMs.
3 Climate data sources include models such as Daymet (Thornton et al., 2012), NOAA National Centers for Environmental Information (NOAA, 2013), PRISM (PRISM Climate Group, 2013), and Western Regional Climate Center (WRCC, 2013).
4 Data or variable required to populate and run Rangeland Hydrology and Erosion Model (RHEM) for runoff and erosion estimates (Nearing et al., 2011; Al-Hamdan et al., 2015).
5 Data sources include published literature and plot data (e.g., NRI data), local knowledge, and supportive field data collected for ESD development.
6 Data sources include the National Cooperative Soil Survey (NCSS, 2013) and the Natural Resources Conservation Service soil classification Web page (NRCS, 2013c).
7 Data sources include hydrology and erosion models, such as the RHEM, and erodibility predictive equations (see Al-Hamdan et al., 2012b, 2015).

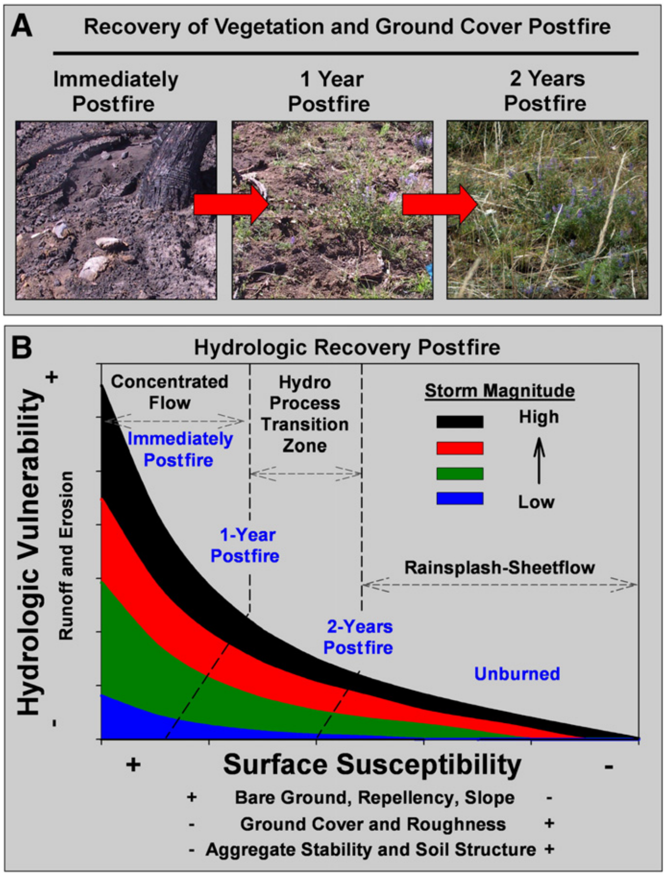

Figure 3. Change in vegetation and ground surface conditions with postfire recovery (**A**); and the associated decline in hydrologic vulnerability and shift in dominant erosion processes with decreasing surface susceptibility during postfire recovery (**B**). Bare, water-repellent soil conditions in the immediate postfire period facilitate runoff generation and promote formation of high-velocity concentrated flow. The decline in hydrologic vulnerability with time post fire is strongly related to changes in ground surface conditions that trap and store water and sediment and inhibit concentrated flow. Although runoff and erosion rates commonly approach prefire levels within the first 3 years post fire, burned rangelands remain susceptible to amplified runoff and soil loss from extreme events until the biotic structure and overall conditions (e.g., vegetation and litter biomass, well aggregated soils) return to near unburned conditions. Figure modified from Williams et al. (2014a,b) and Miller et al. (2013).

selected for evaluation and ecohydrologic enhancement in this study. The study site was selected due to the wealth of published literature on plant community dynamics and similarities in hydrologic function relative to comparable ecological sites (Miller et al., 2005, 2013; Pierson et al., 2007, 2008a,b, 2009, 2013; Petersen and Stringham, 2008; Bates and Svejcar, 2009; Petersen et al., 2009; Davies and Bates, 2010; Bates et al., 2011, 2014; Davies et al., 2012; Williams et al., 2014a). Summary characteristics from the NRCS ESD of the study site are provided in Table 3, and a generalized STM is shown in Fig. 1 (adapted from the NRCS-published STM (NRCS, 2014).).

The NRCS ESD describes five ecological states for the study site (NRCS, 2014). The Reference State (State 1) consists of two community phases: 1.1) a reference plant community phase with an understory of bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve ssp. *spicata*), Idaho fescue (*Festuca idahoensis* Elmer), Sandberg bluegrass (*Poa secunda* J. Presl), Thurber's needlegrass (*Achnatherum thurberianum* [Piper] Barkworth) and other perennial grasses, a shrub component mainly of mountain big (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle) and basin big sagebrush (*A. tridentata* Nutt. ssp. *tridentata*), and antelope bitterbush (*Purshia tridentata* [Pursh] DC.) and 1.2) a second phase, facilitated by burning, that is dominated by bluebunch wheatgrass, Idaho fescue, Thurber's needlegrass, and other perennial grasses and forbs. Invasion of the Reference State by

Table 3
Geographic, climatic, soils, and vegetation characteristics of the "South Slopes 12-16 PZ" (R023XY302OR) Ecological Site as provided in the respective published Ecological Site Description (NRCS, 2014)

	Ecological site characteristics
Site name (ID)	South Slopes 12-16 PZ (R023XY302OR)
Major Land Resource Area[1]	23—Malheur High Plateau (southeast OR, northwest NV, and northeast CA)
Elevation (aspect, slope)	1200–2100 m (south-facing slopes, 15–80% hillslope gradient)
Annual precipitation	300–400 mm (xeric regime)
Air temperature (frost-free days)	−34.4°C minimum, 37.8°C maximum (30-90 frost-free days y^{-1})
Soil depth (temperature regime)	0.35–1.0 m (frigid—low elevations, cryic—upper elevations)
Surface soil texture	medium-textured: gravelly sandy loam; gravelly silt loam; cobbly clay loam
Soil water-holding capacity	25-117 mm (well-drained)
Reference plant community	*Pseudoroegneria spicata* (Pursh) Á. Löve ssp. *spicata*; *Festuca idahoensis* Elmer; *Poa secunda* J. Presl; *Achnatherum thurberianum* (Piper) Barkworth; *Artemisia tridentata* Nutt. ssp. *vaseyana* (Rydb.) Beetle; *Artemisia tridentata* Nutt. ssp. *tridentata*; and *Purshia tridentata* (Pursh) DC

[1]USDA, 2006

annual grasses and forbs facilitates transition to State 2. State 2 includes three community phases: 2.1) one with primarily sagebrush-steppe vegetation and trace coverage of cheatgrass (*Bromus tectorum* L.) and annual weeds; 2.2) a second phase, promoted by mismanaged grazing or reduced fire, with increased coverage of sagebrush and Sandberg bluegrass and trace amounts of cheatgrass and annual weeds; and 2.3) a fire-limited phase with early-succession western juniper (*Juniperus occidentalis* Hook.) encroachment, sagebrush, Sandberg bluegrass, and trace amounts of cheatgrass and annual weeds. Drought, improper grazing, or fire exclusion in State 2 promote transition to State 3. As juniper cover increases, sagebrush, grasses, and forbs decline due to competition for site resources (Bates et al., 2000; Miller et al., 2000, 2005; Roberts and Jones, 2000; Petersen et al., 2009). In State 3, juniper dominates site resources (biotic threshold), sagebrush and other shrubs decline, and extensive bare ground develops in the intercanopy (Miller et al., 2000, 2005; Pierson et al., 2007, 2013; Williams et al., 2014a). Sandberg bluegrass becomes the dominant grass species in State 3, and other perennial grasses are reduced in abundance and productivity (NRCS, 2014). Juniper woodland development is complete in State 3 and soil loss increases, ultimately driving the site across an abiotic threshold to transition to State 4 (NRCS, 2014). In State 4, the site is dominated by juniper, soil loss is evident, and all ecological processes have been significantly altered, limiting perennial plant re-establishment (NRCS, 2014). Catastrophic wildfire in State 4 promotes transition to State 5. In State 5, cheatgrass dominates the site, there is essentially no shrub or perennial grass component, and the hydrologic and nutrient cycles are negatively affected through changes in dynamic soil properties and soil loss (NRCS, 2014). Transition to State 5 sets a course for more frequent burning (annual grass-fire cycle) than preinvasion, and the repeated grass-fire cycle perpetuates the cheatgrass monoculture (Knapp, 1996; Duke and Caldwell, 2001; Brooks et al., 2004; Miller et al., 2011).

