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Assessment of Stream Crossing Impacts to Ephemeral Streams on Military Lands Throughout the Southwestern United States

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FINAL REPORT

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Executive Summary

Ephemeral stream riparian zones provide essential ecosystem services, but their integrity and extent have declined in many regions. Roads are widespread in military training areas, and resource managers across the Southwest have identified road impacts to ephemeral streams as serious concerns. However, there is little information describing the prevalence, extent, or mechanisms of these impacts to riparian ecosystems in arid regions. This project assessed the impacts of stream crossing infrastructure to streamflow hydrology, channel geometry, and riparian communities in ephemeral streams across the warm desert regions of North America.

The frequency, extent, and mechanisms of ecohydrological impacts were quantified at 228 stream crossings at Fort Irwin (IRWIN), Yuma Proving Ground (YPG), Barry M. Goldwater Range-East (BMGR-E), and White Sands Missile Range (WSMR). Streamflow connectivity was altered at 46% of stream crossings, primarily on paved and graded roads. Flow was diverted or impounded in at least 27% of crossings, while streamflow additions occurred in at least 15% of crossings. Streamflow alterations were rare at crossings on primitive roads, and those lacking roadside ditches and berms.

Above-grade roadbeds, berms, ditches, and other infrastructure that can divert or impound water diminished the frequency, magnitude, and duration of downstream flow events. Analysis of 84 flow events entering 14 crossings with these structures showed that streamflow was entirely diverted or impounded 61% of the time. When flows were large enough to traverse stream crossings, peak stage was reduced in 93% of events, and flow duration was diminished in 89% of events. Inflows from roadside ditches strongly affected the frequency, peak stage, and duration of downstream flows where roadways caused diversions or impoundments.

Depending on local topography and roadway configurations, stream crossings can also contribute additional runoff which augments downstream flow. Runoff generated from roadway surfaces can substantially increase downstream flow frequency, but these runoff subsidies did not increase mean streamflow duration or peak stage relative to upstream reaches. The hydrologic effects of roadway infrastructure depend strongly on local topographic setting and channel characteristics.

Roadway infrastructure that reduces streamflow connectivity decreases water availability to downstream riparian plant communities, often resulting in declines to species richness and diversity that alter community structure and composition. Across all installations, stream crossings that diminished downstream flow also reduced species richness by an average of five species, and significantly lowered species diversity compared to communities immediately upstream of the crossings. The most prominent ecological impacts of flow reductions below stream crossings occurred at WSMR and BMGR-E, although more subtle changes to riparian plant community composition were detected at other installations. The effects of streamflow reductions varied considerably across the study region, corresponding to differences in climate, physiography, and biota.

Streamflow augmentation due to runoff inputs from roadways, berms, and ditches caused downstream channel enlargement that varied across installations. The largest channel adjustments to flow additions occurred at YPG, IRWIN, and BMGR-E. Riparian communities downstream of these crossings sometimes had higher species richness and diversity than reaches immediately upstream of the crossings, but these effects were highly variable within and among installations.

Nine invasive plant species were present in 22% of stream crossings, but their frequency and abundance were not strongly related to hydrologic alterations, roadway configuration, or channel characteristics. The most frequent and abundant invasive species were *Schismus barbatus* (Mediterranean grass), *Eragrostis lehmanniana* (Lehmann lovegrass), and *Pennisetum ciliare* (buffelgrass). Nearly half of the sampled stream crossings at BMGR-E supported *E. lehmanniana* or *S. barbatus*, highlighting the need for more extensive invasive species monitoring and management.

Understanding the frequency, extent, and nature of road impacts to riparian ecosystems will facilitate strategic planning and sustainable management of natural resources on military lands. The findings of this study were used to develop general guidelines for road placement and selection of stream crossing infrastructure to minimize ecohydrological impacts to riparian ecosystems, and the study methods were adapted to create a rapid assessment protocol for quantifying potential impacts at other installations. This information can enable resource managers to mitigate the degradation of critical habitats and efficiently identify problematic crossings for infrastructure rehabilitation and ecosystem restoration.

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Contents

List of Tables

List of Figures

Introduction

Ephemeral stream riparian communities influence landscape functioning through the transfer of water, nutrients, and sediment, and they provide critical habitats and travel corridors for many plant and animal species. As such, riparian habitats have been designated as conservation priorities within the Sonoran Desert ecoregion (Marshall et al. 2000), and are broadly recognized sources of critical ecosystem services in arid regions around the world. Degradation and exotic plant invasions in these ecosystems threaten the long-term mission readiness and sustainability of training operations at many Department of Defense installations throughout the southwestern United States.

Stream crossings and other roadway infrastructure can impact stream channel morphology and riparian ecosystems by modifying longitudinal hydrologic connectivity (Forman and Alexander 1998, Trombulak and Frissell 2000, Gucinski et al. 2001). Roadbeds, ditches, and berms can divert or impound streamflow, thereby reducing downstream water availability and potentially leading to plant mortality and changes in community composition. These structures can also divert flow from one stream into an adjacent watershed. Stream reaches receiving diverted water, as well as additional runoff from roadway surfaces, could increase riparian plant productivity and lead to channel widening. The degree of hydrologic alteration will likely depend on the relative size and topography of the channel and stream crossing structures. For example, a low berm or elevated culvert inlet might prevent smaller flow events from reaching downstream channel segments but would have little effect on large floods. In contrast, deep roadside ditches or below-grade roadbeds may capture and divert all flow events in smaller channels, eliminating the majority of downstream flow.

A considerable body of knowledge exists on the direct and indirect impacts of road networks on stream ecosystems in temperate and tropical forested mountainous regions (see review by Gucinski *et al.* 2001), but little of this information is applicable to ephemeral stream ecosystems in arid regions of southwestern North America. Climatic and edaphic disparities between humid and arid landscapes cause the dominant hydrological and ecological processes to differ in many situations. Furthermore, existing research on stream crossing impacts has focused on aquatic ecosystems, while little is known about how they affect riparian ecosystems along ephemeral streams. Several reviews and theoretical papers have identified some broad-scale mechanisms by which transportation infrastructure may affect abiotic and biotic components of ecosystems (Forman and Alexander 1998, Trombulak and Frissell 2000), but none of these studies address ongoing natural resource management needs for ephemeral streams in arid regions. Perhaps the most relevant finding from previous work on road impacts to stream networks is that the nature and extent of hydrologic alteration vary with stream and landscape characteristics (Forman and Alexander 1998, Coffin 2007).

Roads are widespread in military training areas, and resource managers at installations across the Southwest have identified stream crossing impacts to ephemeral streams as serious concerns, with the potential to degrade riparian habitats and promote invasive plant populations. However, there is currently no quantitative information on the prevalence, extent, or mechanisms of these impacts to ephemeral streams in dryland regions (Duniway and Herrick 2011). Identifying the direct impacts of stream crossings is a critical first step in establishing a broader understanding of how transportation infrastructure affects the health and sustainability of ecosystems in arid landscapes (Forman and Alexander 1998, Duniway and Herrick 2011).

This project assessed the prevalence, extent, and types of stream crossing impacts to riparian ecosystems in Fort Irwin, CA, Yuma Proving Ground, AZ, Barry M. Goldwater Range-East, AZ, and White Sands Missile Range, NM. Interdisciplinary analysis of streamflow hydrology, channel morphology, and riparian plant communities identified the types of ecohydrological impacts, and the stream crossing infrastructure that most commonly caused riparian habitat degradation. These findings were used to provide recommendations on road placement and stream crossing structures to mitigate declines in riparian habitat conditions and the species that depend on them. Understanding the types of stream crossings and environmental contexts that result in the greatest impacts will enable resource managers to prioritize habitat protection and restoration that help to prevent the listing of additional plant and animal species. The methods for study site selection, field data collection, and data analyses presented here provide an example for rapid assessment and monitoring techniques that resource managers can use to clarify road and maneuver trail impacts at other installations.

Study Areas

The study area consisted of four installations spanning the warm desert biomes of southwestern North America. Fort Irwin, CA (IRWIN) lies in the western Mojave Desert, the driest region of North America, typified by cold winters and nearly rainless summers (Rundel and Gibson 1996). Yuma Proving Ground, AZ (YPG) and Barry M. Goldwater Range-East, AZ (BMGR-E) are in the Sonoran Desert, where freezing temperatures are rare and biseasonal rainfall supports diverse flora and fauna (Turner et al. 1995, McAuliffe 1999). YPG lies in the more arid Colorado River Valley section of the wester Sonoran Desert, while BMGR-E is within the Arizona Uplands section. White Sands Missile Range (WSMR) occupies the northern

Chihuahuan Desert, which also experiences biseasonal rainfall but has milder temperatures than the Sonoran Desert (Havstad et al. 2006).

All four installations exhibit Basin and Range topography consisting of broad alluvial valleys separated by linear mountain ranges. Bedrock geology and exposed rock types in the mountain ranges are generally igneous in all installations except WSMR, where faulted sedimentary rocks are common. Desert scrub dominated by the ubiquitous *Larrea tridentata* is the primary vegetation type at these installations, although the northern part of WSMR grades into semi-arid grassland.

The four installations represent the primary climatic gradient across the southwestern United States, where mean annual precipitation and the proportion of annual precipitation occurring during the warm season increases from west to east. Thirty-year climate normals (1981-2010) were taken from the PRISM Climate Group (2012), since weather stations are sparsely distributed throughout the region. Mean annual precipitation (MAP) at IRWIN ranges from 88-231 mm and is almost entirely derived from winter frontal storms. Mean annual temperature (MAT) ranges from 9.4 to 12.8˚C. Mean annual precipitation at YPG is 93-228 mm, with about half occurring as summer convective storms. YPG is in the hottest portion of the U.S. with MAT ranging from 12.8 to 17.2˚C. Climatic conditions are similar but slightly milder at BMGR-E, with MAP of 103-327 mm and MAT of 11.1-15.0˚C. WSMR is the wettest and coolest installation in this study, with MAP ranging from 244 to 562 mm, and MAT ranging from 4.4 to 9.4˚C. About 70% of MAP at WSMR is derived from summer convective storms. Within each installation, climatic conditions vary considerably according to elevation and aspect.

Methods

Sampling of stream crossings was based on a spatially balanced random sample of locations along road networks at each installation, since no information was available on the locations or types of existing crossings. Shapefiles of active road networks were used to classify road segments as paved, graded, and primitive. Paved roads have asphalt or concrete wear surfaces that are typically above grade. Graded roads have unpaved surfaces that are periodically maintained with a dozer or road scraper, often resulting in road surfaces that are below grade. Primitive roads are unimproved routes ("two-tracks") that rarely cause significant topographic modification.

Spatially balanced random samples of stream crossings stratified by road type at each installation were obtained with a Generalized Random-Tesselation Stratified (GRTS) sampling design for linear features (Stevens and Olsen 2004), using the R package 'spsurvey' (Kincaid et al. 2020). Areas with restricted access due to testing and training, as well as those lacking defined stream channels (e.g., aeolian sand sheets and playa bottoms), were omitted from the sample design. For each installation, 20 sample points were generated for each road type, along with 40 oversample points that were used when the original sample points fell in unsuitable locations. Field data were collected at the stream crossing closest to each sample point, until approximately 20 crossings were included for each road type.

Channel geomorphology and riparian plant communities were analyzed in study reaches adjacent to 228 stream crossings at the four installations (Table 1). Since few paved road segments intersected with defined stream channels at IRWIN, only eight paved stream crossings were sampled, resulting in a sample of 48 crossings for this installation (Figure 1). Sixty stream crossings each were included from YPG (Figure 2), BMGR-E (Figure 3), and WSMR (Figure 4).

Stream crossings were excluded when proximity to significant tributary junctions, local physiographic boundaries, or extensive disturbance might have imposed confounding effects.

Paired study reaches were established at each stream crossing, consisting of a reference reach upstream of potential road influences and a reach immediately downstream of the crossing, resulting in 456 reaches. Study reaches were located as close to the road edge as possible while avoiding disturbed areas associated with road construction or maintenance, and reach lengths were scaled to 15 mean stream widths (maximum of 100 m length). The dimensions and relative elevations of channels and stream crossing structures were measured with a TruPulse 200 laser rangefinder and clinometer (Laser Technology Inc.). Field data collection occurred during March-April 2016 at YPG and BMGR-E, March 2017 at IRWIN, and October 2017 at WSMR.

Stream Crossing Characteristics

Stream crossings were categorized as on-grade, below-grade, above-grade, culvert, or bridge. On-grade crossings occurred where the difference between the channel bed and road surface elevations was <0.1 m. Below-grade crossings often occurred on graded roads, where repeated resurfacing or travel wear had lowered the road surface by ≥ 0.1 m below the downstream channel bed. Most paved roads and some graded roads exhibited above-grade crossings, in which the road surface was elevated ≥ 0.1 m above the upstream channel bed and lacked any flow conveyance structures. Above-grade crossings with flow conveyance structures were classified as either culverts or bridges. Bridges included box culverts that spanned the channel and minimized flow constrictions during bankfull events.

Paved and graded road corridors often contained water control structures such as roadside ditches and earthen berms that diverted runoff and redirected it parallel to the roadway, where it was discharged to a channel at the nearest conveyance structure or on-grade crossing. In some areas of YPG, BMGR-E, and WSMR, extensive networks of roadside berms collected and diverted sheetflow and runoff in smaller channels towards a single centrally located conveyance structure. On many graded roads, smaller (<0.5 m high) uncompacted earthen berms were also formed incidentally by side-cast material from road resurfacing and maintenance. Field observations indicated that these uncompacted berms were eventually breached by subsequent large flow events but smaller flow events, particularly in headwater channels, were impounded or diverted.

Visual observation was used to categorize stream crossings by potential impacts to streamflow connectivity based on local topography and landscape position, as well as the elevational differences between the channel bed and the road surface, ditch, and berms (where present). Although detailed topographic surveys of roadway infrastructure were beyond the scope of this project, persistent alterations to surface flow paths in these arid landscapes were discernable based on changes to topography and sediment characteristics. An impact of ‘none’ was assigned where crossings did not entail topographic modifications that would affect streamflow transmission across the roadway (e.g., on-grade crossings without berms or ditches). Where changes in road surface elevation, ditches, and/or berms presented the potential to reduce downstream flow by diversion or impoundment, the impact was classified as ‘diversion’. Similarly, when roadway structures contributed additional runoff to the downstream channel, the impact was classed as ‘inflow’. At some stream crossings, upstream flow was diverted or impounded, while flow from ditches or berms was added to the downstream reach, and these sites were categorized as ‘diversion+inflow’. In most of these cases, the relative changes to downstream flow (net diversion or inflow) could not be determined in the field.

Alterations to Streamflow

Changes to the frequency, depth, and duration of streamflow events were quantified at subset of 14 stream crossings where diversion or impoundment was apparent (Table 4). Five crossings were monitored at YPG from 4 March 2016 to 24 April 2018 (Figure 2). Five crossings were monitored at WSMR from 6 July 2017 to 25 April 2018 (Figure 4). Four crossings were monitored at BMGR-E from 11 Apr 2016 to 22 Apr 2018 (Figure 3). Stream stage was recorded at five-minute intervals in reaches above and below each crossing with Rugged Troll 100 pressure transducer loggers (InSitu Inc.), using a nearby logger to correct for changes in barometric pressure. Loggers were housed in 5 cm diameter slotted PVC pipe, and fastened to t-posts driven into the channel thalweg.

Streamflow hydrographs were used to determine the frequency, peak stage, and duration of ephemeral flow events above and below each crossing. Within a reach, streamflow pulses separated by at least 30 minutes were considered to be discrete events. Streamflow events downstream of crossings that did not correspond to upstream inflows, apparently due to localized runoff from roadways or ditches, were identified when the downstream flow event ceased prior to the onset of upstream flow or in the absence of upstream flow.

The effects of stream crossing infrastructure and upstream flow characteristics on the frequency, peak stage, and duration of downstream flow were analyzed using Generalized Linear Models (GLMs). Streamflow occurrence was modeled as a binomial response, while a Gaussian distribution was assumed for changes to flow duration and peak stage (e.g. Δduration = $duration_{downstream} - duration_{upstream}$). Roadway characteristics used for predictors included road crossing elevation relative to downstream bed elevation, berm height, and ditch depth. Upstream peak stage, flow duration, bankfull mean channel depth, and watershed area were used as covariates for downstream flow responses, allowing for two-way interactions with roadway characteristics.

Alterations to Channel Morphology

Within the 456 paired study reaches, mean bankfull channel width, depth, and bed slope were calculated from measurements along five equally spaced cross-sections. Study reaches were classified by hydrogeomorphic channel types (e.g., braided, bedrock with alluvium) based on channel planform, bankfull dimensions, and boundary materials (Sutfin et al. 2014). The predominant particle size classes (e.g., sand, gravel) of the channel substrate were visually determined. Changes to channel geometry at stream crossings were relativized by upstream dimensions (e.g., Δwidth = [$\text{width}_{\text{downstream}}$ – $\text{width}_{\text{upstream}}$] ÷ $\text{width}_{\text{upstream}}$).

Alterations to Vegetation

Canopy cover for all native perennial plants and exotic species within the riparian corridor of each reach (n = 456) was estimated to the nearest 5% by comparison of visual estimates from two independent experienced observers. Native annual species were ignored since they were ubiquitous, and variation in their abundance is driven largely by seasonal and annual rainfall fluctuations rather than long-term site conditions. However, the presence and cover of all annual and perennial exotic plant species were documented in the study reaches, as well as in 14 areas of persistent pounding at roadway flow obstructions. On larger channels with extensive floodplains, five 10 m wide perpendicular belt transects spanning the riparian corridor were surveyed. On all other reaches, the entire riparian corridor was surveyed. The riparian corridor consisted of channel, bank, and floodplain surfaces subjected to periodic inundation, and did not include relict terraces. Since riparian corridor width did not typically vary between upstream and downstream reaches, and standardized reach lengths were used at each crossing, surveyed areas in the paired reaches were similar. Vegetation surveys were conducted at the end of the growing season during maximum vegetation development, corresponding to spring in the Sonoran Desert (YPG, BMGR-E) and Mojave Desert (IRWIN), and autumn in the Chihuahuan Desert (WSMR).

