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Special Series

Using Engineering With Nature® (EWN®) principles to manage erosion of watersheds damaged by large-scale wildfires

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EDITOR'S NOTE:

This article is part of the special series "Ecological consequences of wildfires." The series documents the impacts of large-scale wildfires in many areas of the globe on biodiversity and ecosystem condition in both terrestrial and aquatic ecosystems, the capacity for systems to recover, and management practices needed to prevent such destruction in the future.

Abstract

The US Army Corps of Engineers (USACE) manages hundreds of reservoirs and thousands of miles of navigation channels that provide invaluable flood control, commercial transport of materials, water supply, recreation, and stream flow regulation. This capability is being threatened by the continued occurrence of large-scale wildfires across the western United States. The wildfires damage watersheds in part by denuding landscapes, reducing infiltration rates, and increasing runoff rates, thereby dramatically increasing the potential for the erosion of denuded slopes, destabilizing stream channels, increasing the infilling potential of reservoirs and, hence, reducing their capacity. The increased erosion rates highlight the need to develop innovative solutions to reduce erosion of watersheds laid bare after wildfires engulf the area. The Santa Clara Pueblo in northern New Mexico extends from the top of the eastern Jemez Mountains to the floodplains of the Rio Grande River. The Pueblo designed and constructed thousands of structures built from natural materials, consistent with Engineering With Nature (EWN) principles for erosion control incorporating low-cost and readily available materials such as logs, mulch, vegetation, and local rock to stabilize highly erodible parts of the watershed. The watersheds where these natural structures were constructed were monitored after construction to assess their effectiveness, guiding a series of recommendations for broader implementation. As part of a continued emphasis on updating USACE engineering guidance, research, and development, funding has been focused on developing sustainable and resilient project designs using natural materials like those implemented by the Santa Clara Pueblo. This paper focuses on the innovative EWN-based watershed stabilization practices that were implemented in the upper section of this wildfire affected canyon and tributary streams. Recommendations for future implementation based on lessons learned from this project are also provided. *Integr Environ Assess Manag* 2021;00:1–9. Published 2021. This article is a US Government work and is in the public domain in the USA.

KEYWORDS: Equity, Las Conchas Wildfire, Nature-based solutions, Reservoir, Santa Clara Pueblo

INTRODUCTION

The US Army Corps of Engineers (USACE) manages hundreds of reservoirs and thousands of miles of navigation channels that provide invaluable flood control, commercial transport of materials, water supply, recreation, and stream flow regulation. This capability is being threatened by the continued occurrence of large-scale wildfires across the western United States. The wildfires damage watersheds in part by denuding landscapes and destabilizing stream networks, thereby dramatically increasing the potential for erosion of denuded slopes, hence increasing the infilling potential of reservoirs and reducing their capacity. The reduced reservoir capacity decreases the availability of drinking water and increases the management costs of having to dredge the reservoirs to restore that capacity. The increased erosion rates highlight the need to develop innovative solutions to reduce erosion of watersheds, laid bare after wildfires engulfed the area, and to reduce threats to mission capability.

This article contains online-only Supporting Information.
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In 2011, the Las Conchas Wildfire burned more than 156 000 acres and ranked as the second largest fire in New Mexico history. During the Las Conchas Wildfire, the Santa Clara Canyon suffered a near total burn, which drastically changed the natural canyon environment, stream networks, and sediment stability of the canyon. The effects of the near total burn changed a 1% rain (100-year) event to a 400% increase in peak flow conditions when compared with pre-fire conditions.

The result of the Las Conchas Wildfire was a starkly denuded landscape that greatly increased the risk of erosion caused by surface runoff after storm events the design and implementation of soil erosion treatments to mitigate the enhanced risk. Various treatment options were considered, based in part on known effectiveness of previous strategies implemented elsewhere. The effectiveness of treatments to mitigate soil erosion after large-scale wildfires have been reported previously in the published literature, although documentation of actual field treatment applications remains a pressing need. A meta-analysis of published post-wildfire cover-based, barrier, seeding, and chemical soil erosion mitigation treatments was performed to assess their effectiveness (Girona-García et al., 2021; Robichaud et al., 2000). The results indicated that all four treatment types significantly reduced post-fire soil erosion, but only the cover and barrier treatments substantially reduced post-fire runoff. Results also indicated that overall treatment effectiveness was greatest shortly after fires at severely burned sites. The authors concluded that the application of the studied post-fire erosion mitigation treatments were preferred over doing nothing, especially in areas where soil erosion was high, yet treatment results after larger scale fires were seldom reported (Girona-García et al., 2021; Robichaud et al., 2000).