Changes in plant community physiognomy across the multiple states educe important shifts in hydrologic and erosion processes and retention of water and soil resources. Runoff and erosion are minimal for the reference community vegetation type (Petersen and Stringham, 2008; Pierson et al., 2008a, 2009; Petersen et al., 2009). Runoff and erosion on the Reference State occur primarily by rainsplash and sheetflow (see Fig. 2) due to dense vegetation and litter cover (Table 4; Pierson et al., 2011; Williams et al., 2014b). Increased western juniper cover associated with fire exclusion enhances connectivity of bare ground and

Table 4
Percent cover by growth form applied in RHEM[1] hydrologic and erosion modeling for plant community phases (see Fig. 1) and various disturbances and conservation practices on the "South Slopes 12-16 PZ" (R023XY302OR) Ecological Site (NRCS, 2014). Values are approximated from literature[2] on the study site and other similar ecological sites

State or community phase; disturbance[3]; or conservation practice[3]	Shrub foliar cover (%)	Grass foliar cover (%)	Forb foliar cover (%)	Basal ground cover (%)	Litter ground cover (%)	Cryptogam ground cover (%)	Rock ground cover (%)	Bare soil (%)
Reference State, Phase 1.1 sagebrush,[4] perennial grasses, and forbs	28	14	12	25	40	2	3	30
Reference State, Phase 1.2 perennial grasses and forbs	12	24	6	25	40	2	3	30
State 2, Phase 2.1 sagebrush[4]-steppe with cheatgrass[5]	16	20	10	20	40	2	3	35
State 2, Phase 2.2 sagebrush[4] with cheatgrass[5]	25	15	5	20	40	1	4	35
State 2, Phase 2.3 juniper,[6] sagebrush,[4] and cheatgrass[5] (5% juniper[6] cover)	20	15	5	17	38	1	5	39
State 3, Phase 3.1 juniper[6]-dominated (intercanopy only, 70% of total area)	7	10	3	10	18	0	12	60
State 4, Phase 4.1 juniper[6]-eroded (intercanopy only, 70% of total area)	2	6	2	4	10	0	14	72
State 5, Phase 5.1 cheatgrass[5]	1	35	5	20	40	0	5	35
States 1, 2, & 5 immediately following wildfire	1	0	0	1	5	0	5	89
States 1-2 immediately following prescribed fire	5	1	1	1	10	0	5	84
States 3-4 immediately following wildfire[7]								
Intercanopy (70% of area)	1	0	0	1	1	0	19	79
Canopy (30% of area)	1	0	0	1	5	0	14	80
State 3 immediately following prescribed fire[7]								
Intercanopy (70% of area)	1	5	1	5	6	0	19	70
Canopy (30% of area)	1	1	1	1	16	0	14	69
State 3 approximately 10 yr after prescribed fire	10	15	10	20	35	0	5	40

[1] Rangeland Hydrology and Erosion Model (Nearing et al., 2011; Al-Hamdan et al., 2015).
[2] Bates et al., 2000; Miller et al., 2000; Bates et al., 2005; Pierson et al., 2007; Bates and Svejcar, 2009; Pierson et al., 2009; Davies and Bates, 2010; Bates et al., 2011; Davies et al., 2012; Miller et al., 2013; Pierson et al., 2013; Williams et al., 2014a.
[3] State and/or community phase shown for disturbances and conservation practices indicates the state and/or phase at the time of disturbance or treatment. Cover values shown reflect the effect of the treatment applied to the specified state and/or community phase.
[4] *Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle and *A. tridentata* Nutt. ssp. *tridentata*.
[5] *Bromus tectorum* L.
[6] *Juniperus occidentalis* Hook.
[7] Nearly 100% of juniper burned.

runoff sources and promotes formation of high-velocity concentrated flow through bare intercanopy areas (see Fig. 2; Pierson et al., 2007; Petersen and Stringham, 2008; Petersen et al., 2009; Pierson et al., 2013; Williams et al., 2014a). Concentrated flow has greater sediment transport and detachment capacity than rainsplash and sheetflow and results in greater soil loss relative to conditions representative of the Reference State (Pierson et al., 2008a, 2009, 2013; Williams et al., 2014a; Pierson et al., 2015). Increased runoff and soil loss result in a reduced retention of water and nutrients (Miller et al., 2005). Increased bare ground following juniper dominance also increases soil water loss to evapotranspiration without beneficial intercanopy plant productivity, effectively isolating soil water and soil nutrients to tree islands (Klemmedson and Tiedemann, 2000; Newman et al., 2010). The effects of cheatgrass on infiltration, runoff, and soils are not well known with exception of the postfire environment (Wilcox et al., 2012b). Fire removal of cover for either state increases the connectivity of runoff and erosion generating bare ground and facilitates a temporary shift to concentrated flow as the dominant erosion process across the site (see Fig. 3; Pierson et al., 2011; Al-Hamdan et al., 2013; Williams et al., 2014a,b, 2015). The temporal stability of the process shift depends on factors such as the prefire vegetation and cover (i.e., state or phase), postfire precipitation and vegetation recovery, and land use (Pierson et al., 2011; Miller et al., 2013; Williams et al., 2014b). Postfire vegetation and hydrologic recovery is generally more rapid for the Reference State and State 2 due to the presence of perennial grasses (Miller et al., 2005; Pierson et al., 2009; Bates et al., 2014; Miller et al., 2014). Persistence of State 4 is associated with long-term soil loss and site degradation (Miller et al., 2005). Increased fire frequency in the cheatgrass-dominated State 5 increases the frequency of bare ground exposure to erosion processes and likely results in long-term loss of nutrient rich surface soil through repeated erosion by runoff and wind (Pierson et al., 2011; Sankey et al., 2012; Wilcox et al., 2012b; Williams et al., 2014b). Understanding and quantification of the key ecohydrologic relationships discussed herein are necessary to appropriately assess the potential impacts of state transitions and management practices (e.g. prescribed burning and tree removal) for the study site.