Changes to plant communities at each crossing were assessed using ecological dissimilarity measures, species richness, and the Simpson diversity index (Zar 1999). The Bray-Curtis dissimilarity measure was calculated from canopy cover data, and quantified compositional differences due to changes in species abundance. The Jaccard dissimilarity measure was used for species occurrences to quantify structural differences based on species presence, and was chosen so that shared species absences between reach pairs would be ignored. Both of these dissimilarity measures range from 0 to 1, where 0 indicates identical communities within paired reaches (no dissimilarity), while 1 indicates no shared species. Species diversity was quantified using the Simpson index (0-1), a robust estimator with minimal bias and low sensitivity to sample size (Mouillot and Lepretre 1999, Magurran 2004). Changes in species richness and the Simpson diversity index were compared as the difference between downstream and upstream reaches for each crossing (e.g., $\Delta R = R_{downstream} - R_{upstream}$). Ecological indices were calculated using the R package 'vegan' (Oksanen et al. 2020). Both dissimilarity measures and Simpson diversity were modeled as a quasi-binomial response (0-1), and species richness was modeled with a Poisson distribution, which is used for count data.

Statistical Analyses

Since geomorphic and ecological characteristics at stream crossings varied among installations, the data were analyzed separately by installation in order to preserve degrees of freedom and detect subtle responses. Changes to geomorphic and ecological response variables were tested by fitting GLMs using predictors that described roadway and upstream channel characteristics, allowing for two-way interactions between roadway and channel characteristics. Roadway characteristics included stream crossing type, crossing elevation relative to downstream bed elevation, berm height, and ditch depth. Upstream channel characteristics included bankfull mean channel depth, width, and width:depth, channel bed slope, channel hydrogeomorphic type, and predominant substrate type. The Bayesian Information Criterion (BIC) was used to select best model subsets for each analysis using the ‘leaps’ package (Lumley and Miller 2020) for Gaussian dependent variables, and the ‘bestglm’ package (McLeod et al. 2020) for binomial and Poisson responses. The exhaustive search algorithm in these packages discretized multi-level categorical variables into sets of dummy variables. Best subsets of models were limited to 6 independent variables, since more complex models did not improve explanatory power and hindered interpretation. Post-hoc multiple comparisons were made with Tukey adjusted p-values using the ‘multcomp’ package (Hothorn et al. 2008). All analyses were performed in the statistical software R version 4.0.3 (R Core Team 2020).

Results

Across all installations, stream crossings on paved roads most commonly featured culverts or channel-spanning structures such as bridges and box culverts. All other paved crossings were either on- or above-grade. Stream crossings on graded roads were typically on- or below-grade, while those on primitive roads were predominantly on-grade.

Spatially balanced random sampling revealed that 46% (105 of 228) of stream crossings on the four installations altered longitudinal hydrologic continuity by diverting streamflow and/or adding additional runoff (Table 2). The most common type of visibly detectable alteration was streamflow diversion or impoundment, which occurred in at least 27% of crossings, and ranged from partial loss of low flows to complete elimination of all downstream flow depending on roadway configuration and the presence and size of water control structures. Streamflow diversion was most common at below-grade (19 of 23) and above-grade crossings (20 of 26), and was relatively infrequent at on-grade crossings (19 of 140). While diversion or impoundment was rare at crossings with culverts or bridges, elevated culvert inlets did impound streamflow at four crossings. Significant inflows from roadways, berms, and ditches were added to downstream reaches in at least 15% (n = 34) of stream crossings, which were often equipped with culverts or bridges. At 4% of crossings (n = 9), roadway infrastructure diverted or impounded upstream flow while adding significant runoff to downstream reaches, but the net effects to streamflow could not be determined from field observations. Crossings that did not perceptibly alter streamflow connectivity were on-grade, or had adequately sized culverts, box culvers, or bridges.

Aside from the type of stream crossing, water control structures within the road corridor also strongly influenced streamflow connectivity (Table 3). At crossings without streamflow modifications, roadside ditches and berms were rarely present, or were quite small relative to channel depth. In contrast, ditches and berms were present at the majority of crossings where streamflow was diverted and/or augmented. Diversions or inflows were occasionally apparent at on-grade crossings without ditches or berms, due to preferential flow paths developing along the roadway.

Alterations to Streamflow

A total of 143 discrete flow events were recorded at the 14 stream crossings during 16,356 site-days of monitoring (Table 5). Eighty-four events were recorded in the upstream reaches, with 39% (n = 33) producing downstream flow. At seven of the crossings, 26 streamflow events occurred within the downstream reach prior to, or in the absence of, streamflow from the upstream reach. These events were apparently due to localized runoff from roadways and ditches during storms that did not generate inflows from the upstream reaches. No streamflow events occurred in either reach at one crossing (WSMR-098).

Streamflow Frequency

Streamflow frequency downstream of the crossings was lower than in upstream reaches ($\chi^2 = 22.17$, $p < 0.0001$), even when runoff events originating from roadway drainage were included ($\chi^2 = 4.37$, $p = 0.036$). Differences between upstream and downstream flow frequency were largest at five crossings ($p < 0.10$), and while other crossings exhibited slight downstream reductions, small samples sizes limited the detection of statistical differences (Figure 5). Only one statistically significant model could be fitted from the covariates, showing that flow frequency increased with ditch depth and upstream peak stage (Table 6). The positive relationship with ditch depth, and the lack of other significant predictors, suggests that ditch inflows were the main driver of downstream flow frequency at these 14 crossings with apparent diversions and/or impoundments.

Peak Stage

Mean peak stage relative to bankfull channel depth in upstream reaches (0.48±0.05) was higher than in downstream reaches (0.15±0.03), even when including downstream flows that originated from roadway drainage (0.21±0.03; $p < 0.0001$). Relative peak stage was diminished downstream of crossings for 93% of all events (Figure 6). However, infrequent but large runoff additions from roadways and ditches caused downstream mean peak stage to be reduced ($p < 0.05$) below only six of the 14 crossings (Figure 7). Models that minimized BIC values explained about 60% of variability in downstream peak stage and highlighted the importance of interactions between roadside ditches and upstream flow characteristics (Table 6). Positive model coefficients for interactions between upstream flow duration and ditch depth indicated that inflows from ditches during prolonged storms controlled downstream peak flows. Negative interactions between upstream peak stage and ditch depth reflected the diversion or impoundment of these inputs. Larger downstream flows were associated with shorter duration events.

Streamflow Duration

Cumulative streamflow duration upstream of the crossings was 10.86 days, but declined to 4.73 days in downstream reaches, and was only 3.10 days when events generated solely by roadway runoff were excluded. Mean event duration upstream of the crossings (0.099±0.019 days) was significantly longer than below the crossings (0.043±0.010 days; $p = 0.015$), particularly when considering only flow events that originated upstream (0.037±0.013 days; $p = 0.012$). For 89% of all events, flow duration decreased below the stream crossings (Figure 8). As with peak stage, infrequent but prolonged inflows from roadways and ditches caused reach-level means to be similar at 10 crossings (Figure 9). The depth of roadside ditches was the strongest stream crossing predictor of downstream flow duration (Table 6). Parameter coefficients explained 77% of variability and suggest that roadway inflows proportional to ditch depth are regular inputs to downstream reaches, while upstream inflows are diminished proportionally to ditch depth.

Alterations to Channel Morphology

Channel Width

Averaged across all installations, bankfull channel width increased by 86±30% downstream of crossings where roadway inflows occurred ($p < 0.0001$; Figure 10). Streamflow additions increased downstream mean channel width by 44±18% ($p = 0.031$) at BMGR-E, 100±110% ($p = 0.014$) at IRWIN, and 190±150% ($p = 0.0026$) at YPG. Changes to channel width at stream crossings with diversions were not distinguishable from those lacking apparent flow alterations.

The sign and magnitude of coefficients for roadway infrastructure varied among installations, reflecting divergent hydrologic impacts that are likely due to regional topographic differences (Table 7). Positive coefficients indicated that below-grade crossings and berms produced inflows that increased channel width at BMGR-E. At WSMR, ditches, berms, and elevated roadbeds also appeared to cause net increases to downstream width. Mean channel width increased with ditch depth at IRWIN, but decreased with berm and roadbed height, especially for low-gradient channels. At YPG, downstream channel width decreased with roadbed height and at culvert crossings, but one model indicated that inflows from berms produced channel widening. Crossings with inflows and berms, particularly on piedmont headwater channels, were the best predictors of downstream channel width increases for the pooled data.

Channel Depth

Downstream mean bankfull depth approximately doubled at stream crossings with roadway inflows (110±50%; $p = 0.0002$). This effect was due to substantial downstream deepening of channels at IRWIN (230±45%; $p < 0.0001$), and to a lesser extent YPG (77±51%; $p = 0.0098$), while no effect was apparent at BMGR-E or WSMR (Figure 11). Mean bankfull depth pooled across installations also increased below crossings with both inflows and diversions (106±36%), but this could not be distinguished from other crossings ($p \geq 0.13$) due to variability in this small sample ($n = 7$). Downstream channel deepening was significant below these crossing types at IRWIN (130±50%; $p < 0.0001$).

Similar to channel width, the effects of roadway structures on mean bankfull depth below crossings varied between installations (Table 8). Below-grade crossings, deep ditches, and elevated roadbeds functioned as diversions and reduced downstream depth at BMGR-E, especially where upstream channels had low width:depth. In contrast, below-grade crossings, ditches, and tall berms resulted in deeper downstream channels at IRWIN, but this effect was lessened for wide upstream channels. At WSMR, below-grade crossings appeared to function as diversions, but taller berms added runoff that deepened downstream channels, particularly for smaller upstream channels. Culvert crossings and elevated roadbeds increased downstream depth at YPG, while taller berms reduced downstream depth when inflowing channels had low slopes or width:depth. Averaged across all installations, downstream channel depth increased with berm height, particularly when upstream channels were shallow.

Channel Width:Depth

Pooled across all installations, mean bankfull width:depth increased 77±17% below crossings with flow diversions or impoundment ($p = 0.013$). However, changes to mean width:depth were not significant within any installation, due to large variability. Changes below other crossing types were not detected (Figure 12).

Downstream width:depth increased at above-grade crossings at BMGR-E, WSMR, and YPG, although this was counteracted by deeper upstream channels at YPG (Table 9). Width:depth below crossings was not explained by roadway characteristics at IRWIN. Models with nonzero coefficients could be fitted to the pooled data (Table 9).

Channel Slope

Mean bed slope across all installations increased by 25±1% below stream crossings and did not differ among hydrologic alterations ($p > 0.25$; Figure 13). Differences among impact types did not explain variability in bed slope within any installation. Across all installations, downstream slope decreased with upstream slope and at bridge crossings, but increased slightly below culverts and below-grade crossings (Table 10). Bridge crossings and elevated roadbeds were associated with reduced downstream slope at BMGR-E. Downstream slope declined at above-grade crossings at IRWIN, but increased with ditch depth. Culvert crossings were associated with slope reductions at YPG, but bed slope increased below berms on low-gradient channels. Roadway characteristics did not explain variability in bed slope at WSMR.

Alterations to Vegetation

A total of 221 vascular plant species were recorded within the 456 study reaches, consisting of 212 native perennials and nine exotic species, four of which were annuals. Study reaches at WSMR supported 130 species, while those at YPG and BMGR-E contained 92 and 78 species, respectively. Riparian communities at IRWIN supported only 41 species in the study reaches.

Community Composition: Species Cover

Across all installations, Bray-Curtis dissimilarity between upstream and downstream reaches averaged 0.30±0.01 at stream crossings without apparent flow modification (Figure 14) and was not distinguishable from crossings where flow was diverted or augmented ($p > 0.093$). However, changes to community composition at crossings with diversions were significantly larger than those without alterations at WSMR (0.42±0.06 versus 0.28±0.02; $p = 0.027$). Differences in Bray-Curtis dissimilarity were not detected among streamflow modification types at BMGR-E, IRWIN, or YPG.

For all three desert regions, riparian community composition changed most at above-grade and culvert crossings, proportional to the height of roadbeds and berms (Table 11). Bray-

Curtis dissimilarity increased at above-grade crossings at BMGR-E and WSMR, and at culvert crossings for IRWIN. Berms and ditches were associated with downstream compositional shifts at IRWIN, WSMR, and YPG, but these effects were modified by upstream channel geometry in ways that varied among installations.

Community Composition: Species Occurrence

Jaccard dissimilarity between upstream and downstream reaches across all installations averaged 0.38±0.01 at stream crossings with no apparent flow modification (Figure 15). Community composition based on species occurrence changed more below crossings with flow diversions or impoundments (0.49±0.02) than at crossings without apparent flow alterations ($p < 0.0001$). Compositional changes at crossings with other types of flow modification could not be detected ($p > 0.091$) from the pooled data. Stream crossings with diversions altered community composition at WSMR (0.53±0.05 versus 0.39±0.02; $p = 0.0066$) and YPG (0.51±0.03 versus 0.38±0.03; $p = 0.0091$). Differences in Jaccard dissimilarity were not detected among streamflow modification types at BMGR-E or IRWIN.

Changes to species composition across all installations increased with roadbed height and ditch depth, particularly where flows were diverted (Table 12). Compositional shifts were common at above-grade crossings at BMGR-E and YPG, and at below-grade crossings at IRWIN. Riparian community changes increased with berm height for shallow channels at BMGR-E and IRWIN. At WSMR, Jaccard dissimilarity increased with berm height and ditch depth, especially on wide and shallow channels. The presence and depth of ditches, and other crossing types that diverted upstream flow, magnified compositional shifts at YPG.

Species Richness

Averaged across all installations, mean species richness downstream of crossings without flow modifications was 13±0.7 (Figure 16) and did not differ from upstream reaches ($p = 0.10$). Mean species richness declined significantly below crossings with diversions (8.0±0.1; $p < 0.0001$), and increased slightly below crossings with inflows (15.9±1.4; $p = 0.080$), relative to the upstream reaches. Reaches below diversions supported 3.5±0.7 fewer species than upstream reaches at BMGR-E ($p = 0.0078$), and 6.2±1.4 fewer species at WSMR ($p = 0.016$). No changes to species richness among hydrologic impact types were observed at IRWIN or YPG.

Pooling data from all installations, species richness declined with increasing height of roadside berms, and downstream of above-grade crossings (Table 13). Above-grade crossings and berms decreased richness at IRWIN and BMGR-E, and the impacts of these flow impediments were greatest along low-gradient channels. Hydrogeomorphic channel type and channel geometry strongly affected ecological responses to stream crossings at these installations. In contrast, downstream richness increased with roadbed height, and with berm height on deeper low-gradient channels at WSMR. Similarly, downstream richness at YPG increased below berms, and where wide and shallow channels intersected roadside ditches and berms. The contrasting responses to flow obstructions at WSMR and YPG likely reflect the effects of flow additions at stream crossings.

Species Diversity

Mean Simpson diversity in all reaches below stream crossings without flow modifications was 0.74±0.02, and diversity declined downstream of crossings with diversions or impoundments (0.64±0.03; $p = 0.0004$; Figure 17). No changes in species diversity were detected below crossings with inflows, or diversions and inflows ($p > 0.45$) pooled across all installations. At BMGR-E, crossings with diversions supported less diverse downstream communities, compared to crossings without alterations (0.57±0.06 versus 0.80±0.02; $p < 0.0001$). Crossings with diversions also decreased downstream diversity at WSMR ($p = 0.045$), but this was not statistically distinguishable from crossings without streamflow alterations (0.71±0.05 versus 0.73±0.04; $p = 0.16$). No significant changes to Simpson diversity were detected among apparent hydrologic impact types at IRWIN or YPG.

Roadway structures that commonly result in diversion or impoundment of upstream flows reduced downstream Simpson diversity (Table 14). Above-grade crossings reduced downstream diversity at BMGR-E and WSMR. Downstream diversity also declined with ditch depth at BMGR-E and YPG, and berm height at WSMR, particularly when the upstream channels were wide and of low-gradient. The measured roadway and upstream channel characteristics did not explain variability in Simpson diversity at IRWIN. Pooled across all installations, downstream diversity decreased with ditch depth, particularly at crossings with apparent streamflow diversions. These declines were less severe at culvert crossings.

Occurrence of Invasive Species

Invasive plant species were present in 78 of the 470 study reaches, consisting of seven grasses, one annual herb, and one woody plant. Invasive grasses were most frequent, and included *Bromus tectorum* L. (cheatgrass), *Cynodon dactylon* (L.) Pers. (Bermuda grass), *Eragrostis cilianensis* (All.) Vign. ex Janchen (stinkgrass), *Eragrostis lehmanniana* Nees (Lehmann lovegrass), *Pennisetum ciliare* (L.) Link (buffelgrass), *Schismus barbatus* (Loefl. ex L.) Thellung (Mediterranean grass), and *Sorghum halepense* (L.) Pers. (Johnson grass). The most widespread grasses were *S. barbatus* (48 reaches at BMGR-E), *E. lehmanniana* (11 reaches at WSMR), and *P. ciliare* (11 reaches at YPG and BMGR-E). *Bromus tectorum* was the only invasive species encountered at IRWIN, occurring at one stream crossing. *Tamarix chinensis* Lour. (saltcedar) occurred in two reaches each at WSMR and YPG. The annual herb *Salsola tragus* L. (prickly Russian thistle) was ubiquitous at YPG, BMGR-E, and to a lesser extent WSMR, but was not quantified.