Guidelines for restoring ecosystems after wildfires have identified several mitigation treatments that have been applied both individually and in combination. These include seeding, planting, and transplanting native plant species to promote re-vegetation, and blankets, log barriers, log wattles, logfalls, log cross-vanes, reinforced rock berms, and check dams as erosion control structures (Coalition for the Upper South Platte, 2014; Mauri & Pons, 2019), some of which were implemented in response to the Las Conchas Fire. Factors that affect treatment effectiveness include non-fire-related (e.g., rainfall intensity, topography, land use), and fire-dependency (burn severity, soil burn severity, soil erodibility, and time since the fire; Robichaud et al., 2010). Scale, availability of materials, remoteness, terrain, cost, fire severity, resources prioritized for protection, applying traditional ecological knowledge (TEK), and the desire to implement nature-based solutions (NbS) were the factors driving the Las Conchas Fire response.

Despite recent advancements and applications as innovative responses to promote adaptation and build resilience to tackle numerous environmental challenges, the benefits of NbS are not distributed equitably across social groups (e.g., wealthy vs. low income communities and among racial groups), time (e.g., present vs. future generations), or space (e.g., upstream vs. downstream; Nelson et al., 2020). Inequities may also exist in the process of prioritizing, designing, and managing water resource projects. In addition to reducing USACE capability, the substantially increased erosion of surface soils post-wildfire served as an immediate threat to Santa Clara Pueblo infrastructure and severely disrupted the community's cultural and religious connections to their land. The lands affected by fire serve the Santa Clara People as a church for spiritual sanctuary; pharmacy for medicinal plant gathering; supermarket for produce, fish, and game harvesting; and biology. Establishing a visceral connection to this landscape serves as a foundation for Santa Clara cultural identification. The inability to partake of those traditional lifeways has deprived an entire generation of youth of that connection, which is the foundation of Santa Clara Pueblo culture.

Santa Clara Pueblo is a federally recognized tribe of Native American people located along the Rio Grande River in northern New Mexico, USA. The Santa Clara Pueblo Indian Reservation encompasses 90 square miles of tribal land and is home to 3500 residents who, since time immemorial, have relied on these lands for food, medicine, recreation, and spiritual sanctuary (Altmann, 2021).

Infrastructure managers require guidance on the inclusion of social equity in decision making associated with water resource projects and how equity consideration is different for conventional and nature based infrastructure solutions. In this paper, we demonstrate how equity was successfully addressed using a collaborative approach that, from the outset, included input from the Santa Clara Pueblo in the decision-making process of designing and implementing NbS for watershed erosion management. The objective of this short communication is to provide information to help watershed infrastructure managers understand the importance of equity in decision making, practical techniques for incorporating erosion control measures into current practice, and the unique equity benefits that NbS can offer.

The USACE's Engineering With Nature® (EWN®) initiative is focused on advancing sustainable and resilient projects and outcomes, through the application of natural materials, that are socially acceptable, viable, and widely available. EWN is defined as the intentional alignment of engineering and natural processes to efficiently and sustainably deliver economic, environmental, and social benefits through collaboration (King et al., 2020). Successful EWN projects abide by the following four principles. Project planning and design should use science and engineering to produce operational efficiencies that support sustainable delivery of project benefits. Project designs should rely on natural processes to produce benefits and reduce demands on limited resources, minimize negative impacts, and create new environmental benefits. Projects should be planned and designed to diversify the economic, social, and environmental benefits of the project. Finally, a commitment to collaboration should be used to organize and focus stakeholders and partners to produce more broadly acceptable and productive projects.

The USACE's EWN initiative is advancing practical implementation of these four principles through a network of field-scale projects, demonstrations, research and development, guidance development, education, communication, and partnering (Bridges et al., 2018, 2021), with the Santa Clara Pueblo project described herein being an example. Population growth, economic development, climate change, sea level rise, and the changing character of natural disasters, such as wildfires in the western United States, have introduced enormous pressure and expectations for infrastructure projects. These factors have changed the way USACE and others think about the planning, design, and construction of infrastructure projects and offer opportunities for equitably applying EWN principles to tackle complex environmental challenges.

Trends over the past several years indicate that wildfire threats in the United States will continue well into the future (Dennison et al., 2014); for this reason, innovative solutions are needed to help manage increased post-wildfire erosion and limit future wildfire vulnerability. Such solutions need to be implemented and monitored; the lessons learned should be communicated broadly so that these NbS are readily accessible for widespread application.