Hydrology and Erosion Modeling

The RHEM tool (Nearing et al., 2011; Al-Hamdan et al., 2015), Version 2.1, was applied to estimate event and annual runoff and erosion for each community phase of the South Slopes 12-16 PZ ES (see Table 3) and for dynamic vegetation conditions induced by conservation practices and disturbances. RHEM is a modified version of the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) and was developed specifically for simulation of hillslope-scale runoff and erosion from rangelands (Nearing et al., 2011; Al-Hamdan et al., 2015). RHEM requires the following user input: 1) climate data (obtained via the CLIGEN climate generator [Zhang and Garbrecht, 2003] within model interface); 2) surface soil texture class (upper 4 cm); 3) hillslope length, gradient, and shape (uniform, convex, concave, or S shaped); 4) vegetation (foliar and basal cover); and 5) ground cover (rock, litter, and cryptogams cover). The data required to run RHEM are commonly available from literature, local data sources, and rangeland databases (Weltz and Spaeth, 2012; Hernandez et al., 2013; NRCS, 2013b) and are required for ESD development (see Tables 1 and 2; USDA, 2013). RHEM simulations for multiple ecological states or phases can be run separately and then compared side-by-side within the model interface. The model produces graphical and tabulated output for annual and event (2-, 5-, 10-, 25-, 50-, and 100-yr runoff events) precipitation, runoff, and erosion based on a CLIGEN-generated 300-year record of precipitation events. The RHEM tool and documentation are available free of charge on the Web at: http://apps.tucson.ars.ag.gov/rhem/.

A baseline RHEM model was configured to represent community phases, conservation practices, and disturbances using a single CLIGEN station (Sheaville, OR, USA, Station ID: 357736, 1396 m elevation,

Table 5
Hydrologic functions table developed from RHEM[1] predicted runoff and erosion and associated hydrologic interpretations for a subset of community phases, disturbances, and conservation practices on the “South Slopes 12-16 PZ” (R023XY302OR) Ecological Site (NRCS, 2014) as characterized in Tables 3 and 4

	Average annual	2-yr event	10-yr event	50-yr event	100-yr event	Hydrologic interpretation[2]
Precipitation (mm)	314	24	35	48	57	
State 1, Phase 1.1—sagebrush[3], perennial grasses, and forbs						Ample vegetation and litter promote good infiltration and low runoff and soil loss at the annual scale and for most storms. Runoff and erosion occur primarily by rainsplash and sheetflow in isolated bare patches, but off-site runoff and sediment delivery are minimal except for rare and extreme (>100-yr) events. High infiltration rates recharge soil water and sustain site productivity (high resilience).
Runoff (mm)	1	0	4	9	13	
Erosion ($t \cdot ha^{-1}$)	0.1	0.0	0.3	0.6	0.8	
State 1, Phase 1.2—perennial grasses and forbs						
Runoff (mm)	2	0	6	11	15	
Erosion ($t \cdot ha^{-1}$)	0.1	0.0	0.4	0.7	0.9	
State 2, Phase 2.1—sagebrush-steppe[3] with cheatgrass[4]						State 2 is structurally and hydrologically similar to Phase 1.1. Runoff and erosion are generally low due to ample vegetation and ground cover and occur primarily by isolated rainsplash and sheetflow. Woodland encroachment (Phase 2.3) facilitates competition for limited water and soil nutrients, resulting in increased bare ground. Competition-induced declines in understory vegetation are most evident on sites with shallow soils (<0.6 m depth) and limited soil water storage. Increased bare ground promotes runoff and soil erosion by concentrated flow during high intensity rainfall events (25-yr + events) and induces a decrease in ecohydrologic resilience. Bare ground > 40% further enhances runoff generation and overland flow, reduces intercanopy soil water recharge, and promotes transition to State 3.
Runoff (mm)	2	0	6	11	16	
Erosion ($t \cdot ha^{-1}$)	0.1	0.0	0.4	0.7	1.0	
State 2, Phase 2.2—sagebrush[3] with cheatgrass[4]						
Runoff (mm)	2	0	6	11	16	
Erosion ($t \cdot ha^{-1}$)	0.1	0.0	0.4	0.7	1.0	
State 2, Phase 2.3—juniper[5], sagebrush[3], and cheatgrass[4]						
Runoff (mm)	3	1	8	13	18	
Erosion ($t \cdot ha^{-1}$)	0.2	0.0	0.5	0.8	1.1	
State 3, Phase 3.1—juniper[5]-dominated						State 3 represents a shift from biotic-controlled infiltration and soil retention to abiotic-driven loss of critical soil resources. Bare ground > 50% promotes decreased aggregate stability, connectivity and concentration of runoff, and increased soil loss across spatial scales. Water flow patterns, terracettes, and litter movement may be evident. Persistence facilitates transition to State 4.
Runoff (mm)[6]	8	4	10	13	18	
Erosion ($t \cdot ha^{-1}$)[6]	0.8	0.3	0.9	1.2	1.7	
State 4, Phase 4.1—juniper[5]-eroded conditions						Intercanopy (usually at least 70% of area) may be 90% bare ground, concentrated flow is dominant erosion process, and high runoff and erosion sustain the degraded state. Intercanopy aggregate stability is low, and water flow paths and terracettes are evident. Restoration of vegetation and hydrologic function to that of States 2-3 is considered extremely difficult. Burning may promote transition to State 5.
Runoff (mm)[6]	15	6	12	17	22	
Erosion ($t \cdot ha^{-1}$)[6]	1.7	0.6	1.3	1.8	2.4	
State 5, Phase 5.1—cheatgrass[4]						Ample cover results in relatively low runoff/erosion rates for unburned conditions, but cheatgrass[4] promotes increased fire size and frequency (every 3-5 + yr, abiotic threshold). Recurring fire may result in long-term loss of soil resources (see burned States 1, 2, and 5); however, knowledge is limited regarding long-term effects of cheatgrass[4] dominance on hydrologic function and soil loss.
Runoff (mm)	3	0	7	12	17	
Erosion ($t \cdot ha^{-1}$)	0.2	0.0	0.4	0.7	1.0	
States 1, 2, 5—immediately after wildfire						Runoff and erosion increase substantially post fire due to shift to concentrated flow as the dominant erosion process, particularly where bare ground > 60% and soils are water repellent. Relative hydrologic and erosion recovery common in 1 and 3-5 yr, respectively, or when ground cover ≥ 50%. Fire-induced increases in runoff and erosion are generally less for prescribed burns, and the vegetation and overall hydrologic recovery periods for prescribed fires are generally shorter (1–2 yr). Poor postfire plant recruitment extends elevated runoff and soil loss period. Transition from State 2 to State 5 possible with cheatgrass[4] present.
Runoff (mm)	35	11	20	32	34	
Erosion ($t \cdot ha^{-1}$)	17.5	5.5	12.7	21.7	25.8	
States 1 and 2—immediately after prescribed fire						
Runoff (mm)	30	10	19	30	32	
Erosion ($t \cdot ha^{-1}$)	12.5	4.1	9.9	17.1	20.9	
States 3 and 4—immediately after wildfire						Extensive bare ground postfire results in amplified runoff and substantial erosion at annual and individual storm time scales. Length of vegetation and hydrologic recovery periods are unknown. Restoration of severely burned sites in State 3 considered difficult without intensive management to restore understory vegetation. Irreversible transition to State 5 possible.
Runoff (mm)[7]	26	9	18	28	32	
Erosion ($t \cdot ha^{-1}$)[7]	9.9	3.4	8.5	14.8	18.2	
State 3—immediately after prescribed fire						Low to moderate severity fire increases erosion from concentrated flow, but erosion is reduced to rates similar to Phase 2.3 (in 3–5 yr) by seeding success or with good postfire plant recovery. Poor postfire plant recruitment extends elevated runoff and soil loss period.
Runoff (mm)[7]	21	8	17	24	31	
Erosion ($t \cdot ha^{-1}$)[7]	5.6	2.1	5.4	9.6	11.9	
State 3—approximately 10 yr after prescribed fire						Enhanced intercanopy grass and forb cover (relative to States 3 and 4) reduce bare ground exposure to rainfall and runoff, trap rainfall and overland flow, improve infiltration, and reduce soil erosion to levels similar to State 2. Vegetation and associated hydrologic recovery strongly depend on ample precipitation post treatment and are more rapid on sites with shallow soils.
Runoff (mm)	4	1	8	13	19	
Erosion ($t \cdot ha^{-1}$)	0.3	0.1	0.6	0.9	1.3	

1 Rangeland Hydrology and Erosion Model (Nearing et al., 2011; Al-Hamdan et al., 2015) parameterized as follows: loam surface soil texture, 50 m slope length, uniform slope shape, 35% slope gradient, state- and phase-specific cover as shown in Table 4, and climate data from the Sheaville, OR, U.S. climate station (ID: 357736).