Invasive species were present at 22% of stream crossings and the frequency of occurrence did not differ among apparent hydrologic impacts ($p > 0.97$). At the reach scale ($n = 470$), invasive species occurred at 18% of reaches without impacts, 6% of diverted reaches, and 25% of reaches receiving inflows, but these differences were not statistically significant ($p > 0.27$) due to the much smaller sample sizes of impacted reaches (Figure 18). Invasive species frequency was higher within incised reaches (50%) that occurred upstream of ditches or below-grade crossings, but this was only distinguishable from diverted reaches (6.3%; $p = 0.024$). The incised upstream reaches in this sample ($n = 8$) were infrequent geomorphic impacts not caused by changes to streamflow, but instead developed where below-grade stream crossing infrastructure lowered local base level and initiated upstream head cutting. The higher frequency of invasive species within incised reaches was due to the occurrence of *Schismus barbatus,* which was more frequent in these reaches (50%) than in diverted reaches (3.2%; $p = 0.0076$) and those that were unimpacted (11%; $p = 0.033$). No differences were apparent for other abundant species such as *E. lehmanniana* ($p > 0.10$), *P. ciliare* ($p > 0.95$).

Models that minimized BIC for the occurrence of any invasive species, as well as for the presence of *S. barbatus* and *P. ciliare* consistently indicated that frequency increased with roadbed elevation (Table 15). Only one model with significant terms could be fitted for *P. ciliare* and *S. barbatus*, and the measured roadway and channel characteristics did not explain variability in the occurrence of other invasive species.

Abundance of Invasive Species

The maximum canopy coverage for invasive species in any reach were highest for *C. dactylon* (15%), *E. lehmanniana* (70%), *P. ciliare* (20%), *S. barbatus* (40%), and *Tamarix* spp. (20%). However, reach-level canopy cover did not vary among hydrologic impact types for any species. For all invasive species combined, canopy cover was highest in ponded areas at roadway obstructions (12±6%), but this did not differ from unimpacted reaches (7±2%; $p = 0.97$). None of the measured roadway or channel characteristics could explain variability in the abundance of invasive species.

Discussion

Stream crossing infrastructure in arid landscapes can significantly alter ephemeral streamflow regimes, channel geometry, and riparian plant communities. Roadway infrastructure that reduces streamflow connectivity by diverting or impounding upstream flow decreases water availability to riparian plant communities, often resulting in declines to species richness and diversity that alter community structure and composition. Stream crossings that augment streamflow with roadway runoff, as well as water diverted from nearby channels via ditches, berms, and roadways, can significantly increase downstream channel width and depth. In some cases, the increased water availability below these crossings supports the establishment of additional plant species. Dryland ephemeral stream responses to flow modifications varied among military installations in the Mojave, Sonoran, and Chihuahuan Deserts, reflecting regional differences in climatic, physiographic, and biogeographic factors. At smaller spatial scales, the physical and biotic changes at stream crossings were mediated by the types and dimensions of roadway infrastructure, as well as upstream channel characteristics. In contrast, no changes to channel geometry or plant communities were detected where streamflow connectivity was maintained, such as at on-grade crossings without roadside berms or ditches.

Alterations to streamflow connectivity were common along road networks on military lands. About 46% of sampled stream crossings modified streamflow transmission to downstream channels, and this primarily occurred at crossings on paved and graded roads, particularly where ditches and berms created flow obstructions or preferential flow paths. Flow was diverted or impounded in at least 27% of crossings, while streamflow additions occurred in at least 15% of crossings. Streamflow alterations were rare at crossings on primitive roads.

The frequency, magnitude, and duration of ephemeral streamflow events below stream crossings are diminished by above-grade roadbeds, berms, ditches, and other infrastructure that can divert or impound water. Analysis of 84 flow events entering 14 crossings with these structures demonstrated that streamflow was entirely diverted or impounded 61% of the time. When flows were large enough to traverse the stream crossings, peak stage was reduced in 93% of events, and flow duration was diminished in 89% of events. Mean peak stage of flow events that crossed roadways was reduced by about 69%, and mean duration was reduced by 63%, relative to upstream inflows. Actual reductions were likely larger, since it was not possible to differentiate between roadway runoff contributions and upstream inflows once flow commenced in both reaches. Upstream flow events with higher peak stage were more likely to overtop or breach these structures to produce downstream flow, but model results indicate that inflows from roadside ditches are a primary driver of the frequency, peak stage, and duration of downstream flows where roadways cause diversions or impoundments.

Depending on local topography and roadway configurations, stream crossings can also contribute additional runoff which augments downstream flow. Diverted streamflow and sheetflow is intercepted and conveyed via ditches, berms, and roadbeds to channels in deeper valleys or other low points in the road profile. While the locations and amounts of these inputs are highly variable, runoff generated from roadway surfaces can substantially increase downstream flow frequency. Of 143 observed streamflow events at 14 stream crossings, approximately 18% of these were downstream flows that occurred in the absence of streamflow inputs from the upstream reach. However, these runoff subsidies did not increase mean streamflow duration or peak stage relative to upstream reaches.

The hydrologic effects of roadway infrastructure depend strongly on local topographic setting and channel characteristics. For example, small channels draining planar hillslopes can be entirely diverted by typical roadside ditches, while channels in valley bottoms or other local elevation minima generally receive streamflow additions from roadway structures. While the role of roadside ditches in diverting upstream flow and sometimes augmenting downstream flow was consistent at a subset of streamflow monitoring sites, the interactive effects of upstream channel geometry and roadway characteristics on downstream channel geometry and riparian communities differed considerably between installations, reflecting regional differences channel dynamics and riparian biota that are driven by hydroclimatic regime and physiography. Such differences in the direction and magnitude of these interactions present formidable challenges to the development of quantitative guidelines that are universally applicable. For example, downstream channel width increased with the height of berms and roadbeds at some installations and reflected net streamflow additions were common at these structures, while the opposite patterns were apparent at others. The types and dimensions of structures that produce ecohydrological alterations vary with landscape characteristics and roadway configurations that were not quantified in this study.

Effects of Streamflow Reductions at Stream Crossings

Reductions to ephemeral streamflow downstream of diversions or impoundments significantly alter riparian plant communities in the warm desert biomes of the southwestern United States. Averaged across all installations, stream crossings that diminished downstream flow also reduced plant community richness by about five species and lowered Simpson diversity compared to communities immediately upstream of the crossings. These impacts were reflected in downstream changes to species occurrences, but not species abundance, indicating that losses from impacted communities were generally species that occurred less frequently and with lower canopy cover.

The most prominent ecological impacts of flow reductions below stream crossings occurred at WSMR and BMGR-E. Diversions at WSMR reduced downstream richness by an average of six species, while those at BMGR-E supported an average of four fewer species than upstream reaches. Species losses from the more diverse riparian communities at WSMR were reflected in compositional changes quantified by ecological dissimilarity metrics, but differences in Simpson diversity were not detected. In contrast, the elimination of species downstream of diversions at BMGR-E caused an average 29% reduction in reach-scale Simpson diversity. While streamflow diversion or impoundment did not correlate strongly to changes in species richness or Simpson diversity at YPG, shifts in community composition were demonstrated by differences in Jaccard dissimilarity. Although riparian communities at YPG and IRWIN did not exhibit consistent responses, significant reductions to the richness, cover, and vigor of species below diversions or impoundments were observed in individual reaches at these installations.

Riparian ecosystems at the easternmost installations (WSMR and BMGR-E) were more altered by flow reductions, while plant communities at IRWIN did not vary significantly with hydrologic impacts. This spatial pattern of greater sensitivity to streamflow reductions corresponds to continental-scale climatic gradients. Mean annual rainfall and the proportion of rainfall during the growing season increases from west to east across the study region. Riparian communities at less arid installations such as WSMR likely support more mesophytic species which are likely to be eliminated when water availability declines due to reductions in streamflow frequency, magnitude, and duration, whereas the xerophytic flora of the western Sonoran Desert and central Mojave Desert may be more resilient to ephemeral stream flow reductions. One complicating factor is that study reaches at YPG and IRWIN were frequently disturbed by vehicle maneuvering and troop movements, and the majority of reaches at IRWIN had been disturbed by tracked armored vehicles. In contrast, the testing and training missions at BMGR-E and WSMR involve primarily aerial vehicles, and ground disturbance is localized. Thus it is difficult to determine whether climatic and biogeographic differences, or changes to soils and vegetation from ground disturbance, underlie the variable responses of riparian plant communities at each installation.

Effects of Streamflow Augmentation at Stream Crossings

Across all installations, riparian communities downstream of crossings with roadway and ditch inflows contained an average of 3 more species than reaches immediately upstream of the crossings. However, this pattern was not apparent at the installation level, probably due to the relatively small number of these crossings in this sample ($n = 36$), and high variability between study reaches. Streamflow augmentation did produce slight downstream increases in Simpson diversity at WSMR, suggesting that enhanced water availability resulted in higher abundances across species within riparian communities, rather than benefitting a small subset of species. Multivariate models also suggested that species richness increased downstream of elevated crossings and berms at WSMR and YPG, but this effect varied with stream channel geometry. Additional roadway inflows at these crossings are the most likely explanation for this result, although this was not apparent during site visits. The generally equitable distribution of water subsidies from roadway inflows among riparian species is supported by a lack of significant changes in ecological dissimilarity measures.

Streamflow additions at crossings did significantly alter downstream channel dimensions. Across all installations, bankfull channel width increased by an average of 86% below crossings with inflows. The largest increases to channel width occurred at YPG (mean 190%), IRWIN (100%), and BMGR-E (44%). Increased channel width is a common response to streamflow increases in channels with erodible boundaries, if no changes to local base level have occurred. Downstream bankfull channel depth approximately doubled when significant roadway inflows were present, largely due to an average 230% increase at IRWIN. The substantial increases to channel depth at IRWIN appear to be a function of the aridity and corresponding low rates of runoff generation at this installation. Stream channels here were generally scarce, and were more often poorly defined and longitudinally discontinuous, compared to those at other installations. Large increases in channel depth but not channel width were likely due to the steep topography and coarse granitic soils that lack fine particles to provide soil cohesion.

Invasive Species at Stream Crossings

Invasive plant species were present in 22% of the sampled stream crossings and were most frequent at BMGR-E. Aside from annual herb *Salsola tragus*, which is ubiquitous in many portions of the Sonoran and Chihuahuan Deserts, the most frequent and abundant invasive plants were the grasses *Schismus barbatus*, *Eragrostis lehmanniana*, and *Pennisetum ciliare*. The remaining species were found in less than 1% of study reaches. An unexpected finding was that widespread species such as *Bromus tectorum* and *Tamarix* were not significant components of the sampled ephemeral stream riparian communities. However, nearly half of the sampled stream crossings at BMGR-E supported *E. lehmanniana* or *S. barbatus*, with the former species comprising up to 70% of reach-scale canopy cover. This finding highlights the need for more extensive invasive species monitoring and management at BMGR-E.

The frequency and abundance of invasive species at stream crossings on the four installations was not strongly related to apparent hydrologic alterations, roadway configuration, or stream channel characteristics. Although changes to native species composition, richness, and diversity were apparent below crossings where flow was diverted or impounded, and to a lesser where flow was augmented, the frequency of invasive species at these crossings did not differ from those lacking significant hydrologic alteration. Model results suggest that *S. barbatus* and *P. ciliare* are more likely to establish at above-grade stream crossings, but other unmeasured landscape factors appeared to be more important. It is noteworthy that half of the incised channels upstream of the surveyed crossings supported *S. barbatus* populations. These incised channels developed where deep ditches or below-grade crossings lowered local base level, causing upstream migration of head cuts that were typically < 50 cm deep. Although channel bed incision upstream of crossings was a rare occurrence in this sample (n = 8), the frequency of *S. barbatus* at these locations suggests that actively degrading ephemeral streams on Southwestern military installations are potential locations for invasive plant establishment. More detailed investigation of invasive species occurrences at stream crossings with hydrologic and geomorphic alterations is needed.

Implications for Sustainable Landscape Management

The reduction of species richness and diversity in ephemeral stream riparian ecosystems affected by streamflow reductions has profound implications for landscape-scale ecological functioning. The increased water availability and episodic disturbance regimes of riparian ecosystems can provide critical habitats for mesophytic species that are rare in arid landscapes. Elimination of these rarer species from stream segments below diversions or impoundments could reduce the viability of local populations and impede the movement of genes and individuals within meta-populations.

Even moderate local impacts to riparian community composition and structure at stream crossings can impose significant cumulative effects across arid landscapes, where channel and road densities are high. These results show that minor increases to species richness at crossings with streamflow augmentation did not offset the declines to species richness, diversity, and composition at crossings where streamflow was reduced. Some of this disparity may be attributed to a net loss of streamflow due to transmission losses as diverted flow is conveyed along ditch and berm networks, but this could not be determined within the study design. Another hypothesis is that the depauperate and extremely xerophytic flora in some regions such as the Mojave Desert does not contain species that can capitalize on ephemeral streamflow subsidies over decadal time scales. Regardless, it is clear that the cumulative effects of localized impacts at stream crossings present significant challenges to the sustainable management of arid landscapes.

Military Mission Benefits

This work helps to improve the sustainability and long-term stewardship of Southwestern installations by clarifying the nature and extent of ecological impacts to ephemeral stream riparian ecosystems caused by roadway infrastructure. Declines in riparian habitat quality, the spread of invasive species, and the listing of additional plant and animal species can be minimized by avoiding unnecessary obstructions to ephemeral streamflow connectivity. Incorporating these results into existing natural resource monitoring and management plans can help resource managers anticipate and potentially avoid riparian ecosystem degradation by identifying stream crossings where ecological impacts are likely to occur. This information also provides a data-driven basis for removing, redesigning, or retrofitting problematic crossings to improve streamflow connectivity. This will result in cost savings in managing and restoring impaired habitats, thereby significantly reducing the resources diverted from testing and training missions.

Incorporating these findings into future road development projects, maintenance and reconstruction of existing stream crossings, and decommissioning abandoned roads will support a broad range of natural resource conservation priorities that are not currently addressed by provisions of Clean Water Act. Minimizing obstructions to ephemeral stream connectivity will help protect the riparian zones which provide valuable habitats for many species, including those protected by the Endangered Species Act (ESA) and Migratory Bird Treaty Act. At least 15 species currently protected under ESA rely on southwestern riparian habitats for part or all of their life histories. Monitoring and addressing actively incising ephemeral stream channels can help minimize likely locations for the establishment of invasive species, helping resource managers to comply with the Executive Order 13751 – Safeguarding the Nation from the Impacts of Invasive Species. This information facilitates strategic planning and sustainable management of natural resources, helping resource managers to execute the requirements of the Sikes Act and the National Environmental Policy Act.

Applicability to Other Military Lands

While climate, topography, soils, and biota vary considerably across military lands, the basic hydrologic mechanisms of streamflow alteration by stream crossings apply in any environmental setting. Obstructions such as berms and above-grade crossings, and preferential flow paths that divert water such as ditches and below-grade crossings, can reduce the frequency, magnitude, and duration of ephemeral streamflow events downstream of roadways. Streamflow is augmented where ditches, berms, and roadways intercept runoff from other areas and discharge it to downstream channels. Channels with erodible boundary materials will enlarge to accommodate additional streamflow inputs but may not reflect streamflow reductions over decadal time scales.

The ecological responses to streamflow alterations vary across biogeographical regions, and these data demonstrate that riparian ecosystem alterations due to flow reduction and augmentation differed among four Southwestern installations. However, the patterns observed at IRIN, YPG, BMGR-E, and WSMR are directly applicable to nearby installations with similar climate, physiography, and biota. At larger scales, water-limited ecosystems in arid and semi-arid landscapes should exhibit similar types of responses after other confounding variables (e.g., disturbance) are accounted for, even if the degree of impacts differ. In this context, the findings of this report are applicable to at least 25 installations throughout the warm desert regions of North America. These include: Barry M. Goldwater Range-East and -West, Camp Pendleton, Cannon AFB, Davis-Monthan AFB, Dyess AFB, Edwards AFB, El Centro Naval Air Field, Fallon NAS, Fort Bliss, Fort Huachuca, Fort Irwin, Goodfellow AFB, Holloman AFB, Kirtland AFB, Laughlin AFB, Luke AFB, March AFB, MCAGCC 29 Palms, MCLB Barstow, NAS Lemoore, Nellis AFB, China Lake NAWS, White Sands Missile Range, Yuma MCAS, and

Yuma Proving Ground. Similar studies at installations in other regions will expand and refine our understanding of riparian ecological responses to streamflow alteration by roadway infrastructure. This work provides a basis for more detailed and focused investigations within each region.

Guidelines for Road Placement and Stream Crossing Design

The results of this study highlight the importance of maintaining longitudinal streamflow connectivity by minimizing the extent of roadway structures that can divert or impound water. In some cases, water control structures that alter streamflow connectivity are clearly required for the protection of roadway infrastructure and maintenance of safe travel routes. Furthermore, changes to the planning, design, and construction of roadways and stream crossings may impose additional costs. However, planners and resource managers can use the information from this study as a basis for finding opportunities to optimize the balance between efficient and safe road networks, and sustainable landscape management.

Where possible, stream crossings should be minimized by siting roadways on higher terrain between channels and along watershed divides to reduce the probability of impacts. These road placements reduce the frequency of streamflow alterations and could significantly reduce maintenance costs at stream crossings on larger channels that require sediment removal and roadway repairs after large flood events.