METHODOLOGY FOR IMPLEMENTING INNOVATIVE NbS

A collaborative approach

The Native American worldview does not consider the natural world as separate from the cultural world. Attachments to the landscape are intrinsic and form an integral part of the individual's identity. It is both a source of individual identity and cultural identity for the Tribe as a group. The canyon and creek are considered their source of life. It is this holistic, systemic worldview that justifies the value of incorporating TEK in any project where the objective is providing a "nature-based" solution. However, is often not valued by people who approach issues from a Western, nontraditional viewpoint. For example, some areas are restricted by tribal rules, so there are access restrictions and limitations on material usage appropriate to NbS erosion control design. In another example, engineers on the Las Conchas team were frequently confounded by the Santa Clara government's rejection of NbS that sacrificed cultural attributes of the landscape to affect perceived benefits in the so-called natural world. The involvement of team members from the USACE Tribal Nations Technical Center and Tribal Liaison for the USACE Albuquerque District, who understood such trade-offs were unacceptable from a traditional perspective (e.g., springs are sacred so work around them is severely restricted), served as key facilitators during the initial hours of the Las Conchas Fire and greatly contributed to the success of the collaboration.

To design and implement project erosion measures that were socially acceptable, viable, and equitable, the use of in situ materials was prioritized because the Tribe's preference was to limit the introduction of foreign materials into the canyon. Because of widespread availability of rock and woody debris, utilizing these natural materials proved viable in reducing costs for transport and sourcing off-site. The measures implemented were considered equitable because the Tribe considered these materials part of their heritage. Equity was most notable in that the Tribe was included throughout the proposal, design, and review process.

Historically, Santa Clara Pueblo has collaborated with multiple agencies and nongovernmental organizations to accomplish resource management objectives. Following the Las Conchas Fire and subsequent flood events, this collaborative approach became central to their recovery strategy when the Federal Emergency Management Agency (FEMA) activated the National Disaster Recovery Framework (NDRF) in 2011 (FEMA, 2016). Initially developed in response to Hurricane Katrina in 2005, the NDRF provided states, tribes, and local jurisdictions opportunities to effectively develop: (1) recovery strategies that identify roles and responsibilities of recovery coordinators and stakeholders, (2) an inclusive and equitable coordinating structure that facilitates communication and collaboration, (3) guidance for pre- and post-disaster recovery planning, and (4) core recovery principles to rebuild stronger, smarter, and safer communities. The NDRF provided an organizational structure that brought all partners together and formed the Las Conchas Team, which met regularly to provide updates on plans and activities. The team was able to share success stories and lessons learned, and provide recommendations, based on their experiences, on both tribal and non-tribal lands. This resulted in a collaboration of federal, state, tribal, local, and nongovernmental agencies working together to implement landscape-scale mitigation and restoration efforts. Collaborations included strategies and recommendations from the National Interagency Fire Center-Burned Area Emergency Response team, USACE assessments and reports including the Santa Clara Creek Watershed Management Plan, the FEMA 4199 Flood Mitigation and Creek Restoration Project, Natural Resources Conservation Service (NRCS) Emergency Watershed Protection Program (EWP), Bureau of Indian Affairs (BIA), US Forest Service, US National Park Service, US Bureau of Reclamation, US Environmental Protection Agency, US Fish and Wildlife Service, New Mexico Department of Homeland Security, New Mexico State Forestry Division, New Mexico Department of Game and Fish, New Mexico Water Trust Board, San Manuel Band of Mission Indians, Shackopee Mdewakanton Sioux, The Nature Conservancy, Audubon Society, Forest Stewards Guild, Wild Earth Guardians, Trout Unlimited, Western Native Trout Initiative, and National Fish and Wildlife Federation, among others.

Many of the elements considered relevant to enabling effective and equitable development of NbS were implemented as key components of the response, including addressing uncertainty through adaptive management, involving multiple stakeholders, using TEK and other science and engineering knowledge, developing a common understanding of multifunctional solutions, trade-offs, and