2 Key citations: Craddock and Pearse, 1938; Pierson et al., 1994, 2007, 2008a,b, 2009; Cline et al., 2010; Pierson et al., 2010, 2011; Wilcox et al., 2012b; Pierson et al., 2013, 2014; Williams et al., 2014a,b.

3 *Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle and *A. tridentata* Nutt. ssp. *tridentata*.

4 *Bromus tectorum* L.

5 *Juniperus occidentalis* Hook.

6 Value is 70% of that reported by RHEM for intercanopy parameterization (see Table 4). Intercanopy represents 70% of the total area. Remainder is area under tree canopy, where runoff and erosion are assumed negligible (Pierson et al., 2010, 2013; Williams et al., 2014a; Pierson et al., 2014).

7 Value is sum of area weighted RHEM results for burned intercanopy (weighted by 0.7) and canopy (weighted by 0.3) areas.

315 mm annual precipitation); loam surface soil texture (46% sand, 39% silt, 15% clay); 50-m hillslope length; uniform slope topography; and 35% slope gradient representative of the climate, soil, and topographic attributes for the study site (see Table 3). This study used a recently enhanced version of RHEM as described by Al-Hamdan et al. (2015) for unburned and burned vegetation and soil conditions. The enhanced version requires the following input amendments to the online version of the model, as specified by Al-Hamdan et al. (2015): 1) for unburned conditions, calculation and input of an average concentrated flow erodibility factor, and 2) for burned conditions, calculation and input of an average and a maximum concentrated flow erodibility factor and an erodibility decay constant. We used the following equations from Al-Hamdan et al. (2015) to calculate average concentrated flow erodibility factors (K_ω, s^2•m^{-2}) for all modeled unburned and burned states and phases:

$$\log(K_\omega) = -4.14-(1.28 \times res)-(0.98 \times rock)-(15.16 \times clay) + (7.09 \times silt) \quad (1)$$

and, for burned conditions, to calculate maximum concentrated flow erodibility ($K_{\omega(max)adj}$, s^2•m^{-2}):

$$\log\left(K_{\omega(max)adj}\right) = -3.64-[1.97 \times (res + bascry)]-(1.85 \times rock) -(4.99 \times clay) + (6.06 \times silt) \quad (2)$$

The variables *res, rock, clay, silt,* and *bascry* are, respectively, the percentages (in decimal form) of residue (i.e., litter), surface rock cover, surface soil clay and silt contents, and the sum of total basal and cryptogam covers. We applied the value −5.53 m^{-2} as the erodibility decay constant for the burned simulations, as suggested by Al-Hamdan et al. (2015). The calculated erodibility factors and decay constant for each RHEM simulation were entered into the model interface through replacement of the respective default parameters. Our baseline RHEM model was applied to each community phase, conservation practice, and disturbance by adjusting cover characteristics (retaining the baseline climate, soil, and topography data) to reflect changes in the community composition as shown in Table 4. We did not attempt to represent all possible conservation practices and disturbances applicable to the study site. Rather, we selected limited scenarios (wildfire and prescribed fire) commonly associated with management of the study site and other similar ESs to demonstrate the utility of RHEM in guiding management within the ESD concept.

Currently, RHEM does not include hydrologic and erosion parameterization for conifers. Therefore, the baseline RHEM runs for States 3 and 4 without fire (juniper-dominated and juniper-eroded states) were populated with cover data for intercanopy areas solely (see Table 4). We assumed runoff and erosion were minimal from tree canopy areas in States 3 and 4 based on our previous studies of woodland runoff and erosion (Pierson et al., 2010, 2013, 2014; Williams et al., 2014a). To account for this assumption, we scaled the RHEM-predicted cumulative runoff and erosion values for unburned States 3 and 4 by the percent area representative of the intercanopy, assumed to be 70% of the total area (see Table 4). For conditions immediately postfire, RHEM simulations were populated for both the tree canopy and intercanopy areas as shown in Table 4. Runoff and erosion rates are typically greater from burned tree canopy than intercanopy areas the first few years postfire and must be accounted for in assessing overall fire effects (Pierson et al., 2013, 2014; Williams et al., 2014a). Site-level cumulative runoff and erosion for burned woodland conditions were calculated by area-weighting (0.3 for canopy areas and 0.7 for intercanopy) RHEM-predicted runoff and erosion for the separate tree canopy and intercanopy model runs. Longer-term effects (~10 yr)