Where stream crossings are required, on-grade crossings without roadside berms and ditches minimize the likelihood for ecohydrological alterations. On frequently traveled road segments where low-water on-grade crossings are not acceptable, appropriately sized bridges and box culverts that do not cause flow restrictions are the best option. While above-grade crossings and culverts may provide a less expensive alternative, the data show that they commonly result in downstream flow reductions that impact riparian communities. Field observations throughout the Southwest have shown that existing culverts are generally undersized for peak flows in arid regions, and they almost always become plugged with accumulated sediment and debris. Blocked culverts not only reduce streamflow connectivity to downstream ecosystems, but they also increase the likelihood of roadway overtopping and damage to stream crossings during large flow events.

Graded roads are an inexpensive alternative to paved roads for routes with lower traffic loads but are not recommended in arid settings. Repeated grading and travel wear lowers the roadbed surface over time, resulting in below-grade roads that are not passable during wet conditions and can provide preferential flow paths that divert streamflow. Furthermore, the considerable dust load generated from each vehicle pass under dry conditions impair air quality.

Water control structures such as ditches and berms along roadways significantly alter streamflow connectivity, regardless of stream crossing type. The depth of roadside ditches strongly affects the degree of streamflow modification, as it controls the amount of water that is diverted and rerouted between small watersheds. Model coefficients relating ditch depth to streamflow alterations indicate that the effects of ditch depth depend on flow event duration and peak stage. As a result, the effects of ditch depth on changes to downstream channel geometry and riparian communities vary among installations in different hydroclimatic and physiographic settings. Similar relationships were observed for berm height. Therefore, it is difficult to prescribe generalized dimensions for these structures to minimize streamflow alterations. Furthermore, undersized ditches and berms that cannot convey design flows without spilling onto road surfaces present travel hazards. A recommended best practice is to minimize the frequency and extent of these structures where they are not required for infrastructure protection and roadway safety.

At site-specific scales, careful attention should be paid to the elevation of roadway infrastructure relative to the channel bed. Overly deep ditches and below-grade crossings can promote upstream channel incision, which appears to be conducive to the establishment of invasive species such as *Schismus barbatus* (Mediterranean grass). Above-grade crossings that cause persistent ponding upstream of roads create novel habitats in arid landscapes, which may be sites for invasive species establishment.

Rapid Assessment Protocol

The methods employed in this report comprise an assessment protocol designed to obtain unbiased estimates of stream crossing impacts to ephemeral stream riparian ecosystems and provide a framework for monitoring and predicting the effects of a widespread resource management challenge. No special training is needed for visual assessments of altered streamflow connectivity, although the accuracy and utility of visual assessments is strongly dependent on the observer's aptitude and understanding of basic fluvial geomorphology and channel hydraulics. In contrast, quantification of the resulting impacts does require competency in plant identification, the measurement of channel geometry and plant community characteristics, and statistical data analysis.

For settings with climatic, physiographic, and biotic attributes similar to the installations analyzed in this report, knowledge of the type and degree of alterations to streamflow connectivity at existing stream crossings (obtained through visual assessment) or proposed crossings (obtained through review of grading and construction plans) are sufficient to predict the general types of impacts that are likely to occur. For example, a stream crossing that significantly augments streamflow with discharge from roadside ditches and berms is expected to increase downstream channel width and depth, potentially causing slight increases to plant species richness and cover. A stream crossing that completely diverts upstream flow may have no appreciable effect on channel geometry over decadal timescales but is expected to significantly reduce plant species richness and alter community structure.

At installations with different physical environments, biotic communities, and disturbance regimes than those analyzed here (e.g., within the Great Basin), geomorphic and ecological responses to flow alterations may differ considerably. Visual identification of preferential flow paths, flow obstructions, and reduced streamflow connectivity during a brief site visit is sufficient to predict which stream crossings are likely to alter downstream flow regimes, channel geometry, and riparian plant communities, but the nature of those responses will likely vary among installations. In these cases, a quantitative assessment of impacts is recommended.

The study design in which the assessment protocol is executed should depend on the management questions. To understand the frequency and extent of stream crossing impacts within a defined area, a spatially balanced random sample (as described in the methods of this report) is recommended. The sample size may be scaled to match the degree of confidence required or the importance of the resource. If the goal is to understand the effects of a certain type of stream crossing infrastructure, or the impacts to a specific stream type or locality, replicated sampling in the system of interest is advised. An assessment may focus on a single stream crossing of interest, but spurious results from confounding factors are a real possibility without replication. Regardless of the scale of investigation, a simple assessment of the impacts of stream crossing infrastructure on a dryland riparian ecosystem includes:

1. Identify a standard reach length. This study used 15 mean channel widths to a maximum length of 100 m. Longer reach lengths may be desired for larger or more complex channel systems.
2. Define an unimpacted reference reach immediately upstream of the crossing, taking care to avoid any backwater effects or hydraulic alterations from the crossing, and a downstream reach where impacts are to be assessed. Avoid areas with confounding factors such as disturbance from roadway maintenance, physiographic changes (e.g.., transition from confined canyon to unconfined valley), and junctions with tributaries with mean widths greater than half of the main channel.
3. Measure bankfull channel width and depth at five equally spaced cross sections within each reach. Calculate the mean for each parameter in each reach. Identification of bankfull in dryland channels can be difficult and requires knowledge and experience, particularly for entrenched channels such as arroyos.
4. Identify and count individuals of each perennial plant species rooted within the riparian corridors of the reaches. If floodplain width varies significantly between reaches, a standard sampling width from the channel (e.g., 10 m) can ensure uniform sampling effort. On braided channels or those with extensive floodplains, 10 m belt transects (placed on the channel cross sections) oriented perpendicular to flow direction is an efficient approach. Identifying individual plants can be difficult where rhizomatous grasses, flood-trained woody plants, or clonal shrubs occur, and requires

careful attention, knowledge of their growth forms, and expert judgement. A consistent rule set can standardize errors.

5. Visually estimate the relative canopy cover for each species, ideally using the average from multiple experienced observers. In larger reaches than cannot be observed from a single vantage point, walking the reach or occupying higher ground can be helpful. Use of cover classes is recommended for less experienced observers.
6. Additional ecological response variables may be measured or calculated, depending on the management questions. For example, a census of seedlings or size class distributions for a particular species would clarify the effects on recruitment. Many ecological indices for the diversity and dominance of species or functional groups are possible.
7. Calculate the changes to each geomorphic and ecological response variable for the crossing. Changes to channel geometry are most easily understood and interpreted as relative changes, as shown in the methods section. Changes to species richness and diversity are best reported as absolute differences. The ideal expression of differences between reaches depends on the parameters of interest.
8. Statistical analysis of changes depends on the sample design (e.g., a single crossing or many within an area) and the parameter of interest. Competency in univariate and multivariate data analysis is required. The methods section of this report provide a succinct description of the analytical approach.

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Table 1. Distributions of sampled stream crossings at IRWIN, YPG, BMGR-E, and WSMR.

Road Type	Crossing Type	IRWIN	YPG	BMGR-E	WSMR	Total
Paved	**On-grade**	3	8	3	3	**17**
	Below-grade					**0**
	Above-grade	3	7	3	7	**20**
	Culvert	2	6	6	8	**22**
	Bridge			8	2	**10**
Subtotal		**8**	**21**	**20**	**20**	**69**
Graded	**On-grade**	8	14	13	15	**48**
	Below-grade	11		6	2	**19**
	Above-grade	2	3		1	**6**
	Culvert		2	1	4	**7**
	Bridge					**0**
Subtotal		**21**	**19**	**20**	**22**	**82**
Primitive	**On-grade**	18	20	17	18	**75**
	Below-grade	1		3		**4**
	Above-grade					**0**
	Culvert					**0**
	Bridge					**0**
Subtotal		**19**	**20**	**20**	**18**	**77**
Total		**48**	**60**	**60**	**60**	**228**

Table 2. Frequency of hydrologic impacts for stream crossing types at IRWIN, YPG, BMGR-E, and WSMR.

Impact Type	Crossing Type	IRWIN	YPG	BMGR-E	WSMR	Total
None	**On-grade**	26	34	22	28	110
	Below-grade					0
	Above-grade					0
	Culvert	1	1	4	3	9
	Bridge			3	1	4
Subtotal		**27**	**35**	**29**	**32**	**123**
Diversion	**On-grade**	3	6	7	3	19
	Below-grade	9		9	1	19
	Above-grade	3	10	3	4	20
	Culvert		3		1	4
	Bridge					0
Subtotal		**15**	**19**	**19**	**9**	**62**
Inflow	**On-grade**		2	3	5	10
	Below-grade	1			1	2
	Above-grade				1	1
	Culvert	1	3	3	8	15
	Bridge			5	1	6
Subtotal		**2**	**5**	**11**	**16**	**34**
Diversion+Inflow	**On-grade**			1		1
	Below-grade	2				2
	Above-grade	2			3	5
	Culvert		1			1
	Bridge					0
Subtotal		**4**	**1**	**1**	**3**	**9**
Total		**48**	**60**	**60**	**60**	

Table 3. Frequency of roadway structures at stream crossings by hydrologic impact types for IRWIN, YPG, BMGR-E, and WSMR. Xing = crossing only, Ditch = ditch present, Berm = berm present.

		IRWIN			**YPG**			**BMGR-E**			**WSMR**		
Impact	**Crossing Type**	Xing	Ditch	Berm	Xing	Ditch	Berm	Xing	Ditch	Berm	Xing	Ditch	Berm
None	On-grade	23		3	31		3	22			26		2
	Below-grade												
	Above-grade												
	Culvert	1			1			4			2		
	Bridge							3			1		
Diversion	On-grade			3		1	5		6	7		1	3
	Below-grade	2		7				4		5	1		
	Above-grade	1	2		5	3	2		3	1		5	2
	Culvert				2								1
	Bridge												
Inflow	On-grade						2	3			3		2
	Below-grade										1		
	Above-grade										1		
	Culvert	1			1	3		1	2	1	2	7	1
	Bridge			1				2	1	2		1	
Diversion+Inflow	On-grade								1	1			
	Below-grade		1	2									
	Above-grade		1	1								1	
	Culvert					1							
	Bridge												

Table 4. Characteristics of 14 stream crossings monitored at BMGR-E, YPG, and WSMR. Road, berm, and ditch elevations are relative to upstream channel bed elevations. [1]Downstream reach receives drainage from roadway. [2]Anastamosing stream network. X-sec depth = bankfull channel depth at sensor.

Site	Days	Road Elev. (m)	Berm Elev. (m)	Ditch Elev. (m)	X-sec Depth (m)	Drainage Area (ha)	Mean Width (m)	Mean Depth (m)	Mean Slope (m/m)
BM_003	741	2.0	2.0	-0.5	1.20	11,800[2]	2.66	0.56	0.0067
BM_048[1]	741	0.0	0.2	-0.2	0.13	189	3.58	0.12	0.010
BM_024	741	0.8	--	-1.8	0.45	185	3.08	0.52	0.0044
BM_076[1]	585	0.0	0.5	-0.5	0.10	2.45	1.12	0.16	0.067
YP_066[1]	781	0.0	1.0	--	0.40	2,810[2]	7.38	0.20	0.015
YP_067	781	1.0	1.0	--	0.25	526[2]	5.58	0.28	0.0048
YP_064	781	0.5	--	-0.3	0.25	10.7	3.76	0.17	0.0022
YP_079	781	1.5	1.5	--	0.20	6.28	1.58	0.18	0.012
YP_094	781	1.0	--	-0.4	0.15	0.56	1.42	0.10	0.013
WS_095	293	0.4	0.4	-0.3	0.20	5,800[2]	0.78	0.10	0.0067
WS_107	293	0.0	0.8	-0.4	0.11	203[2]	1.96	0.06	0.020
WS_098	293	1.2	--	-0.3	0.15	51.7	1.02	0.09	0.018
WS_118	293	0.5	--	-0.4	0.05	35.5	5.54	0.12	0.037
WS_076	293	1.5	1.0	--	0.20	1.83[2]	5.62	0.34	0.048

Table 5. Streamflow characteristics for 14 stream crossings monitored at BMGR-E, YPG, and WSMR. Number of flow events, cumulative flow duration, and maximum stage observed within the upstream (U/S) and downstream (D/S) reaches at each crossing. [1]Downstream reach receives drainage from roadway. [2]Includes streamflow events when upstream reach was dry.

Site	Days	Flow Events		Cumulative Flow Duration (hr)		Maximum Stage (m)	
		U/S	D/S	U/S	D/S	U/S	D/S
BM_003	741	7	2	18.33	4.67	1.11	0.09
BM_048[1]	741	11	7[2]	43.17	19.83[2]	0.29	0.20[2]
BM_024	741	8	0	8.58	--	0.62	--
BM_076[1]	585	5	10[2]	3.42	15.08[2]	0.23	0.10[2]
YP_066[1]	781	12	14[2]	9.13	19.25[2]	0.15	0.11[2]
YP_067	781	5	2	3.33	1.33	0.27	0.07
YP_064	781	4	4[2]	10.75	12.50[2]	0.22	0.14[2]
YP_079	781	3	4[2]	3.42	1.80[2]	0.15	0.15[2]
YP_094	781	8	4	12.83	2.33	0.07	0.09
WS_095	293	13	2	145.1	4.17	0.24	0.22
WS_107	293	1	2[2]	0.33	0.25[2]	0.6	0.04[2]
WS_098	293	0	0	--	--	--	--
WS_118	293	4	5[2]	1.50	1.75[2]	0.10	0.10[2]
WS_076	293	3	2	0.75	0.33	0.06	0.07

Table 6. Model subsets that minimized Bayesian Information Criterion (BIC) for downstream flow occurrence, peak stage, and duration from 84 streamflow events at YPG, BMGR-E, and WSMR. BIC = Bayesian Information Criterion. berm = berm height, ditch = ditch depth, RB = roadbed height, PEAK = upstream peak stage relative to bankfull depth, DUR = upstream flow duration, W = upstream mean bankfull width, D = upstream mean bankfull depth, S = upstream bed slope.

Downstream Flow	Model Terms	BIC	Adj. R^2	p-value
Frequency	-0.55 + 1.7·ditch + 1.0·PEAK	109.8	0.163	0.0047
Peak Stage	-0.11 – 5.2·DUR + 15·DUR·ditch – 1.2·PKR·ditch	-59.80	0.588	<0.0001
	-0.063 – 6.0·DUR – 1.4·DUR·RB + 20·DUR·ditch – 1.4·PKR·ditch	-58.50	0.600	<0.0001
	0.004 – 6.0·DUR + 17·DUR·ditch – 1.3·PKR·ditch – 0.49·D	-57.71	0.594	<0.0001
Duration	0.0017 + 0.13·ditch – 3.4·DUR·ditch	-110.7	0.766	<0.0001
	-0.023 + 0.14·ditch – 3.3·DUR·ditch + 1.3·S	-108.9	0.770	<0.0001
	0.024 + 0.13·ditch – 3.5·DUR·ditch – 0.0051·W	106.9	0.765	<0.0001

Table 7. Model subsets that minimized Bayesian Information Criterion (BIC) for downstream changes in mean bankfull channel width at BMGR-E, IRWIN, WSMR, and YPG. Upstream channel characteristics: W = width, D = depth, WD = width:depth, S = bed slope, BA = bedrock with alluvium channel, BD = braided channel, PH = piedmont headwater channel. Roadway characteristics: RB = road bed height, berm = berm height, BERM = berm present, ditch = ditch depth, AG = above-grade crossing, BG = below-grade crossing, BR = bridge crossing, CV = culvert crossing.

Base	Model Terms	BIC	Adj. R^2	p-value
BMGR-E	0.32 – 0.54·diverted + 0.42·BG - 0.081·WD + 0.42·WD·berm + 0.25·WD·ditch	-17.76	0.460	<0.0001
	0.35 – 0.20·diverted - 0.082·WD + 0.38·WD·berm	-17.35	0.400	<0.0001
	0.28 – 0.065·WD + 0.97·D·berm	-17.18	0.336	<0.0001
IRWIN	0.041 + 2.1·inflow + 0.50·BD – 2.4·RB + 61·S·RB – 0.12·WD·berm + 0.40·WD·ditch	-16.84	0.541	<0.0001
	0.043 + 2.0·inflow + 0.52·BD – 2.3·RB + 61·S·RB – 0.17·W·berm + 0.40·WD·ditch	-16.74	0.540	<0.0001
	0.006 + 2.0·inflow + 0.46·BD – 2.3·RB + 63·S·RB + 0.33·WD·ditch	-16.69	0.513	<0.0001
WSMR	0.33 + 10·ditch – 0.30·W·RB + 0.56·WD·RB - 1.2·WD·ditch - 230·S·ditch	-5.68	0.340	<0.0001
	0.23 + 0.54·BERM + 10·ditch – 0.31·W·RB + 0.58·WD·RB - 1.2·WD·ditch - 230·S·ditch	-5.51	0.370	<0.0001
	0.26 + 0.43·inflow + 9.6·ditch – 0.30·W·RB + 0.56·WD·RB - 1.2·WD·ditch - 230·S·ditch	-4.24	0.357	<0.0001
YPG	0.24 + 2.9·inflow + 1.7·BERM – 0.17·W·RB + 0.88·W·berm – 2.0·WD·berm	-10.22	0.388	<0.0001
	0.035 + 2.5·inflow + 0.72·PH – 2.4·D·RB	-9.07	0.311	<0.0001
	-0.021 + 2.6·inflow + 0.74·PH – 1.2·CV	-8.83	0.308	<0.0001
All data	-0.042 + 0.71·inflow + 0.32·BERM + 0.36·PH	-14.23	0.134	<0.0001
	0.023 + 0.71·inflow + 0.40·PH	-13.48	0.115	<0.0001
	-0.006 + 0.81·inflow + 0.30·BERM – 0.022·W·RB + 0.32·PH	-11.23	0.140	<0.0001

Table 8. Model subsets that minimized Bayesian Information Criterion (BIC) for downstream changes in mean bankfull channel depth at BMGR-E, IRWIN, WSMR, and YPG. See Table 6 caption for variable explanations.