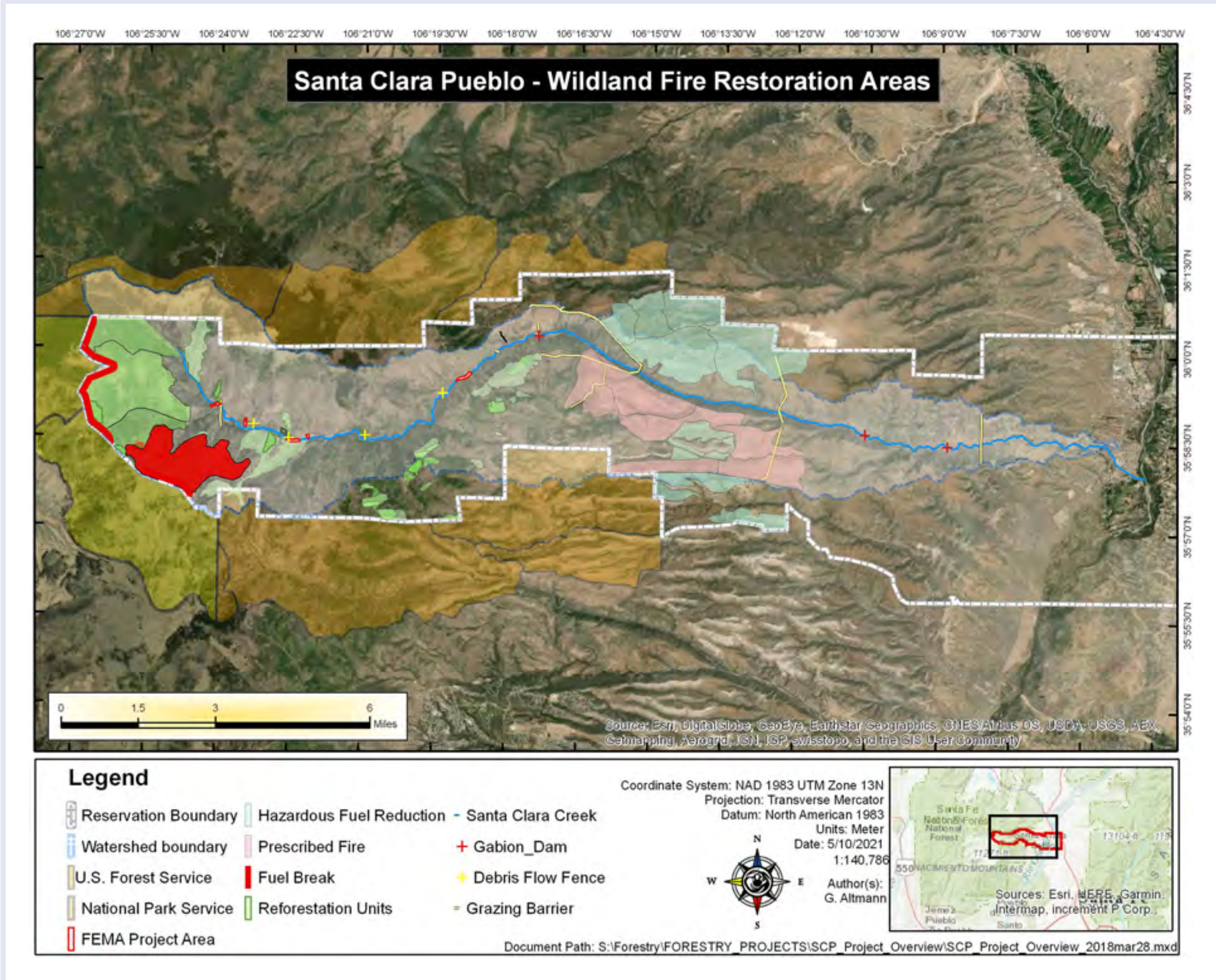

FIGURE 1 Locations within the Santa Clara Canyon where natural infrastructure materials were installed to manage post-wildfire erosion

natural adaptation, and monitoring for mutual learning (Cohen-Shacham et al., 2019; Nesshöver et al., 2017).

Methods for designing and constructing natural material structures

TEK from the Santa Clara Pueblo was gathered based on the Tribe's rules and customs, and used as described above to drive the design and subsequent construction of the natural material structures. All proposed activities were initially reviewed by the Tribal Historic Preservation Office (THPO). Based on this feedback and utilizing TEK, the preference for using on-site natural materials was prioritized, which contributed to the low implementation cost because the construction materials were readily available. This approach was also inherently practical, because most of the eroding landscape was steep canyon terrain, so access for large equipment to haul materials was logistically infeasible and cost prohibitive. The results of this collaboration with the Tribe yielded a holistic and sustainable approach to managing post-wildfire erosion. The resultant response to the post-wildfire challenges was the design and construction of hundreds of erosion control structures that used readily available natural materials such as logs, re-vegetation, mulching practices, and native rock to stabilize parts of the watershed. The Pueblo Forestry Department worked on small structure construction in the tributary streams while the NRCS implemented mulching and contour felling projects, and USACE implemented large grade control structures in the Santa Clara Creek mainstem to dissipate flood energy and collect the vast quantities of sediment coming from upstream sources. The erosion control structures are in various sections of the canyon (Figure 1). A priority for restoration also included implementing environmentally sustainable projects to stabilize the stream system utilizing readily available natural materials to encourage native populations of trout to return to the area.