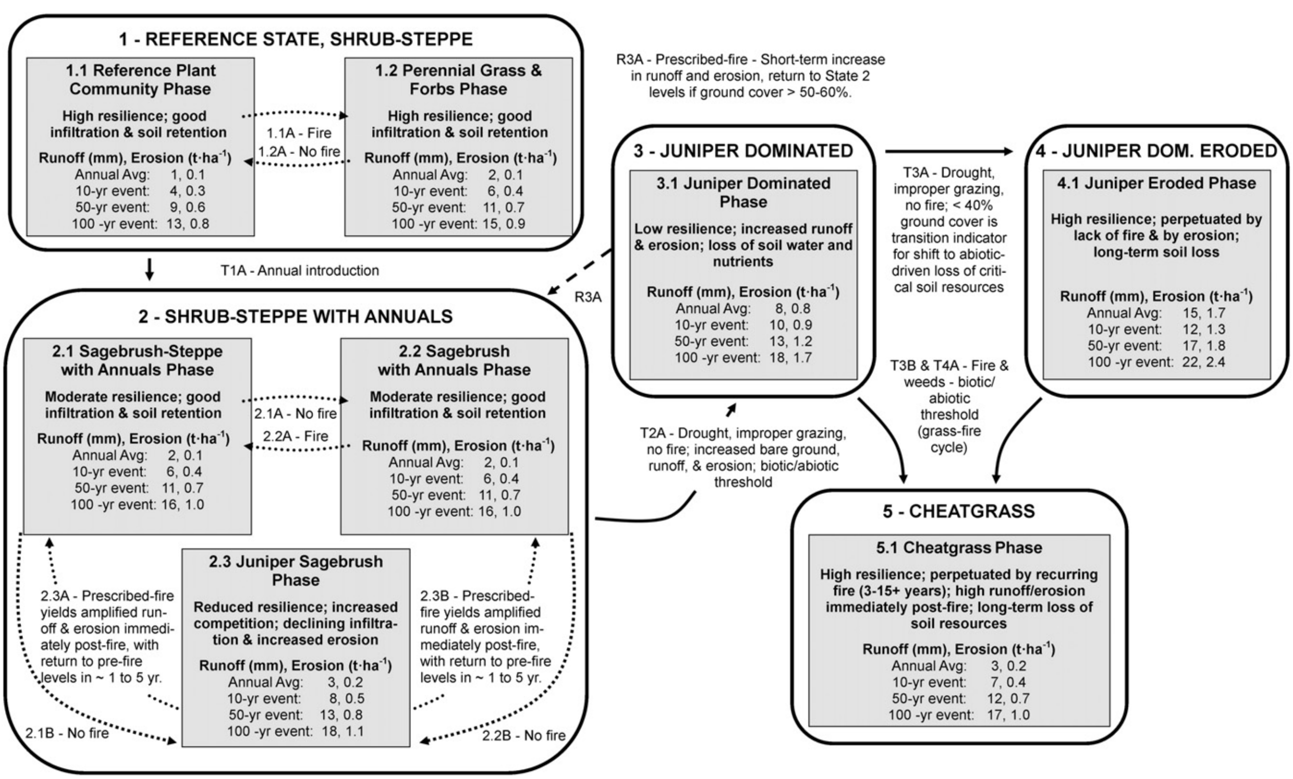

Figure 4. Example state-and-transition (STM) model showing fundamental components of a multiple-state ecological site as described by Stringham et al. (2003), Briske et al. (2005, 2006, 2008), and Bestelmeyer et al. (2009, 2010) and with quantitative and qualitative ecohydrologic information suggested by this study. Ecological states are outlined by bold black rectangles. Community phases within states are shown by light gray rectangles. Cumulative runoff and erosion, as predicted by the Rangeland Hydrology and Erosion Model (Nearing et al., 2011; Al-Hamdan et al., 2015), are shown for the average annual time step and for the 10-yr, 50-yr, and 100-yr events for each community phase. State transitions are indicated by solid black arrows. Within-state community pathways are indicated by dotted black arrows. Restoration pathways are indicated by dashed black arrows. See Table 4 for vegetation characterization of each of the plant community phases shown.

Table 6
Example of ecohydrologic-based narrative for the ecological site dynamics and state and transition model components of the state and community phases feature in an Ecological Site Description (USDA, 2013). See Figs. 1 and 4 for respective state and transition model of example ecological site, "South Slopes 12-16 PZ" (R023XY302OR)

State and Phase	Community Characteristics	Community Pathways/Transitions and Resilience
1. Reference state		
1.1 Sagebrush, perennial grasses and forbs	Mountain big sagebrush (*Artemisia tridentata* Nutt. ssp. *vaseyana* [Rydb.] Beetle) and basin big sagebrush (*A. tridentata* Nutt. ssp. *tridentata*) overstory with bitterbrush (*Purshia tridentata* [Pursh] DC.); bluebunch wheatgrass (*Pseudoroegneria spicata* [Pursh] Á. Löve), Idaho fescue (*Festuca idahoensis* Elmer), Sandberg bluegrass (*Poa secunda* J. Presl; minor amounts), and Thurber's needlegrass (*Achnatherum thurberianum* (Piper) Barkworth) understory.	Plant community phase change is controlled by fire. Ample cover favors infiltration and retention of water and soil resources (high resilience). Runoff and erosion are low and biotically controlled by the plant community physiognomy. Fire promotes shift to Phase 1.2. Burning alters surface susceptibility to runoff and erosion and dramatically increases annual and event responses (see hydrologic interpretations section). Runoff and erosion rates post fire generally return to near prefire levels within 1–3 years with successful ground cover recovery (bare < 50%). Cheatgrass (*Bromus tectorum* L.) invasion promotes transition to State 2.
1.2 Perennial grasses and forbs	Co-dominated by bluebunch wheatgrass, Idaho fescue, and Thurber's needlegrass. Sandberg bluegrass and perennial forbs subdominant. Limited sagebrush and bitterbrush. Rabbitbrush (*Chrysothamnus viscidiflorus* [Hook.] Nutt.) may be extensive following fire.	Phase results from burning Phase 1.1 or successful restoration from other States. Runoff and erosion rates are elevated relative to Phase 1.1 in recovery years postfire. Once stable, plant community promotes infiltration and retention of water and soil resources (biotic control, high resilience) that sustain plant productivity. As with Phase 1.1, burning increases runoff and erosion (see hydrologic interpretations section). Runoff and erosion rates post fire generally return to near prefire levels within 1-3 yr with ground cover recovery (bare < 50%; threshold). Lack of fire is pathway to Phase 1.1. Cheatgrass invasion promotes State 2.
2. Shrub-steppe with annuals		
2.1 Sagebrush-steppe and cheatgrass	Plant community consistent with that of Phase 1.1 except that cheatgrass is present in trace amounts.	Phase is promoted by invasion of cheatgrass into State 1. Hydrologic vulnerability is low, as with State 1. Burning results in similar community as Phase 1.2, but with cheatgrass. High-severity fire may favor State 5 transition. As in State 1, burning increases risk of runoff and erosion (see hydrologic interpretations section). Runoff and erosion rates post fire generally return to near prefire levels within 1–3 yr with ground cover recovery (bare < 50%; threshold). Reduced fire (drought, land use, etc.) facilitates increased shrub cover and shift to Phase 2.2. Western juniper (*Juniperus occidentalis* Hook.) invasion with reduced fire is pathway to Phase 2.3.
2.2 Sagebrush and cheatgrass	Overstory dominated by mountain big and basin big sagebrush. Understory dominated by Sandberg bluegrass. Other native perennials present, but at limited density and with low vigor. Cheatgrass present at least in trace amounts.	Overall hydrologic vulnerability similar to State 1, with runoff and erosion low due to ample cover (biotically controlled). Runoff and erosion occur as rainsplash and sheetflow in isolated bare patches. Burning results in similar community as Phase 1.2, but with cheatgrass. As in State 1, burning dramatically increases runoff and erosion at annual and event scales. Runoff and erosion rates postfire generally return to near prefire levels within 1–3 yr with ground cover recovery (bare < 50%; threshold). Under drought conditions or heavy grazing, fire frequency and herbaceous cover decline and susceptibility to runoff and erosion increases. Juniper encroachment fire-free periods facilitate Phase 2.3 and further increase runoff and erosion rates.
2.3 Juniper, sagebrush, and cheatgrass	Plant community similar to that of Phase 2.2, but with juniper present. Cheatgrass is present. Sandberg bluegrass is dominant perennial. Other native perennials present, but with very low vigor. Bare ground greater than Phase 2.2.	Phase contains similar ground cover as State 1 and other Phases in State 2, but bare ground is increasing. Runoff and erosion rates remain low and biotically regulated and are generally consistent with Phase 2.2. Severe fire promotes transition to State 5 depending on cheatgrass cover. Low to moderate severity fire can facilitate a community similar to that of Phase 1.2 with cheatgrass and prevent transition to State 3. Extensive bare ground postfire enhances concentrated flow and results in high runoff and erosion rates in the years immediately postfire. However, runoff and erosion rates postfire generally return to near prefire levels within 1–3 yr with ground cover recovery (bare < 50%; threshold). Drought, improper grazing, and lack of fire advance State 3.
3. Juniper-dominated		
3.1 At-risk phase–juniper-dominated	Overstory dominated by juniper with mountain big and basin big sagebrush as subdominant (but with decreased vigor). Sandberg bluegrass is dominant understory grass. Other perennial grasses present in trace amounts. Bitterbrush present, but with low vigor. Extensive bare ground in the intercanopy between trees. Cheatgrass is present at least in trace amount.	Extensive bare intercanopy area (bare > 40%) develops and becomes source of runoff and sediment detachment by rainsplash and overland flow. Concentrated flow develops during intense rainfall, resulting in increases in runoff and erosion (onset of abiotically controlled soil loss; structural/functional threshold). Burning creates uniform bare ground, and water repellent soils under burned trees promote rapid runoff. Postfire runoff and erosion rates can be 2- to more than 10-fold higher than for unburned conditions. Burning may create a restoration pathway to State 2 by decreasing understory competition with trees, but restoration may require seeding.