Base	Model Terms	BIC	Adj. R^2	p-value
BMGR-E	-0.038 - 0.37·BG - 0.47·RB + 0.21·WD·RB - 1.4·W·ditch + 2.7·WD·ditch	-63.90	0.750	<0.0001
	-0.038 - 2.1·ditch - 0.64·D·RB + 0.17·WD·RB - 0.93·W·ditch + 3.2·WD·ditch	-58.43	0.726	<0.0001
	-0.060 - 0.39·diverted - 0.47·RB + 0.21·WD·RB - 1.6·W·ditch + 3.3·WD·ditch	-58.12	0.774	<0.0001
IRWIN	-0.001 – 0.87·diverted + 1.1·BG – 3.1·CV + 3.2·RB + 4.2·berm – 0.92·W·berm	-31.02	0.658	<0.0001
	0.024 – 0.37·diverted + 1.8·inflow + 4.3·DITCH + 1.4·berm - 4.5·W·ditch + 310·S·ditch	-30.81	0.657	<0.0001
	0.31 + 2.1·inflow + 3.4·DITCH – 1.8·D + 11·ditch - 4.3·W·ditch	-30.52	0.635	<0.0001
WSMR	0.41 – 2.1·diverted + 23·berm + 9.6·S·berm – 1.0·W·berm – 31·D·berm – 3.3·WD·berm	-7.138	0.343	<0.0001
	0.27 – 2.0·diverted – 2.7·BG + 26·berm – 1.1·W·berm – 33·D·berm – 3.7·WD·berm	-7.136	0.387	<0.0001
	0.42 – 2.0·diverted + 23·berm – 1.1·W·berm – 30·D·berm – 3.2·WD·berm	-7.058	0.333	<0.0001
YPG	0.054 + 0.90·CV + 0.12·W·RB – 2.8·D·RB – 0.33·W·berm + 0.70·WD·berm	-22.23	0.499	<0.0001
	0.086 + 0.86·CV – 0.31·BERM + 0.12·W·RB – 2.8·D·RB – 0.39·W·berm + 0.91·WD·berm	-21.09	0.514	<0.0001
	0.063 + 0.86·CV + 0.12·W·RB – 2.7·D·RB – 0.33·W·berm + 0.81·WD·berm - 36·S·berm	-20.71	0.511	<0.0001
All data	0.42 + 1.2·inflow – 1.2·D	-17.25	0.126	<0.0001
	0.28 + 1.3·inflow – 0.97·D + 1.6·berm – 4.0·D·berm	-15.73	0.157	<0.0001
	0.239 – 0.43·diverted + 1.1·inflow – 0.99·D + 2.0·berm – 4.6·D·berm	-15.13	0.169	<0.0001

Table 9. Model subsets that minimized Bayesian Information Criterion (BIC) for downstream changes in mean bankfull channel width:depth at BMGR-E, IRWIN, WSMR, and YPG. See Table 6 caption for variable explanations.

Base	Model Terms	BIC	Adj. R^2	p-value
BMGR-E	1.6 - 0.60·PH + 1.8·AG + 0.55·BR - 0.32·WD - 48·S	-25.81	0.528	<0.0001
	1.8 - 0.68·PH + 1.7·AG - 0.337·WD - 50·S	-25.40	0.501	<0.0001
	1.8 -0.69·PH + 1.7·AG + 17·S·RB - 0.35·WD - 55·S	-24.36	0.517	<0.0001
IRWIN	1.1 – 0.21·WD	-3.203	0.187	0.0013
	0.86 + 0.12·W – 0.26·WD	-3.173	0.233	0.0010
	0.59 + 2.4·D – 0.18·WD	-2.514	0.222	0.0013
WSMR	0.64 + 0.58·PH + 0.91·AG – 0.14·WD	-4.448	0.255	0.0002
	0.85 + 0.64·PH + 0.75·AG – 0.24·WD + 0.28·WD·ditch	-3.467	0.280	0.0002
	0.67 + 0.61·PH + 0.73·AG – 0.18·WD + 1.1·ditch	-2.431	0.263	0.0003
YPG	0.30 + 2.6·inflow+ 3.1·RB – 6.9·D·RB – 0.53·WD·RB – 0.96·WD·berm + 250·S·berm	-18.38	0.492	<0.0001
	0.32 + 2.8·inflow + 3.2·RB – 7.5·D·RB – 0.53·WD·RB + 16 ·D·berm – 1.2·WD·berm	-17.75	0.487	<0.0001
	0.29 + 2.8·inflow + 3.1·RB + 3.21·berm – 7.3·D·RB – 0.53·WD·RB – 1.1·WD·berm	-16.92	0.479	<0.0001

Table 10. Model subsets that minimized Bayesian Information Criterion (BIC) for downstream changes in mean bed slope at BMGR-E, IRWIN, WSMR, and YPG. See Table 6 caption for variable explanations.

Base	Model Terms	BIC	Adj. R^2	p-value
BMGR-E	1.5 - 110·S - 0.33·RB	-26.31	0.456	<0.0001
	1.5 - 0.74·BR - 120·S	-24.49	0.439	<0.0001
	1.4 + 0.45·BG - 0.64·BR - 110·S	-24.45	0.467	<0.0001
IRWIN	0.42 + 0.25·BA – 0.49·AG + 0.036·W - 13·S + 0.24·WD·ditch	-17.79	0.524	<0.0001
	0.58 + 0.25·BA – 0.39·AG - 14·S + 0.24·WD·ditch	-16.94	0.487	<0.0001
	0.43 + 0.25·BA – 0.53·AG + 0.036·W - 13·S + 1.43·ditch	-16.69	0.513	<0.0001
WSMR	0.58 - 15·S	0.388	0.107	0.0063
	0.61 – 0.73·BD - 16·S	2.98	0.114	0.0121
	0.49 + 0.19·D - 15·S	-3.58	0.105	0.0160
YPG	1.3 – 0.97·CV – 0.85·D - 67·S + 2.2·berm + 34·S·RB - 200·S·berm	-11.91	0.434	<0.0001
	1.4 – 1.0·CV – 0.95·D - 72·S + 36·S·RB + 6.5·D·berm - 120·S·berm	-11.87	0.434	<0.0001
	1.3 – 1.8·CV – 0.72·D - 71·S + 0.14·WD·RB + 35·S·RB - 130·S·ditch	-11.45	0.430	<0.0001
All data	0.63 – 18·S – 0.61·BR	-20.42	0.141	<0.0001
	0.60 – 19·S – 0.58·BR + 0.32·BG	-20.28	0.157	<0.0001
	0.66 – 18·S – 0.65·BR + 0.29·CV	-19.91	0.156	<0.0001

Table 11. Model subsets that minimized Bayesian Information Criterion (BIC) for Bray-Curtis dissimilarity measure between upstream and downstream reaches at BMGR-E, IRWIN, WSMR, and YPG. See Table 6 caption for variable explanations. Downstream channel characteristics: Wd = width, Dd = depth, WDd = width:depth, Sd = bed slope.

Base	Model Terms	BIC	Adj. R^2	p-value
BMGR-E	0.22 + 8.0·S + 0.24·AG	-1.39	0.176	0.0015
	0.30 + 0.21·AG	-0.64	0.122	0.0036
	0.28 – 0.14·D + 7.7·S + 0.27·AG	-0.38	0.203	0.0013
IRWIN	0.23 + 0.18·BERM + 0.010·Wd + 0.15·W·RB – 5.5·D·RB - 21·S·berm + 0.50·CV	-12.17	0.494	<0.0001
	0.27 + 0.17·BERM + 0.16·W·RB – 5.4·D·RB - 21·S·berm + 0.46·CV	-12.00	0.463	<0.0001
	0.21 + 0.16·BERM + 0.018·W + 0.14·W·RB – 5.7·D·RB - 19·S·berm + 0.55·CV	-11.95	0.492	<0.0001
WSMR	0.28 + 0.42·berm – 0.11·W·berm + 0.13·AG + 0.092·CV	-1.93	0.262	0.0003
	0.37 – 0.022·W + 2.7·S·berm + 0.058·W·ditch	-1.88	0.223	0.0006
	0.30 + 0.42·berm – 0.10·W·berm + 0.10·AG	-1.49	0.218	0.0007
YPG	0.39 + 0.61·ditch – 0.020·WD + 16·S·berm - 1.2·D·ditch	-3.80	0.242	0.0006
	0.27 + 0.53·ditch + 15·S·berm - 0.81·D·ditch + 0.10·PH	-3.75	0.261	0.0003
	0.27 + 0.29·ditch + 15·S·berm + 0.11·PH	-3.51	0.238	0.0004
All data	0.33 – 0.098·D + 0.52·RB + 0.024·dWDd	-2.78	0.089	<0.0001
	0.28 + 0.18·berm - 0.52·W·berm + 0.12·BA + 0.11·AG + 0.078·CV	-1.62	0.120	<0.0001
	0.29 + 0.094·AG + 0.085·CV + 0.022·dWDd	-1.43	0.085	<0.0001

Table 12. Model subsets that minimized Bayesian Information Criterion (BIC) for Jaccard dissimilarity measure between upstream and downstream reaches at BMGR-E, IRWIN, WSMR, and YPG. See Table 6 and 10 captions for variable explanations.

Base	Model Terms	BIC	Adj. R^2	p-value
BMGR-E	0.45 – 0.023·WDd – 0.54·D·berm + 36·S·berm + 0.40·AG	-9.89	0.353	<0.0001
	0.39 –0.53·D·berm + 37·S·berm + 0.30·AG	-9.86	0.320	<0.0001
	0.44 – 0.010·Wd – 0.46·D·berm + 34·S·berm + 0.32·AG	-9.76	0.352	<0.0001
IRWIN	0.38 – 0.11·W·berm + 0.13·BG – 0.053·dWDd	1.84	0.196	0.0055
	0.38 – 0.38·berm + 0.14·BG – 0.53·dWDd	2.50	0.185	0.0073
	0.44 – 0.019·WDd – 2.7·D·berm + 0.13·BG	2.96	0.177	0.0089
WSMR	0.54 – 0.12·D – 0.035·WD + 0.059·WD·berm + 0.076·W·ditch	-20.33	0.457	<0.0001
	0.52 – 0.13·D + 0.091·Dd – 0.036·WD + 0.056·WD·berm + 0.080·WD·ditch	-20.21	0.482	<0.0001
	0.56 – 0.12·D – 0.037·WD + 0.059·WD·berm + 0.077·W·ditch – 0.13·BG	-19.79	0.478	<0.0001
YPG	0.38 + 1.0·D·ditch – 0.10·WD·ditch + 0.13·diverted	-4.81	0.260	0.0002
	0.39 + 0.18·AG	-4.75	0.180	0.0004
	0.37 + 0.27·DITCH + 1.7·D·ditch + 0.13·diverted	-3.22	0.256	0.0002
All data	0.37 + 0.053·RB + 0.096·diverted + 0.020·dDd	-14.28	0.135	<0.0001
	0.37 + 0.040·RB + 0.12·ditch + 0.084·diverted + 0.020·dDd	-14.13	0.147	<0.0001
	0.39 + 0.19·ditch + 0.068·diverted	-13.16	0.101	<0.0001

Table 13. Model subsets that minimized Bayesian Information Criterion (BIC) for differences between upstream and downstream species richness at BMGR-E, IRWIN, WSMR, and YPG. See Table 6 and 10 captions for variable explanations.

Base	Model Terms	BIC	Adj. R^2	p-value
BMGR-E	-2.9 – 4.3·BERM + 0.69·WDd + 480·S·berm + 2.4·PH – 8.9·AG	-9.69	0.383	<0.0001
	-2.6 + 0.61·WDd + 200·S·berm + 2.3·PH – 6.5·AG – 3.2·diverted	-9.52	0.381	<0.0001
	-2.4 + 0.61·WDd + 2.5·PH – 6.2·AG – 2.9·diverted	-9.51	0.321	<0.0001
IRWIN	0.75 – 0.23·Wd + 110·S·RB + 46·D·ditch + 2.0·BA + 3.8·BD – 3.8·AG	-1.28	0.365	0.0003
	0.68 – 0.19·Wd + 110·S·RB + 1.9·BA + 3.1·BD – 2.4·AG	-1.26	0.238	0.0005
	0.74 – 0.23·Wd + 110·S·RB + 1.4·W·ditch + 2.0·BA + 3.7·BD – 3.4·AG	-0.66	0.357	0.0004
WSMR	-1.4 + 4.0·RB - 210·S·berm	-12.78	0.318	<0.0001
	-3.9 + 3.8·RB + 100·Sd + 20·D·berm - 410·S·berm	-12.74	0.383	<0.0001
	-4.0 + 1.0·RB + 110·Sd + 0.28·WD·RB + 23·D·berm - 420·S·berm + 11·D·ditch	-12.36	0.402	<0.0001
YPG	-1.3 + 1.9·W·ditch - 4.0·WD·ditch	-3.41	0.203	0.0006
	-1.2 - 2.1·WD·ditch	-3.24	0.159	0.0009
	-1.3 + 2.9·BERM – 1.8·WD·berm + 1.9·W·ditch - 3.9·WD·ditch	-3.13	0.276	0.0002
All data	-0.59 – 0.84·WD·berm	0.0251	0.025	0.0095
	-0.59 – 2.0·berm	0.0253	0.025	0.0093
	-0.59 – 2.3·AG	0.0307	0.031	0.0046

Table 14. Model subsets that minimized Bayesian Information Criterion (BIC) for differences between upstream and downstream Simpson diversity at BMGR-E, IRWIN, WSMR, and YPG. See Table 6 and 10 captions for variable explanations. No statistically significant models could be fitted for IRWIN.

Base	Model Terms	BIC	Adj. R^2	p-value
BMGR-E	-0.058 - 0.35·ditch + 6.2·S·RB + 0.079·PH	-26.47	0.484	<0.0001
	-0.11 + 0.0087·Wd - 0.34·ditch + 6.1·S·RB + 0.11·PH	-25.33	0.423	<0.0001
	-0.14 + 0.028·WDd + 6.5·S·RB - 0.088·W·ditch + 0.093·PH – 0.24·AG	-25.24	0.524	<0.0001
WSMR	-0.018 + 0.060·W·berm – 0.10·WD·berm	-1.45	0.177	0.0015
	-0.0090 + 0.064·W·berm – 0.11·WD·berm – 0.064·AG	-0.639	0.207	0.0011
	0.031 – 0.019·WD + 0.011·WD·RB + 0.050·W·berm – 0.090·WD·berm + 0.18·BD – 0.067·AG	-0.242	0.312	0.0002
YPG	-0.016 + 0.14·W·ditch - 0.15·WD·ditch – 0.21·BD	-2.08	0.225	0.0006
	-0.007 – 7.5·S·berm + 0.13·W·ditch - 0.15·WD·ditch – 0.17·BD	-1.51	0.256	0.0004
	0.0067 + 0.14·W·ditch - 0.16·WD·ditch – 0.23·BD - 0.048·PH	-1.31	0.254	0.0004
All data	-0.34·ditch – 9.2·S·ditch + 0.074·CV – 0.047·diverted	-23.80	0.186	<0.0001
	-0.24·ditch – 0.084·CV – 0.047·diverted	-23.68	0.170	<0.0001
	-0.25·ditch – 0.083·BR + 0.090·CV – 0.040·diverted	-23.50	0.182	<0.0001

Table 15. Model subsets that minimized Bayesian Information Criterion (BIC) for the occurrence of invasive plant species at BMGR-E, WSMR, and YPG. See Table 6 captions. Only one model with significant coefficients could be fitted for *P. ciliare* and *S. barbatus*.