For context on what types of practices are applicable to treating massive erosion in watersheds, the physical processes that cause the accelerated rates must be identified and understood. Network-wide channel instability was identified by localized steepening of slopes, mass wasting of streambanks, and widespread channel expansion, in some cases 5–10 times the pre-fire widths (Figure 2). Many of these tributary channels were shallow, easily crossable

FIGURE 2 Incised tributary to Santa Clara Canyon showing a markedly expanded channel width post-wildfire

streams prior to the wildfire, so changing the watershed runoff characteristics.

Modeling approach to guiding natural infrastructure material design

The tributary watersheds experienced large-scale channel degradation and deposited massive amounts of debris and sediment to the main channel and floodplain of Santa Clara Creek (Figure 3). Channel evolution models (CEM; Cluer & Thorne, 2013; Hawley et al., 2011; Schumm et al., 1984; Simon & Hupp, 1986) can be used to predict spatial and temporal extents of channel stability within watersheds. Based on a simplistic approach, the qualitative five-stage CEM (Schumm et al., 1984) was selected to assess the tributary and mainstem geomorphology. The CEM was used to identify primary post-wildfire stream morphologic processes and potential future channel stability trends.

RESULTS

Natural material design implementation

Some of the most intense fires were in the farthest upstream reaches of the Santa Clara Canyon, and so field reviews were completed to assess watershed stability in these areas. Active watershed, channel, and floodplain processes were identified, including: (1) Santa Clara Creek tributary channels were experiencing erosion and mass wasting zones; (2) floodplain depositional zones-old pond sites, sediment basins, and channel margins on tributaries and mainstem were being infilled; and (3) active tributary and main channel erosion and/or floodplain building and planform changes were being adversely altered (Figure 4).

FIGURE 3 Santa Clara Creek illustrating large deposits of post-wildfire sediment deposition from watershed runoff events

The locations of the nature-based structures that were constructed in Switchback, Chicoma, and Sasquatch canyons are shown in Figures 5, 6, and S1–S6. The NRCS recommended contour felling of existing burned tree areas to provide erosion control and promote re-vegetation. Field crews used in situ materials to construct structures. This reduced the cost of hauling restoration materials to the site and utilized existing natural materials present in the immediate vicinity. The field crews used available plant materials, willows and other transplants, logs, rootwads, cut wood, branches, and rock. Based on initial, post-construction review of the projects, the structures have provided erosion control benefits during recent runoff events as designed, and all were structurally sound.

DISCUSSION

Erosion management lessons learned

Based on the approach used to model, design, and construct the natural material structures in Switchback, Chicoma, and Sasquatch canyons, several lessons were learned that could inform future applications for reducing erosion in the wake of large-scale wildfires.

The Santa Clara Canyon structures were constructed in a design-and-build manner. No major survey, design, and review were carried out prior to construction. Instead, the structures were constructed in real time as the designer and crew oriented the readily available local materials to combat channel and hillside erosion. The efficacy of the side-channel designs will be used along with surveys to inform the designs for stabilizing the future Santa Clara Creek mainstem project.

Implementation of key construction and engineering techniques is important to achieve resilient designs; the results of these techniques can be seen in Figures 5, 6, and S1–S6, and are briefly described here. Structures should be tied into the existing bank. Trenches should be cut into the bank to lock the structures in place. The farther back into the bank, the better the tie-in or key-in will work. This is a practice that is imperative to prevent the structures from being flanked or cut around. Structures should also be keyed into the existing channel bed. The slopes of many of the tributaries are very steep, so keying the structures into the bed is as important as the bank key-in.

By using the CEM concepts described earlier, the CEM stage most appropriate to be used as a starting point should be qualitatively determined and preliminary designs selected based on the field experience of the project team. For example, if there are signs of a headcut or nick point (channel degradation), bank protection type measures