(continued on next page)

Table 6 *(continued)*

State and Phase	Community Characteristics	Community Pathways/Transitions and Resilience
		Severe fire and cheatgrass re-establishment foster transition to State 5. Long-term runoff and erosion are reduced by tree removal where vegetation and ground cover return to levels of State 2. A lack of fire associated with drought and/or improper grazing promotes woodland succession and extensive intercanopy bare ground. Intercanopy bare ground in excess of 50–60% is warning sign for likely transition to State 4 and persistence of abiotic-driven soil loss.
4. Juniper-dominated eroded		
4.1 Juniper eroded	Dominated by juniper. Sandberg bluegrass is dominant grass; remnants of bluebunch wheatgrass and Idaho fescue may be present. Shrub cover minimal with mortality > 75%. Bare ground extensive in intercanopy, often > 60%. Cheatgrass present, but typically < 5% cover.	Lack of fire sustains juniper dominance, decreased shrub/understory cover, and extensive intercanopy bare ground, commonly 60+% (structural/functional threshold for persistence of abiotic control). Runoff and erosion extensive (can be 2- to more than 10-fold higher than reference state) and potential exists for long-term loss of critical soil resources. Burning with cheatgrass re-establishment advances State 5. This state is considered difficult to reverse.
5. Cheatgrass		
5.1 Cheatgrass	Plant community is cheatgrass-dominated with little to no shrub cover or perennial grasses.	Results from frequent burning (3–15 years) or drought. High erosion by wind/water (2- to more than 100-fold > reference state) likely in immediate postfire years. Sustained grass-fire cycle represents an abiotic threshold, as restoration of State 2 is difficult without adequate seeding and posttreatment precipitation. Long-term loss of critical soil resources. Transition is difficult to reverse.

of burning State 3 were evaluated by populating RHEM with site-level cover characteristics shown in Table 4. Separate runs for tree canopy versus intercanopy areas were not considered for the longer-term effects given the tree canopies were no longer present. Residual effects of tree mounds were accounted for through the litter cover variable and its effect on RHEM-predicted infiltration, runoff, and erosion (Nearing et al., 2011; Al-Hamdan et al., 2012b, 2015).

We also assessed the effect of static site characteristics (soil texture and slope gradient) on RHEM-predicted runoff and erosion using cover data for unburned conditions of State 4 (juniper-eroded, intercanopy only). To assess the effect of soil texture, the baseline RHEM model for State 4 was rerun, but with cases of silt loam (35% sand, 50% silt, 15% clay) and sandy loam (55% sand, 30% silt, 15% clay) surface soil textures, common along gradients between the study ESD and neighboring ESDs. To assess the effect of slope gradient, the baseline RHEM model was rerun for State 4 for cases with slope gradient set to the minimum (15%) and maximum (80%) values in the NRCS-published ESD for the study site (see Table 3). The aggregated effects of burning, soil texture, and slope gradient on runoff and erosion for State 4 were also assessed using the following model scenarios: 1) baseline model with burned vegetation conditions, the silt loam soil texture, and a 15% slope gradient, and 2) baseline model with burned vegetation conditions, the sandy loam soil texture, and an 80% slope gradient. The model runs for varying soil texture, slope gradient, and aggregated effects explore the utility of RHEM for evaluating further division of currently mapped ESDs and assessing the influence of soils and topography on treatment effects for ecological sites with wide-ranging hillslope steepness and along soil transitions.

Application of the Framework

Description of Framework

The proposed framework for integration of hydrologic data and ecohydrologic feedbacks into ESDs consists of three primary steps: 1) acquisition of required data (see Tables 2–4), 2) compilation of a "hydrologic functions" table (Table 5), and 3) integration of the information from the "hydrologic functions" table into the STM and site-narrative elements of the "states and community phases" feature (see Fig. 4, Table 6). In the case of new ESD development, NRCS-recommended steps (USDA, 2013) should be taken to develop the primary ESD features (see Table 1) before compilation of the "hydrologic functions" table. In the case of existing ESDs, much of the required quantitative and qualitative data are already available within the approved and published ESD (NRCS, 2013a). Literature and local and regional databases are additional sources for populating the required data (see Table 2). Quantitative hydrologic and erosion data for applying the framework can be acquired through RHEM simulations using the necessary site descriptive data as described earlier. Development of the "hydrologic functions" table requires quantitative runoff and erosion data and knowledge of hydrologic responses to transitions in ecosystem structure and function relative to each community phase, disturbance, and conservation practice.

An example "hydrologic functions" table for the South Slopes 12-16 PZ ES is shown in Table 5. The example provides relative measures of precipitation, runoff, and erosion at the annual and return-interval event scales in context with hydrologic interpretations of the associated plant community dynamics. The hydrologic interpretations define key ecohydrologic relationships, early warning signs of state transitions, structural and functional thresholds that mark transitions, and applicable rangeland health indicators. Key elements (e.g., structural-functional thresholds, rangeland health indicators) identified in the "hydrologic functions" table can then be integrated with the runoff and erosion and community dynamics data into the STM and site narrative as demonstrated in Fig. 4 and Table 6 for the South Slopes 12-16 PZ ES. The integrated STM and narrative provides a model of plant community dynamics and ecohydrologic feedbacks that regulate persistence and transitions of the various states and community phases. Inclusion of the hydrologic data and indicators of looming thresholds and state transitions provides a basis for evaluating current conditions, targeting management strategies, assessing disturbance effects, and forecasting long-term benefits of applied conservation practices (Briske et al., 2006, 2008; Bestelmeyer et al., 2010; Herrick et al., 2012; Williams et al., 2014a). Our detailed STM (see Fig. 4) can be reduced to a more simplified presentation if desired but is provided in this study to visualize the integration of hydrology data with the ecological state dynamics. Where a more simplified STM is desired, the key ecohydrologic relationships can simply be retained in the site narrative (see Table 6) and hydrologic functions section (see Table 5).

Application to the South Slopes 12-16 PZ Ecological Site

Application of the proposed framework to the South Slopes 12-16 PZ ES is demonstrated in Tables 5 and 6 and Fig. 4. The aggregated information provides a description of ecosystem feedbacks and a predictive model for guiding resilience-based management as described herein. The South Slopes 12-16 PZ ES is subject to two major plant community transitions (western juniper encroachment and cheatgrass invasion) that mark undesired shifts in ecosystem structure, function, and resilience. Two states, the Reference State and State 2, are composed primarily of sagebrush and various grasses and forbs (see Fig. 1). For these states, the dense vegetation and ground cover promote infiltration and soil retention that, in turn, enhance plant productivity (negative feedback, see Figs. 1 and 4; Table 5). Runoff and erosion are generally low for the Reference State and State 2 except for extreme events (25-yr to > 100-yr events; see Table 5). These states exhibit moderate to high ecological resilience due to ecohydrologic feedbacks, but resilience declines for State 2 under drought and fire-free periods (see Tables 5 and 6). Burning of State 2 dramatically increases runoff and erosion within the first few years postfire (see Table 5; Fig. 4), but ground cover recovery is commonly more rapid than for wildfire or prescribed fire in western juniper-dominated States 3 and 4 (Pierson et al., 2009; Miller et al., 2013; Pierson et al., 2013; Williams et al., 2014a; Table 6). Decreased ground cover associated with western juniper encroachment (Phase 2.3) during fire-free periods increases runoff and erosion for storms ≥ 10-yr rainfall event (see Table 5). Sites with shallow soil depths (<0.6 m depth) may exhibit more rapid declines in understory vegetation following juniper encroachment due to greater competition for limited soil water storage (Miller et al., 2000, 2005). An increase in bare ground to 40–50% generally marks the transition to a juniper-dominated state (State 3) with higher rates of runoff and erosion (see Tables 5 and 6; Fig. 4). This transition ultimately results in a shift from biotically controlled water and soil retention to abiotically controlled losses of water and soil resources (Williams et al., 2014a). Transition and degraded hydrologic function may be avoided where management actions sustain 50–60% ground cover and limit western juniper encroachment (see Table 6). Persistence of juniper dominance and an increase in bare ground beyond 60% advance transition to a juniper-eroded state (State 4) with abiotically driven long-term loss of dynamic soil properties and critical soil nutrients (see Table 6; Fig. 4). Estimated erosion on the annual scale and for the 100-yr runoff event may approach or exceed 2 t • ha^{-1} in State 4; estimated annual and 100-yr event erosion can range 0.1 to near 1.0 t • ha^{-1}for the Reference State and State 2 (see Table 5; Fig. 4). Prescribed-fire may provide a restoration pathway from State 3 to State 2 (Pierson et al., 2013; Williams et al., 2014a), however, soil loss can increase by a factor of five in the years immediately following fire (Table 5, Fig. 4). Sites on steep slopes (>35%) may exhibit even greater increases in runoff and erosion postfire (Williams et al., 2014b). Runoff and erosion following burning of State 3 may return to similar levels of State 2 if the treatment restores ground cover to approximately 50–60% (Pierson et al., 2009). Burning of States 3 and 4 poses risk of transition to a cheatgrass-dominated community (State 5), where postfire recovery of native perennials is limited (Pierson et al., 2011; Miller et al., 2013; Bates et al., 2014). Increased fire frequency in State 5 further promotes long-term soil loss associated with frequently recurring high postfire erosion rates (Pierson et al., 2011; Williams et al., 2014b; see Tables 5 and 6). Restoration efforts in State 3 may require seeding to re-establish ground cover and restore negative ecohydrologic feedbacks that sustain ecosystem productivity (Sheley and Bates, 2008; see Table 6). The above catalog of community dynamics and ecohydrologic feedbacks is not exhaustive but demonstrates the utility of the proposed framework for enhancing ESDs and guiding management.