Species	Model Terms	BIC	p-value
All	-0.53 + 0.79·RB – 0.17·WD – 61·S	375.8	<0.0001
	-0.69 + 0.76·RB + 0.11·W – 0.31·WD – 53·S	376.8	<0.0001
	-0.46 + 0.78·RB – 0.16·WD – 61·S – 1.1·diverted	377.3	<0.0001
P. ciliare	-4.3 + 0.89·RB	104.3	0.012
S. barbatus	0.67 + 0.57·RB + 0.34·W – 1.3·WD – 110·S	242.3	<0.0001

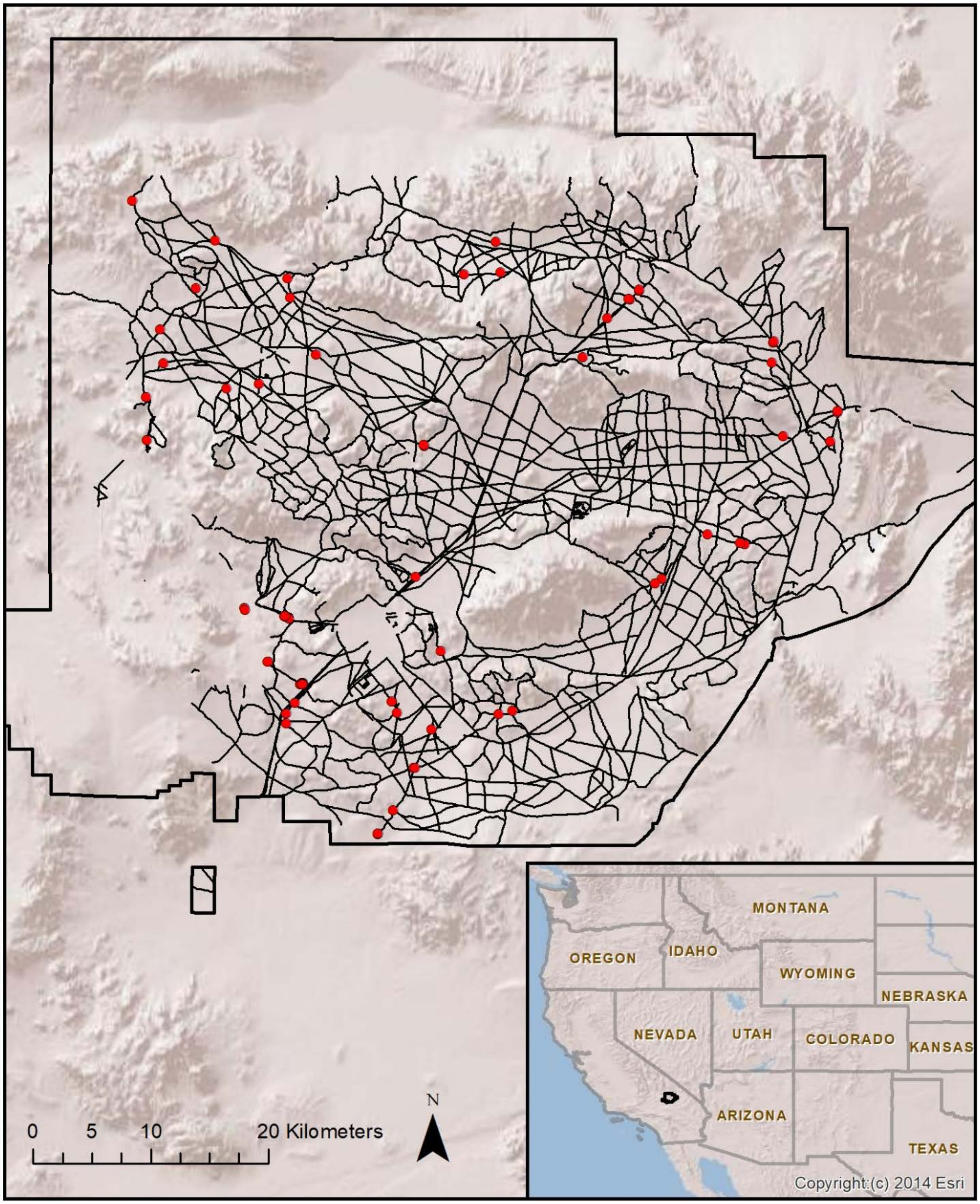

Figure 1. Location of sampled stream crossings (red) at Fort Irwin (IRWIN), California.

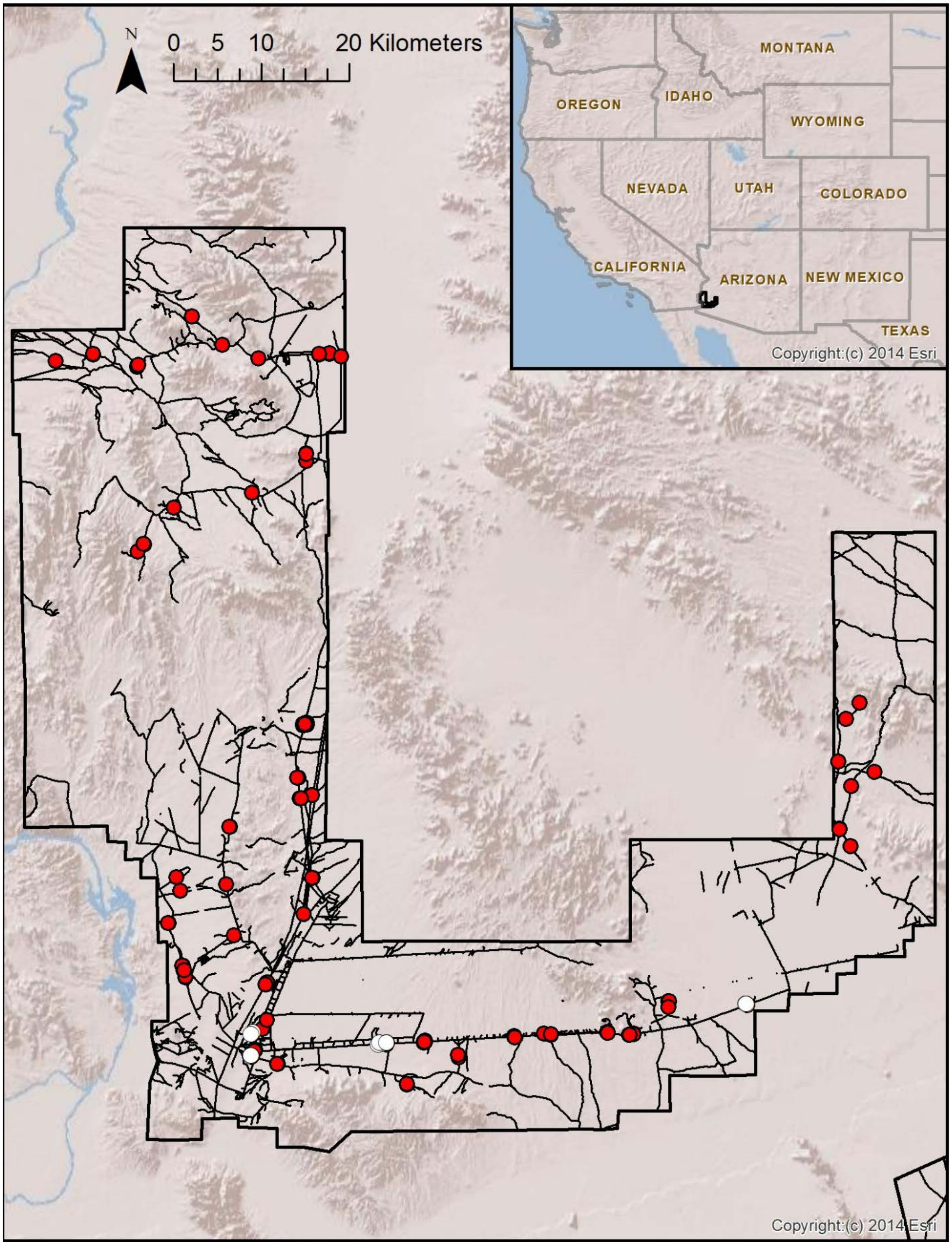

Figure 2. Location of sampled stream crossings (red) and streamflow monitoring sites (white) at Yuma Proving Ground (YPG), Arizona.

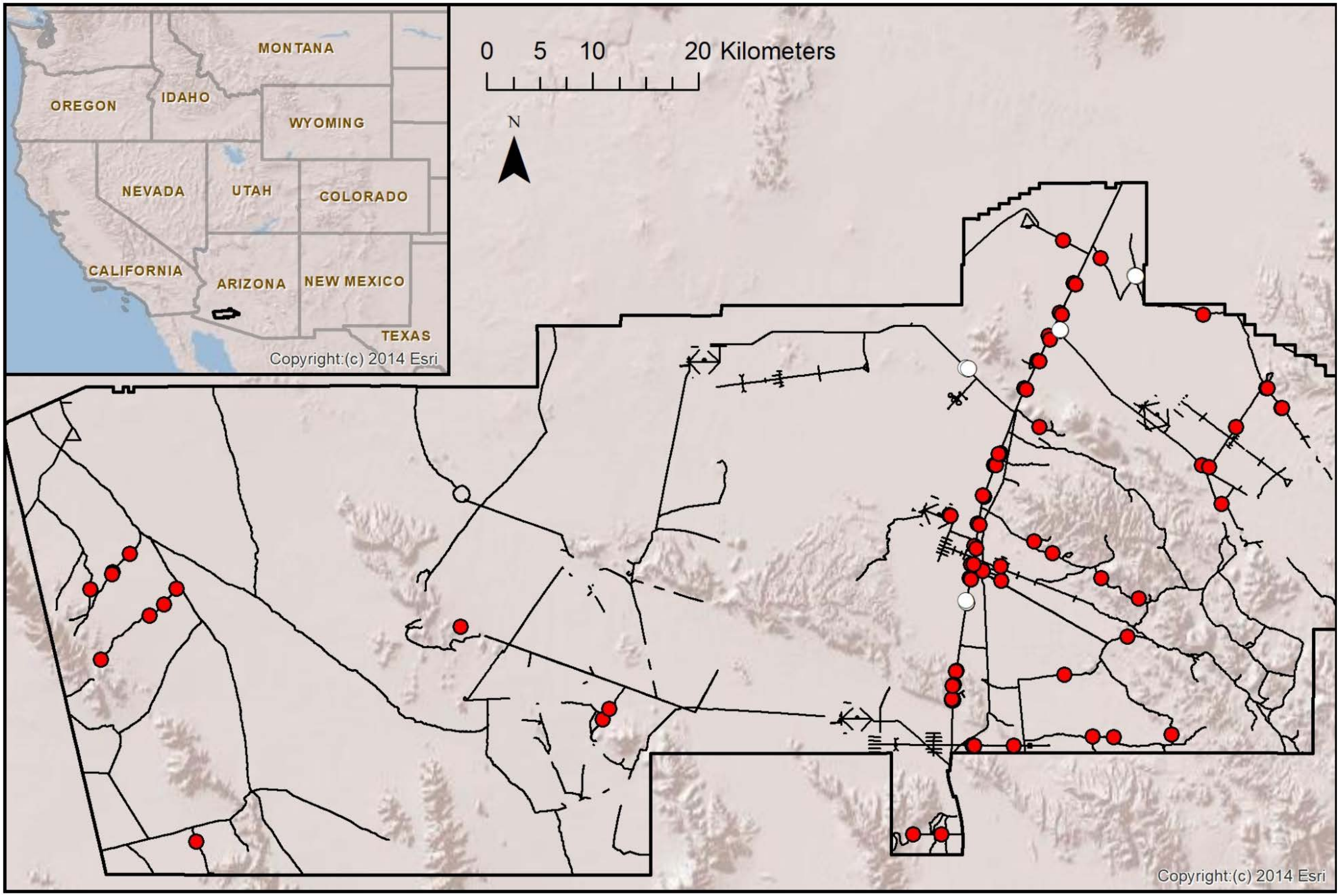

Figure 3. Location of sampled stream crossings (red) and streamflow monitoring sites (white) at Barry M. Goldwater Range-East (BMGR-E), Arizona.

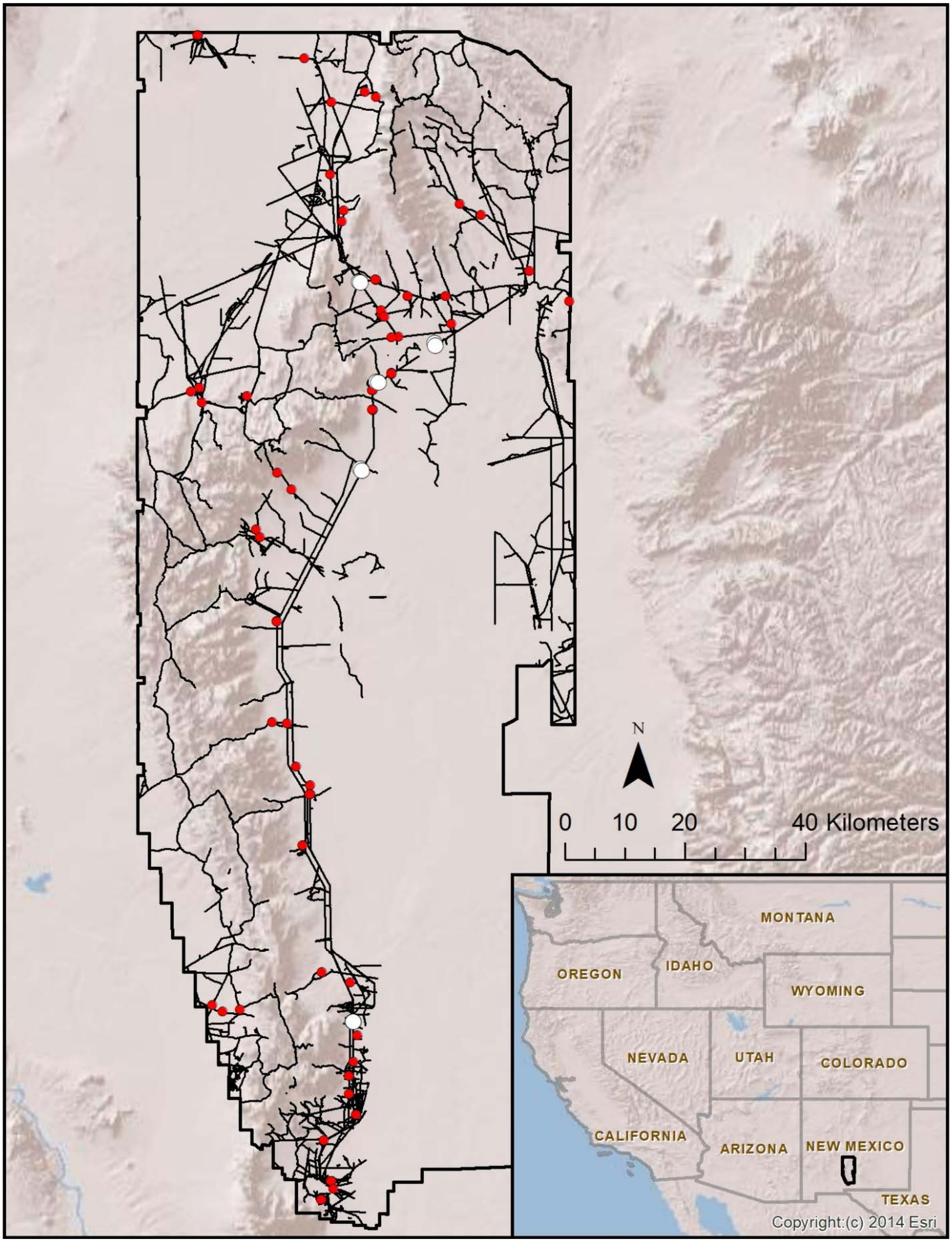

Figure 4. Location of sampled stream crossings (red) and streamflow monitoring sites (white) at White Sands Missile Range (WSMR), New Mexico.

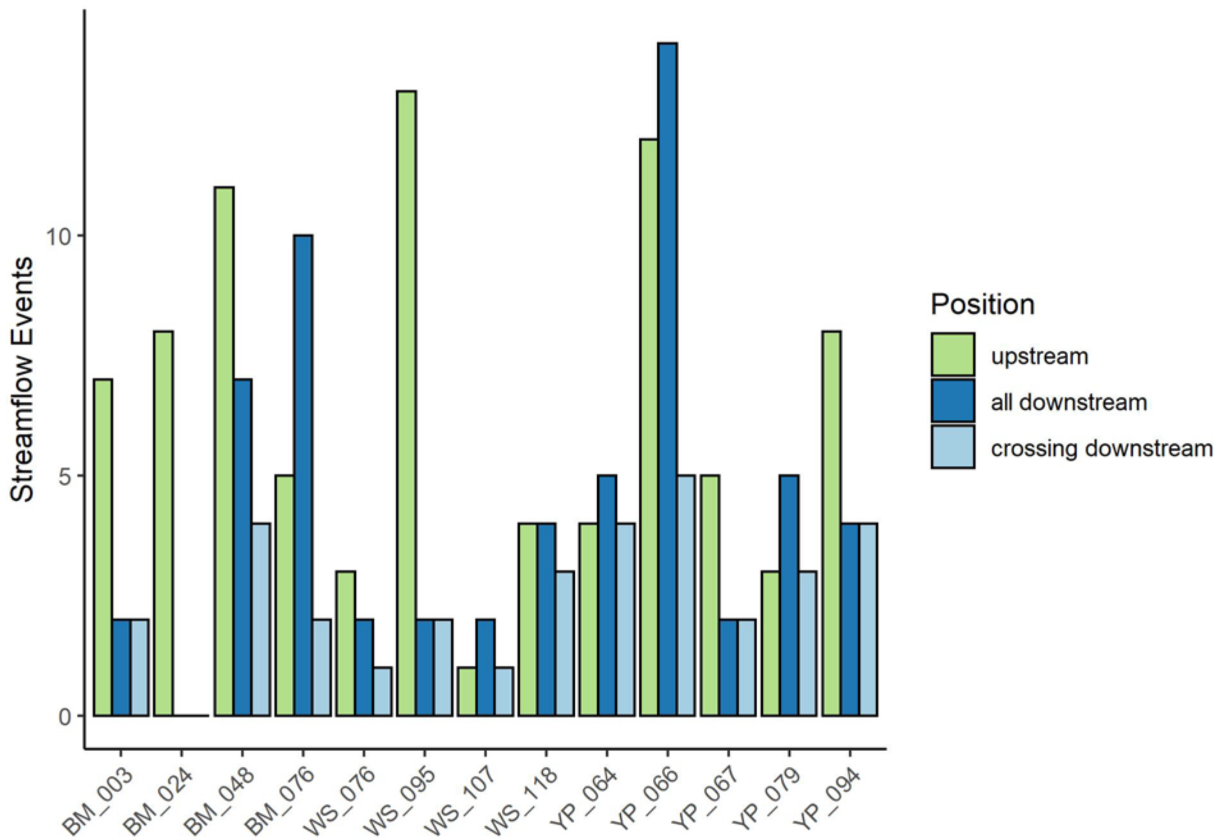

Figure 5. Streamflow frequency in upstream and downstream reaches at 14 stream crossings at BMGR-E, WSMR, and YPG. All downstream events includes events from roadway runoff. Crossing downstream includes only events from upstream reach.