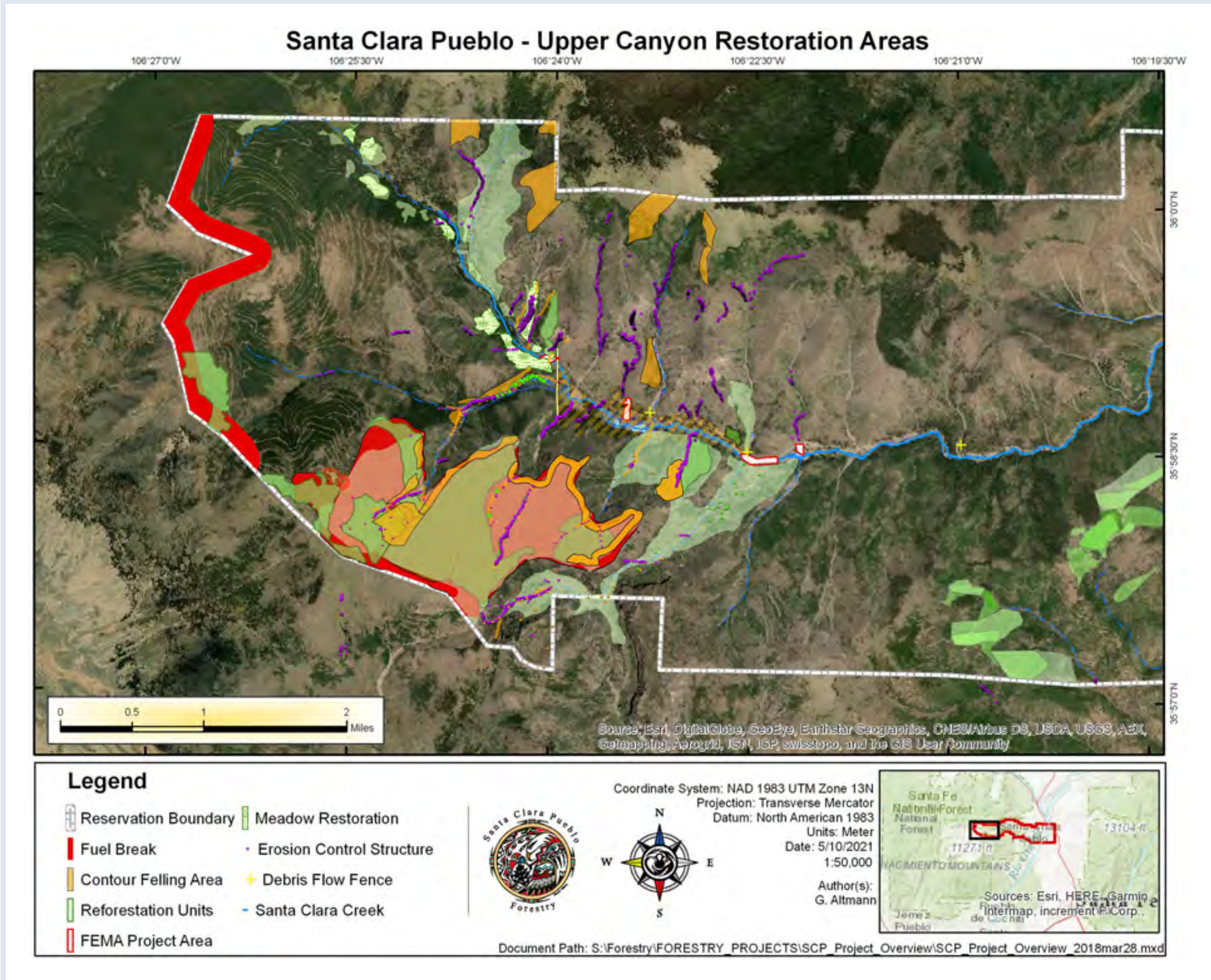

FIGURE 4 Locations where natural infrastructure materials were installed as erosion control features in the Upper Reach of the Santa Clara watershed

should not be considered, but instead, some form of bed control should be implemented.

If constructing grade control to stabilize bed degradation, determine elevations during structure layout so that the downstream structure will retain water on the upstream structure. This will stabilize the upstream structure and dissipate energy at the outlet of the upstream structure (Figure S1).

Structures built from natural materials should not completely block the channel from one floodplain or terrace to another. Blocking the channel in this way will cause the stream to erode around the structure, creating multiple new channels and leading to additional erosion.