Application to Other Ecological Sites

A critical component of the proposed framework is its broad applicability to the diverse rangeland domain. The framework was organized concurrent within the existing broadly applicable ESD concept (see Table 1). The data requirements (see Table 2) to develop the "hydrologic functions" table are mined from those required in ESD development (USDA, 2013) and application of those data to the RHEM model. For this study, we varied our application of the RHEM model to reflect a tree-encroached landscape, running separate simulations for tree canopy and intercanopy areas. This approach is merited where woody plant encroachment coarsens a landscape into hydrologically unique components that govern the overall landscape response. Similar or novel approaches could be developed to apply aggregated RHEM simulations to other sparsely vegetated plant communities with or without disturbance. The RHEM model is already formulated to predict hillslope scale runoff and erosion for less-fragmented rangelands (e.g., grasslands and well-vegetated shrublands) and has been applied across diverse rangeland sites (USDA, 2011; Weltz and Spaeth, 2012; Hernandez et al., 2013; Al-Hamdan et al., 2015). The RHEM results in any modeled framework should be considered relative runoff and erosion estimates for the modeled condition. RHEM results can be qualified in context with reported runoff and erosion rates from literature. The integration of the RHEM results and the hydrologic interpretations (i.e., "hydrologic functions" table) into the STM and narrative elements requires some understanding of ecohydrologic feedbacks and thresholds for the ecological site of interest. This component may be limited for some rangeland ecological sites. We suggest that expert opinion and other resources used in the development of the various ESD features may provide insight in such cases (Bestelmeyer et al., 2009; Moseley et al., 2010; USDA, 2013). At a minimum, RHEM results could be presented in context with literature on similar sites and with rangeland health indicators as a relative assessment of hydrologic function for various states and transitions.

For some sites, key variables omitted in our example study site may merit inclusion in the "hydrologic functions" table and site narrative. For example, wind erosion may also be a concern on gently sloping or recently burned sites with extensive bare ground (Sankey et al., 2009; Ravi et al., 2010; Zhang et al., 2011; Sankey et al., 2012; Wagenbrenner et al., 2013). Soil water recharge and plant water demands may be primary drivers of community dynamics and ecosystems function (Peters et al., 2010; Hamerlynck et al., 2012; Schlaepfer et al., 2012; Mollnau et al., 2014) and can be characterized within the hydrologic interpretations. We did not attempt to model soil water for our example, but numerous rangeland models are available from implementation into the proposed framework (Flerchinger et al., 1996; Flerchinger et al., 2012; Finzel et al., 2015). Evapotranspiration data may also be useful in interpreting ecosystem response to vegetation transitions and can be included where available (Moran et al., 2009; Flerchinger et al., 2010; Newman et al., 2010). In short, we do not suggest that the proposed framework is a binding or exhaustive approach, but rather, that it provides a flexible foundational framework for incorporating ecohydrologic data into ESDs.

Evaluaton and Utility of the Rhem Tool

Runoff and erosion rates predicted by the RHEM tool were consistent with published literature on the South Slopes 12-16 PZ site and other similar ESs (Pierson et al., 2007; Petersen et al., 2009; Pierson et al., 2009, 2013; Williams et al., 2014a). Williams et al. (2014a) conducted rainfall simulations (102 mm • h^{-1}, 45 min, 77 mm total rainfall, 13 m^2 plots) in burned and unburned areas of a late-succession western juniper-encroached sagebrush site (sandy loam to loam surface soils) in southwestern Idaho, United States. They measured 43 mm of runoff and 2.7 t • ha^{-1} of soil loss from unburned intercanopy areas. This would translate to approximately 30 mm of runoff and 1.9 t • ha^{-1} soil loss when weighted by a factor of 0.7 as applied to unburned intercanopy RHEM simulations in this study. Runoff values for unburned conditions in the Williams et al. (2014a) study are most similar to the 100-yr event (57 mm rainfall) simulated by RHEM for unburned State 4 (see Table 5), yielding 22 mm of runoff and 2.4 t • ha^{-1}. Williams et al. (2014a) reported 43 mm and 5.7 t • ha^{-1} of runoff and soil loss from burned intercanopy areas and 50 mm and 10.8 t • ha^{-1} of runoff and soil loss from burned tree canopy areas for the simulated storm. Area weighting the tree canopy values by 0.3 and the intercanopy values by 0.7 results in 45 mm of runoff and 7.3 t • ha^{-1} of soil loss in aggregate for the burned site. For prescribed-fire conditions, the 100-yr runoff and erosion predicted by RHEM for State 3 were, respectively, 1.4-fold less than and 1.6-fold higher than the plot-scale values measured by Williams et al. (2014a). We attribute the differences in runoff and soil loss between our RHEM simulations and the plot-scale Williams et al. (2014a) study to scale differences for the measured versus simulated values. Cumulative runoff commonly declines or remains similar across spatial scales for disturbed conditions, whereas erosion is unchanged or increases with increasing scale along a hillslope following disturbance due to connectivity of runoff and erosion processes (Pierson et al., 2009, 2011, 2013; Williams et al., 2014a, 2015). Pierson et al. (2007) reported 13 mm of runoff and 1.2 t • ha^{-1} of soil loss for a 53-mm simulated rainfall event in intercanopy areas of an unburned late-succession woodland on the South Slopes 12-16 PZ ES. Area weighting the intercanopy area by 0.7 yields 9 mm of runoff and 0.9 t • ha^{-1}, similar to the RHEM predicted values for the 50-yr runoff event for State 3 and approximately half that predicted for State 4 (see Table 5). Plots in the Pierson et al. (2007) study were 32.5 m^2. The similarities in RHEM results as applied in this study with values reported in literature demonstrate RHEM's utility for predicting relative measures of runoff and erosion within the ESD concept. We caution against interpretation of RHEM results as absolute measures of runoff and erosion given the potential variability in soil loss across widely variable conditions within an individual ecological state or community phase and with increasing spatial scale. It is not practical to parameterize the model for all possible vegetation conditions of a given state or community phase. Rather, we suggest applying the model for average vegetation conditions and utilizing the results to interpret relative hydrologic and erosion function.