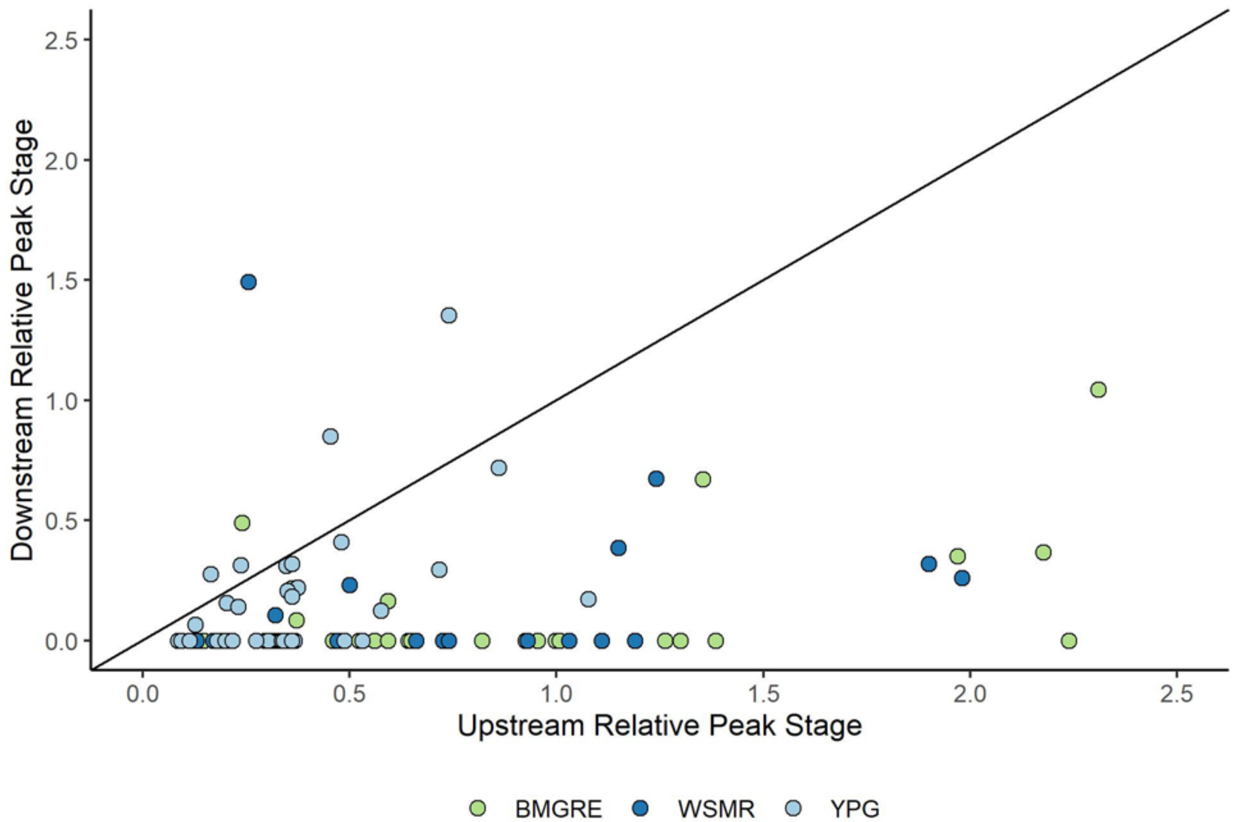

Figure 6. Change in peak stage relative to bankfull channel depth for events in upstream and downstream reaches at 14 crossings at BMGR-E, WSMR, and YPG. Flow event peak stage increased downstream for points above the 1:1 line, and decreased downstream for points below the line.

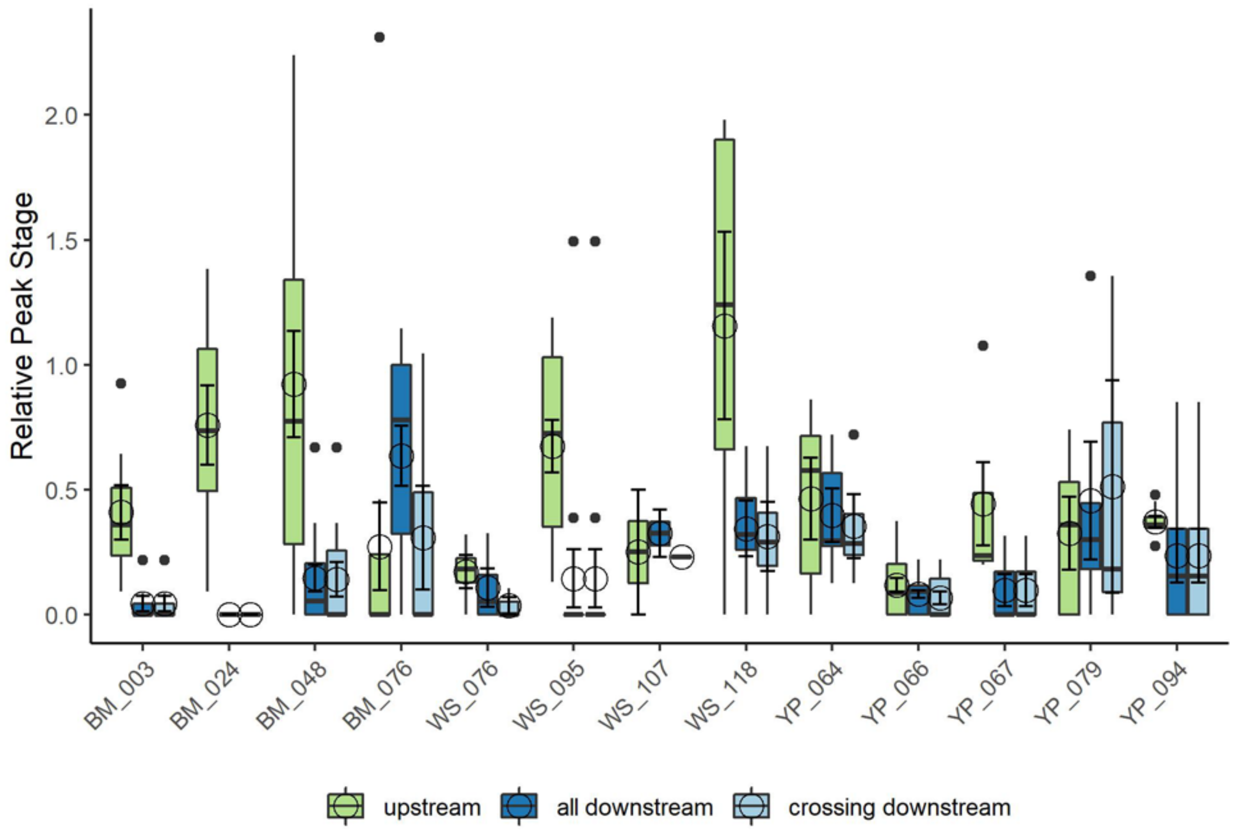

Figure 7. Relative peak stage in upstream and downstream reaches for streamflow events at 14 crossings at BMGR-E, WSMR, and YPG. All downstream events includes events from roadway runoff. Crossing downstream includes only events from upstream reach. Circles with error bars are mean ± SE. Box plot shoulders are 25th and 75th percentile, whiskers are 1.5·interquartile range, and black dots exceed 1.5·interquartile range.

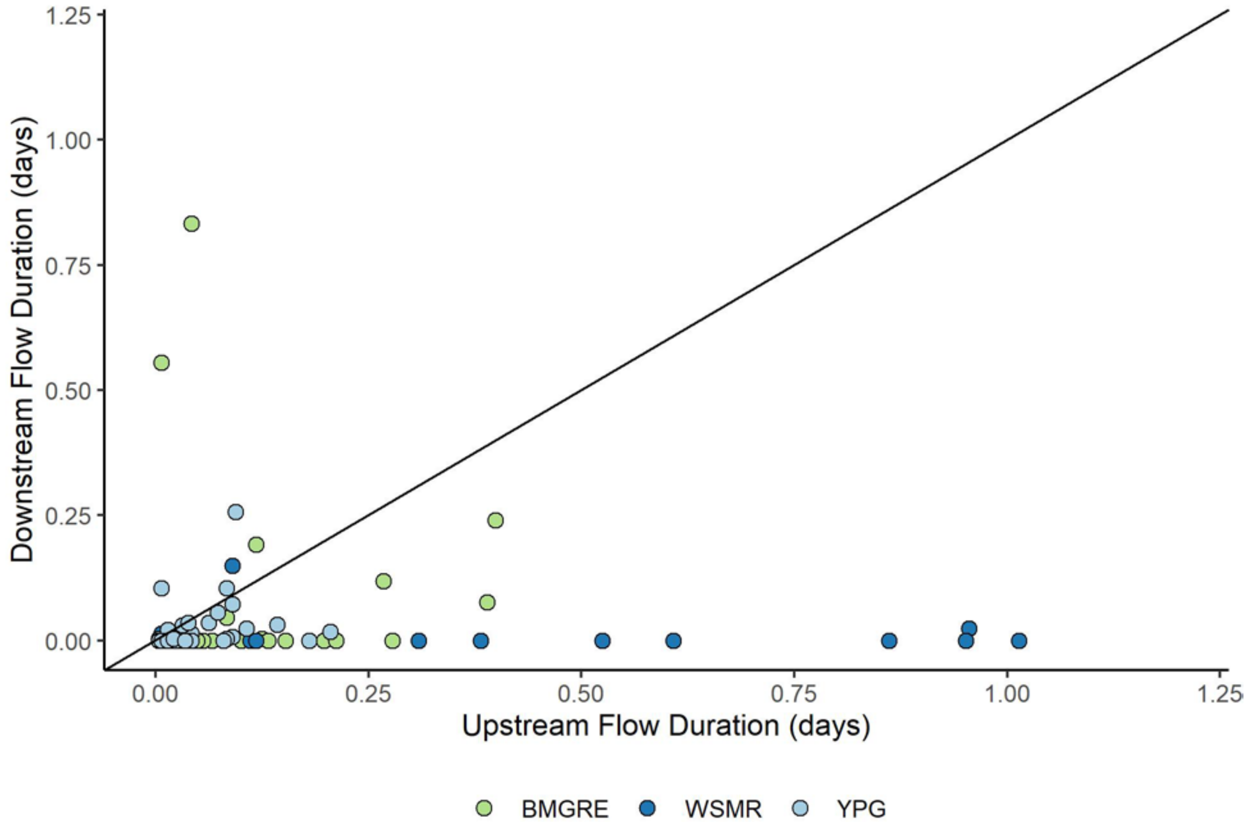

Figure 8. Change in flow duration for events in upstream and downstream reaches at 14 crossings at BMGR-E, WSMR, and YPG. Flow event duration increased downstream for points above the 1:1 line, and decreased downstream for points below the line.

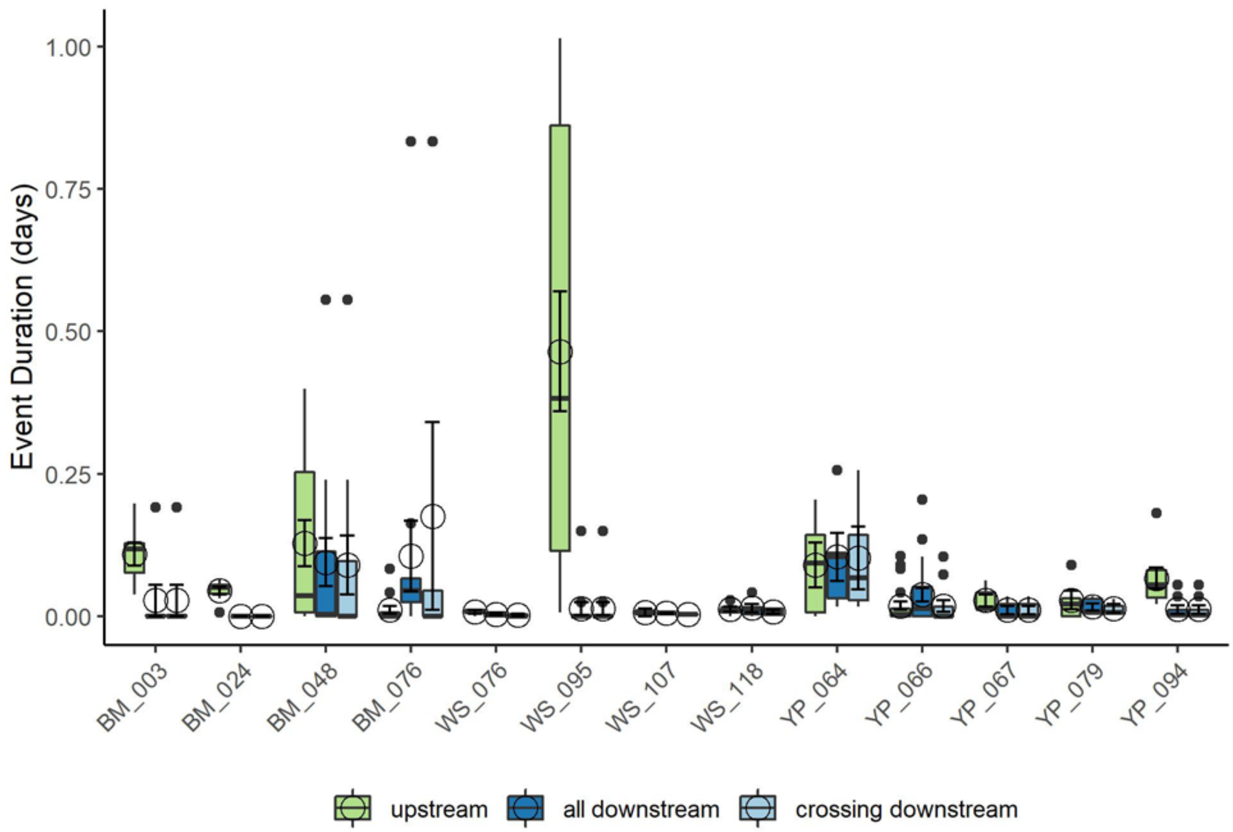

Figure 9. Event duration in upstream and downstream reaches for streamflow events at 14 crossings at BMGR-E, WSMR, and YPG. See Figure 7 caption for description of symbology and box plots.

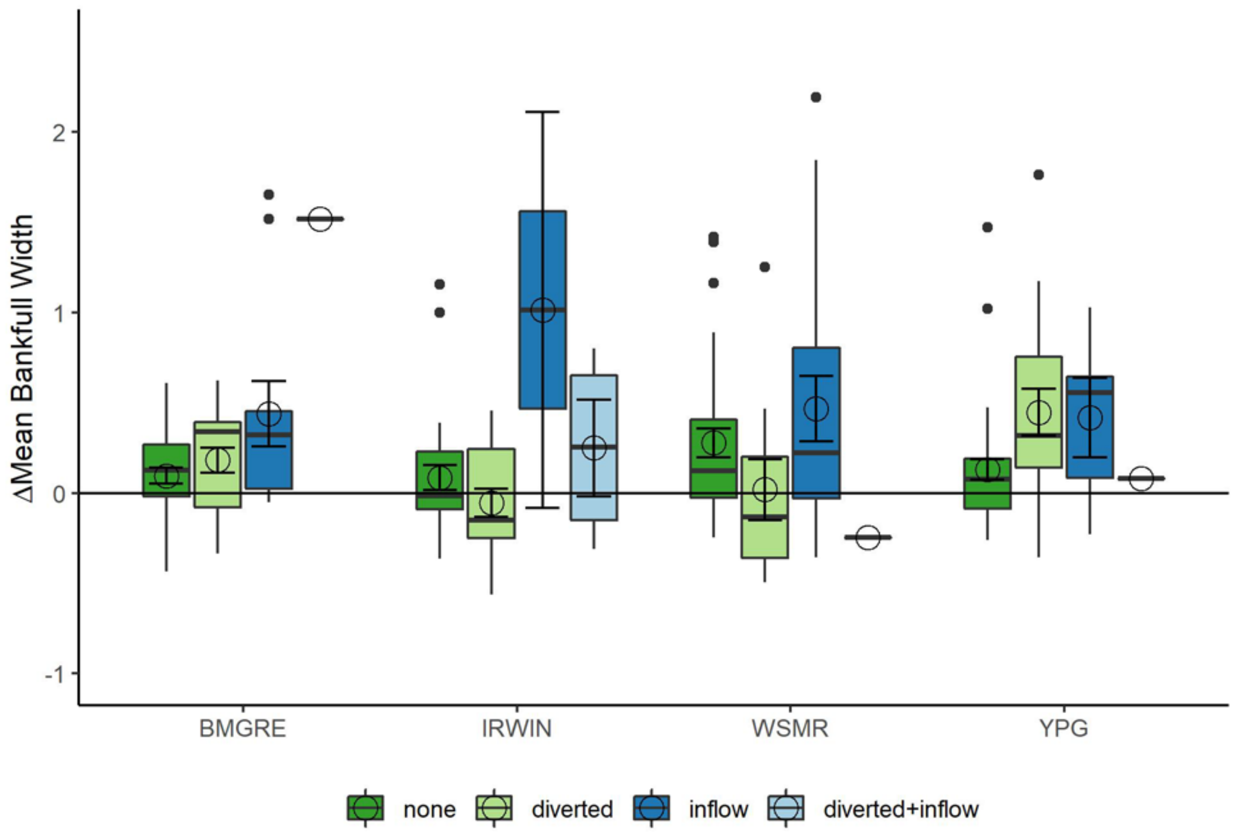

Figure 10. Relative change in mean bankfull channel width between upstream and downstream reaches at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG. Data are grouped by streamflow impacts. See Figure 7 caption for description of symbology and box plots.