Vegetation should not be planted in channel. If willows or similar species are planted, they should be used on the channel margins and banks to provide some protection

FIGURE 5 Switchback Canyon tree check dam erosion control structures designed to slow water and stabilize the channel

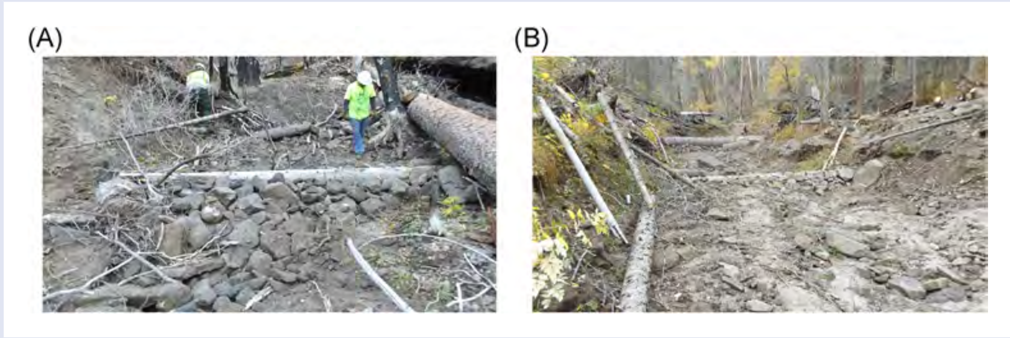

FIGURE 6 Sasquatch Canyon Erosion Control Structures—rock and lateral tree grade control structures to dissipate energy and stabilize the channel bed and banks

and stabilization to those areas. Planting in the channel will potentially clog channel flow and likely flank the structure.

Livestock exclusion or plant protection is a must when re-establishing vegetation as a primary alternative for restoration measures. The willows that were planted (Figure S2) exhibit damage from livestock, along with deer and elk that forage in the area. Planted vegetation requires at least one full growing season to become established and serve the intended erosion reduction function. Grazing pressure on newly planted vegetation features may require future re-planting. Traditional metal fencing can be supplemented with wood post fencing and/or woody debris positioned to provide a "jack-straw" effect to limit browsing. These structures can be constructed to last short durations (1–3 years) to facilitate vegetation establishment and eventual wood decomposition.

When possible, use some form of ties or wrapping to bind the structure together to improve the structure's function. Jute, fine rope, or even locally sourced yucca fibers can be used to bind the materials together within the structure. The use of staples or metal wire is not recommended because they are not biodegradable.

If standing trees, logs, and rootwads that are otherwise damaged by the wildfire (Figure S3) are available adjacent to the channel, use the materials to bind the structures together (Figures 5, 6, and S4). Depending on the reach alignment, concentrate flows in the center of the channel and away from the opposite bank to reduce potential erosion.

Structures built from natural materials should be designed so materials are in compression. For example, cross-vanes, j-hooks, bank barbs, or other features should be constructed with stacked rock in the upstream direction (Figures S5 and S6) to most effectively counteract bed shear stress and keep the structures in place. USACE (1999) and NRCS (1996, 2007) provide additional information on channel rehabilitation and grade control structures, which can be applied to control erosion in such situations.

Vegetation management is a key component in stream design. Native vegetation should be incorporated whenever possible to dissipate energy that occurs in natural stream systems—especially in the floodplain. Where possible, plant native species that are of cultural or medicinal significance to complement the erosion control. Consult with the Tribe on how TEK can be used to inform these planting decisions. When effectively included in the design, native vegetation provides channel margin and floodplain roughness, and reduces velocities, leading to energy dissipation of the surface flow. Native vegetation can also provide seasonal variability at differing elevations, age of plantings, and composition of species. For example, it is best to avoid planting a monotype species to control erosion, because disease, age of stand, and other environmental factors may decimate the species, leaving the area susceptible to future erosion.

Existing on-site materials such as downed trees should be used to mulch channel margin areas. Burned logs and brush can be staked and secured to treat overbank floodplain scour areas where concentrated flows are not advised and require mitigation. If designed properly, sediment will infill areas as a result of the installed structures. Further enhancement would include planting willow or other water-loving species to assist the staked woody materials in dissipating flow energy across the floodplain and catching sediment to stabilize it. The dispersal of woody debris following heavy equipment operations will facilitate biomass accumulation, moisture retention, and seed catchment.

Collaboration lessons learned

Integrating Tribal feedback throughout the proposal, design, and construction process was paramount to project success. Proposed activities were initially reviewed by the THPO, and culturally sensitive areas were field surveyed and excluded at times. Project measures needing to use heavy equipment required pre- and post-design approval by the Tribal Council and Tribal Cultural Committee. Specific restoration treatments introduced by collaborators were adapted to integrate TEK from Tribal Forestry staff, such as flood history, wildlife migrations, and historical vegetation occurrence. This led to more effective project location determination and increased the sense of involvement and ownership by tribal personnel. Adaptive management facilitated field TEK innovation for more effective implementation, such as substituting logs when rock availability was limited, and when consecutive treatments and monitoring was required. Tribal feedback allowed a more collective process, increased natural material integration, facilitated field innovation, prioritized NbS, all while rebuilding a sense of resource stewardship and ownership by the Tribe.