Results from RHEM simulations using variable static site characteristics (soil texture, slope gradient, etc.) indicate the model may be useful for identifying and separating ecological sites based in part on hydrologic function. We altered our baseline RHEM model for State 4 of the South Slopes 12-16 PZ ES to reflect the possible variability in soil texture and the minimum and maximum slope gradients for the site as defined in the NRCS-published ESD (see Table 3). Runoff was primarily unaffected by soil texture variability, but erosion was approximately sixfold higher for a silt loam and threefold lower for a sandy loam soil texture relative to the loam texture baseline model (see Table 7). Varying slope gradient within the baseline model likewise did not alter runoff predictions. However, erosion was twofold less for baseline conditions with 15% slope and nearly twofold more for baseline conditions with 80% slope (see Table 7). The influence of slope gradient on soil erosion is most evident for burned simulations of State 4. Applying a fine-textured silt loam soil and gentle slope gradient (15%) to State 4 for the burned condition (cover shown in Table 4) resulted in similar RHEM-predicted runoff and erosion (see Table 7) as for burned State 4 in the baseline model (see Table 5). In contrast, applying a coarse-textured sandy loam soil and steep slope gradient (80%) generated twofold to threefold more erosion (see Table 7) than the baseline model of burned State 4 with a loam soil and 35% slope gradient (see Table 5). Increasing the slope gradient did not alter runoff prediction for the burned condition. We anticipate the model would generate even more soil loss for a silt loam soil with an 80% slope but did not simulate those conditions. We assume soils at 80% slope gradient for the South Slopes 12-16 PZ ES are more likely to be coarse textured. The results from the variable soil texture and slope gradient RHEM simulations imply a potentially widely variable hydrologic function for sites along soil transitions of the South Slopes 12-16 PZ ES and for the slope gradients in the NRCS-published ESD (see Table 3). Furthermore, the results indicate sites within the steeper range of the ESD for the study site may merit re-evaluation relative to the current ESD classification. Our results for the study ESD further suggest that RHEM provides a new methodology to evaluate (in context with other supportive data) potential separation of currently approved ESDs and to assist development of ESDs in general through integration of hydrologic function into the ESD concept.

As ESDs are developed nationally with their associated geospatial location and shape, the application of RHEM to multiple hillslopes and watersheds can be rapidly facilitated with the KINEROS2 rainfall-runoff-erosion model within the Automated Geospatial Watershed Assessment tool (AGWA; Goodrich et al., 2012). RHEM has been incorporated into KINEROS2 and serves as its engine for hillslope runoff and erosion simulation. AGWA is a Geographic Information System tool that uses nationally available spatial datasets (Digital Elevation Models, soils, and land cover) to develop input parameter files for both KINEROS2 and SWAT watershed models. Simulation results for a variety of RHEM/KINEROS2 model outputs can be displayed across the entire watershed by importing them back into the GIS environment for display. AGWA also facilitates the ready identification of at-risk hillslopes or downstream channels under alternate management scenarios. It accomplishes this by conducting a simulation with a given ecological state configuration, saving the results (temporal and spatial), and then

Table 7
RHEM[1] predicted runoff and erosion for varying soil texture and slope gradient under unburned[2] and burned[3] conditions of State 4, juniper-eroded[4] (see Table 4), on the "South Slopes 12-16 PZ" (R023XY302OR) Ecological Site (NRCS, 2014). Deviation from the baseline model parameterization[5] is noted in italics

	Average annual	2-Yr event	10-Yr event	50-Yr event	100-Yr event
Precipitation (mm)	314	24	35	48	57
Baseline model[5]					
Loam (45% sand, 15% clay), 35% slope, unburned[2]					
Runoff (mm)	15	6	12	17	22
Erosion (t·ha^{-1})	1.7	0.6	1.3	1.8	2.4
Effect of soil texture					
Silt loam (35% sand, 15% clay), 35% slope, unburned[2]					
Runoff (mm)	16	6	12	18	22
Erosion (t·ha^{-1})	9.2	3.4	7.3	10.1	13.5
Sandy loam (55% sand, 15% clay), 35% slope, unburned[2]					
Runoff (mm)	14	6	12	17	22
Erosion (t·ha^{-1})	0.5	0.2	0.5	0.6	0.8
Effect of slope					
Loam (45% sand, 15% clay), 15% slope, unburned[2]					
Runoff (mm)	15	6	12	17	22
Erosion (t·ha^{-1})	0.8	0.3	0.7	0.9	1.1
Loam (45% sand, 15% clay), 80% slope, unburned[2]					
Runoff (mm)	15	6	12	17	22
Erosion (t·ha^{-1})	3.0	1.1	2.3	3.3	4.4
Aggregated effects of soil texture, slope, fire					
Silt loam (35% sand, 15% clay), 15% slope, burned[3]					
Runoff (mm)	24	9	18	28	32
Erosion (t·ha^{-1})	9.0	3.2	7.6	12.0	13.8
Sandy loam (55% sand, 15% clay), 80% slope, burned[3]					
Runoff (mm)	24	9	17	27	31
Erosion (t·ha^{-1})	32.3	11.8	24.4	33.4	43.5

[1] Rangeland Hydrology and Erosion Model (Nearing et al., 2011; Al-Hamdan et al., 2015).
[2] Unburned conditions refer to canopy and ground cover as shown in Table 4 for unburned State 4, juniper eroded. All values for runoff and erosion under unburned conditions reflect a 30% reduction in RHEM predicted runoff and erosion given the simulations are for the intercanopy area (70% of total) solely. Runoff and erosion from areas underneath tree canopies (30% of area) were assumed negligible (Pierson et al., 2010, 2013; Williams et al., 2014a; Pierson et al., 2014).
[3] Burned conditions refer to canopy and ground cover as shown in Table 4 for States 3–4, immediately following wildfire.
[4] *Juniperus occidentalis* Hook.
[5] Baseline parameterized is as follows: loam surface soil texture, 50 m slope length, uniform slope shape, 35% slope gradient, canopy and ground cover for unburned State 4 as shown in Table 4, and climate data from the Sheaville, OR, U.S. climate station (ID: 357736).

conducting another simulation with alternate ecological states using the same precipitation inputs. The results of the original and alternate simulation can then be differenced (magnitude or percent change) and displayed spatially across all watershed model elements. This readily enables users to identify hillslopes at risk of high runoff and erosion and where management efforts might be focused to mitigate those risks.

Management Implications

We suggest that inclusion of key ecohydrologic data and relationships enhances the utility of ESDs for the ecological assessment and management of rangeland ecosystems and the targeting of conservation practices. Water is the primary limiting resource in rangeland plant communities, and ecohydrologic feedbacks strongly influence the resilience of ecological states and transitions between states for many rangeland ES. Furthermore, ecohydrologic relationships are affected by various conservation practices and land uses. The recommended framework provides a methodology to capture these key relationships within the current ESD structure and to incorporate key ecohydrologic information in models of ecological state dynamics. The RHEM tool provides a new technology for predicting relative runoff and erosion responses for ecological states, state transitions, and short- and long-term responses to management actions and disturbances. The integration of this new technology and our suggested framework on ecohydrologic relations expands the ecological foundation of the overall ESD concept for rangeland management and is well matched with recent shifts toward resilience-based STMs and management approaches. Finally, we believe the proposed enhancement of ESDs will improve communication between private land owners and resource managers and researchers across multiple disciplines in the field of rangeland management.

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