Recommendations for further study and next steps

Based upon on-site qualitative assessments of the NbS material structures post-construction, further activities should include a watershed-based geomorphic assessment approach to determining the appropriate actions for stabilizing, restoring, and implementing new projects. Continuing to use and apply simplistic models, such as the CEM, will assist in identifying geomorphic channel processes and expected change. Applying similar EWN principles within the upper tributary streams will provide further erosion control with reductions in sediment delivery to the downstream reaches and reduce nick point migration upslope, further enhancing erosion mitigation in the watershed.

Larger equipment can be used in the canyons where space and access are both available to effectively gather existing materials to stabilize these reaches. Use of larger equipment in smaller upslope tributaries may not be possible owing to the lack of access; in these cases, field crews are the only option.

Designs for all projects, especially for mainstem dams, roadway construction, and road crossings, require the most up-to-date data to develop effective NbS designs. High-resolution elevation data such as LiDAR (light detection and ranging) should be collected when more detailed watershed analysis is desired. Utilizing FluvialGeomorph (FG), a geomorphic and GIS-based watershed assessment capability (Haring et al. 2020), will be used as the next step in determining how the entire watershed has responded after the structures were installed. FluvialGeomorph will also provide insight into how the structures can be repaired, modified, or replaced or new NbS material structures designed and constructed in other areas so that watershed erosion can be effectively managed in the future.

Next steps in the wildfire watershed recovery effort include continued consultations with the Tribe on how TEK can be used to inform further efforts to design and install additional NbS material channel stabilization measures while considering the following recommendations. Perform geomorphic and watershed surveys of new reaches to determine priority areas for future restoration and stabilization. Future efforts should concentrate on tributaries to the canyons. The new developing channels should be traced to the top sediment source points and stabilized through application of natural materials as described herein. Much of this work will likely need to be completed by hiking and manual labor owing to the lack of access for heavy equipment. Worker safety should be paramount when constructing structures in steep terrain. Innovate and develop new stabilization measures using readily available natural materials, keeping in mind that material availability may change with changing canyon elevation. Livestock should be removed from any areas that are using vegetation as a restoration measure until the vegetation has become well established.

And finally, methods should be deployed post-construction to analyze the success of the treatments to inform future NbS designs. Consistent with this recommendation, the USACE will apply FG to monitor long-term effectiveness of the NbS implemented within the Santa Clara Creek watershed.

CONCLUSIONS

In this paper, we demonstrate how a collaborative effort between the Santa Clara Pueblo, the USACE, and other federal, state, and local organizations was successfully implemented to manage Pueblo lands that were threatened by a large-scale wildfire in the western United States. The project team leveraged collaborative expertise by combining diverse organizational resources and identifying erosion mitigation strategies that were then modified using the principles of TEK, adaptive management, and EWN to complete the design and construction of various erosion control measures. The team implemented a wide range of innovative structures made from natural materials that were consistent with EWN principles for erosion control, incorporating low-cost and readily available logs, mulch, vegetation, and local rock to stabilize highly erodible parts of the watershed. The features were monitored after construction to assess their effectiveness, guiding a series of recommendations and next steps for broader implementation. This is part of a continued effort to emphasize the application of sustainable and resilient project designs using natural materials, as implemented on the Santa Clara Pueblo. The implementation of the natural material designs is restoring the cultural and medicinal traditions on Pueblo land and is an example of how EWN can be applied equitably in practice.

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CONFLICT OF INTEREST

The authors of this paper declare they have no conflicts of interest.

DISCLAIMER

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DATA AVAILABILITY STATEMENT

Data available upon request from author Chris Haring (Christopher.P.Haring@usace.army.mil).

SUPPORTING INFORMATION

FIGURE S1. Switchback Canyon wattles and lateral log energy dissipators supplemented with willow plantings installed to control stream erosion.

FIGURE S2. Switchback Canyon erosion control structures—willow plantings with lateral log energy dissipators.

FIGURE S3. Santa Clara Canyon—contour felling of existing burned trees for erosion control and promotion of re-vegetation.

FIGURE S4. Chicoma Canyon erosion control structures—tree check dams with large in situ rock for channel stabilization.

FIGURE S5. Chicoma Canyon erosion control structures—lateral log, woody debris, and in situ rock were combined to reduce flow and potential erosion.

FIGURE S6. Sasquatch Canyon erosion control structures—rock and lateral tree grade control structures to provide channel bed stability.

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