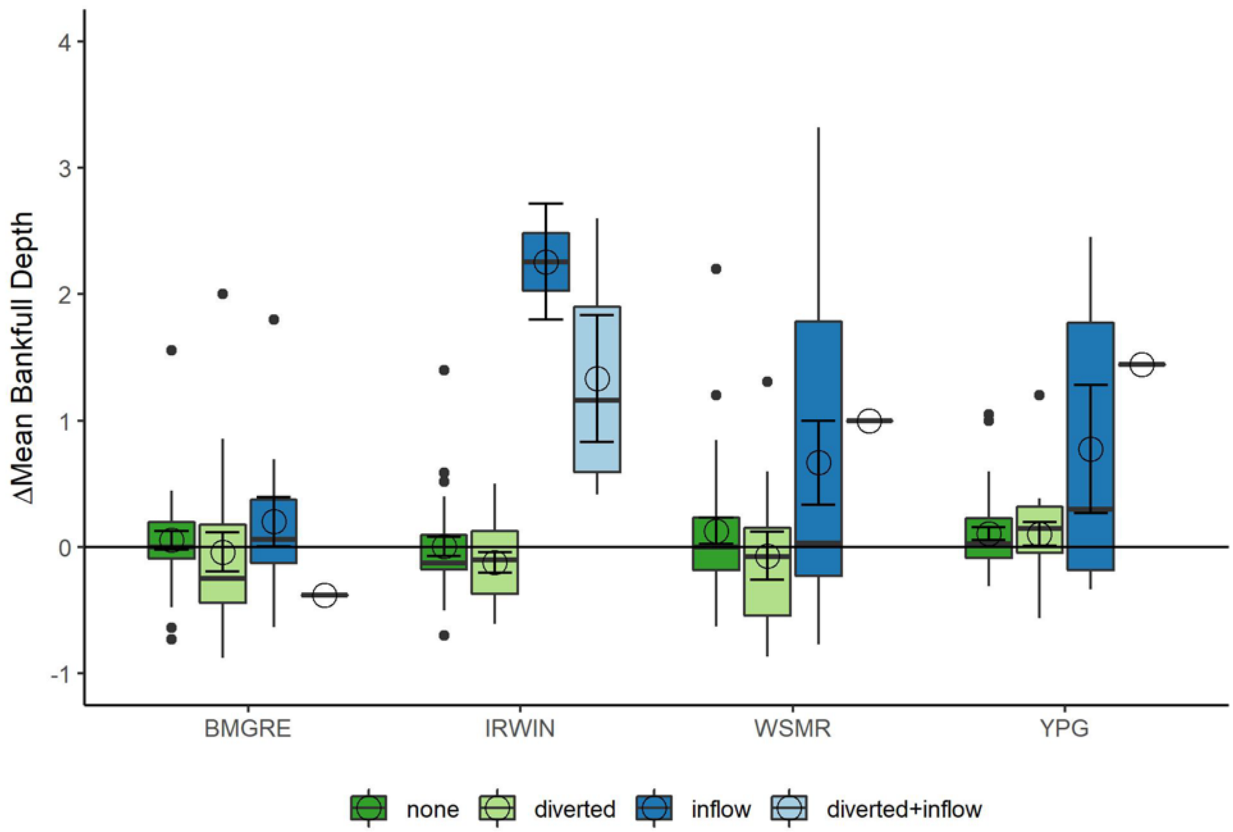

Figure 11. Relative change in mean bankfull channel depth between upstream and downstream reaches at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG. Data are grouped by streamflow impacts. See Figure 7 caption for description of symbology and box plots.

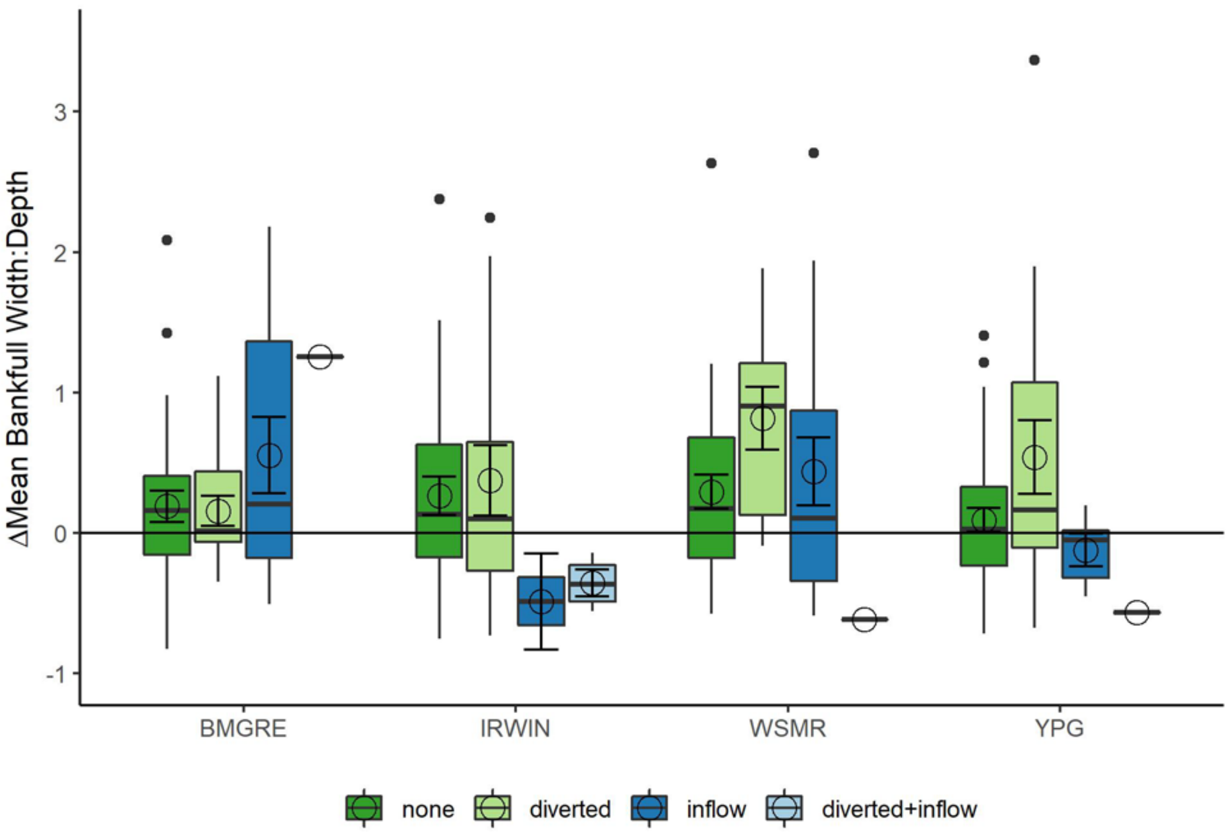

Figure 12. Relative change in mean bankfull channel width:depth between upstream and downstream reaches at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG. Data are grouped by streamflow impacts. See Figure 7 caption for description of symbology and box plots.

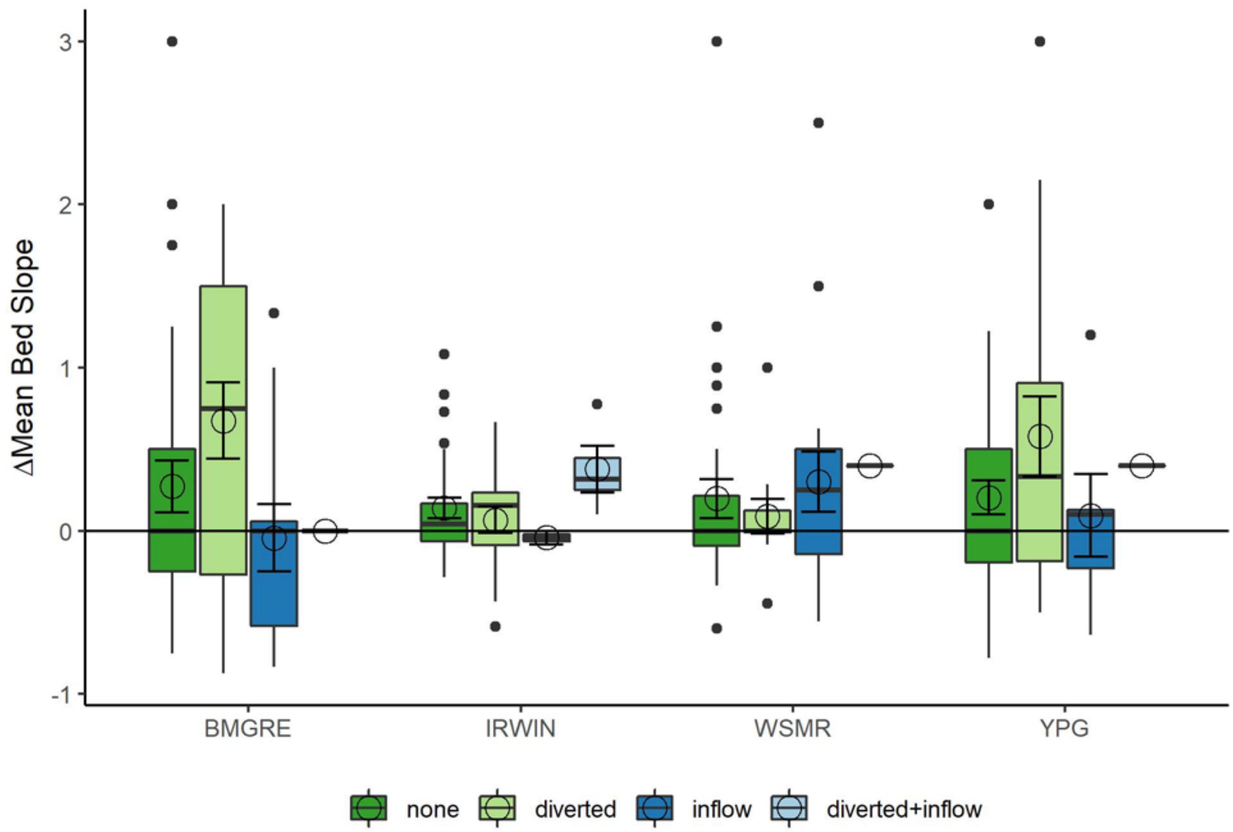

Figure 13. Relative change in bed slope between upstream and downstream reaches at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG. Data are grouped by streamflow impacts. See Figure 7 caption for description of symbology and box plots.

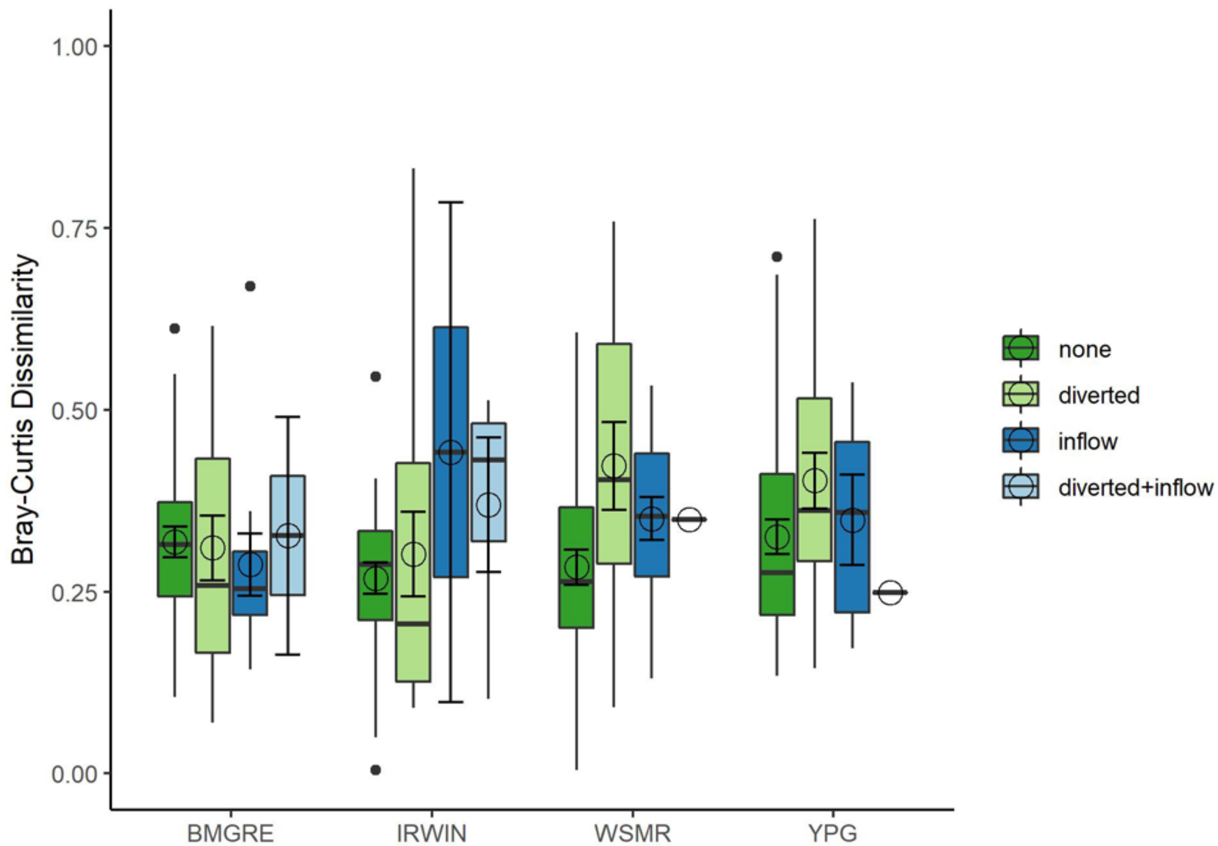

Figure 14. Bray-Curtis dissimilarity between upstream and downstream reaches among hydrologic impact types at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG. See Figure 7 caption for description of symbology and box plots.

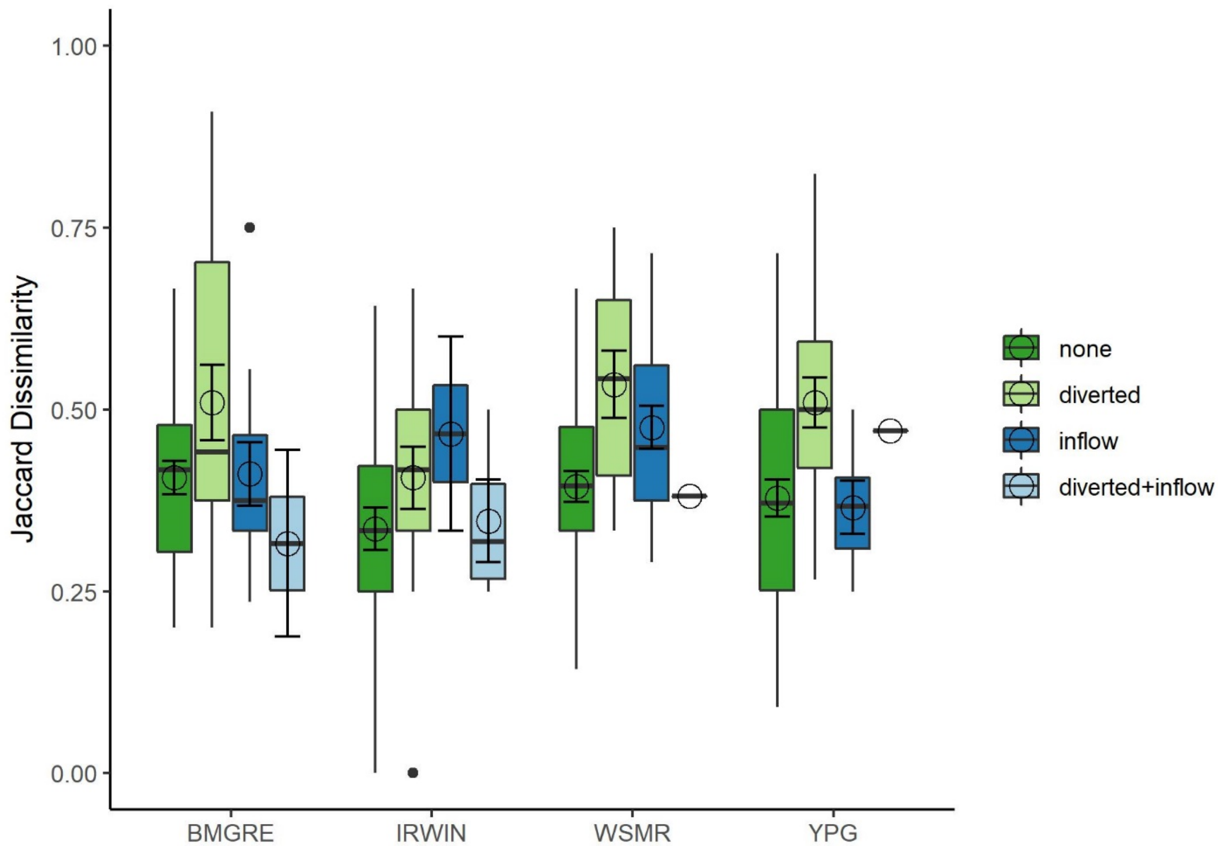

Figure 15. Jaccard dissimilarity between upstream and downstream reaches among hydrologic impact types at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG. See Figure 7 caption for description of symbology and box plots.

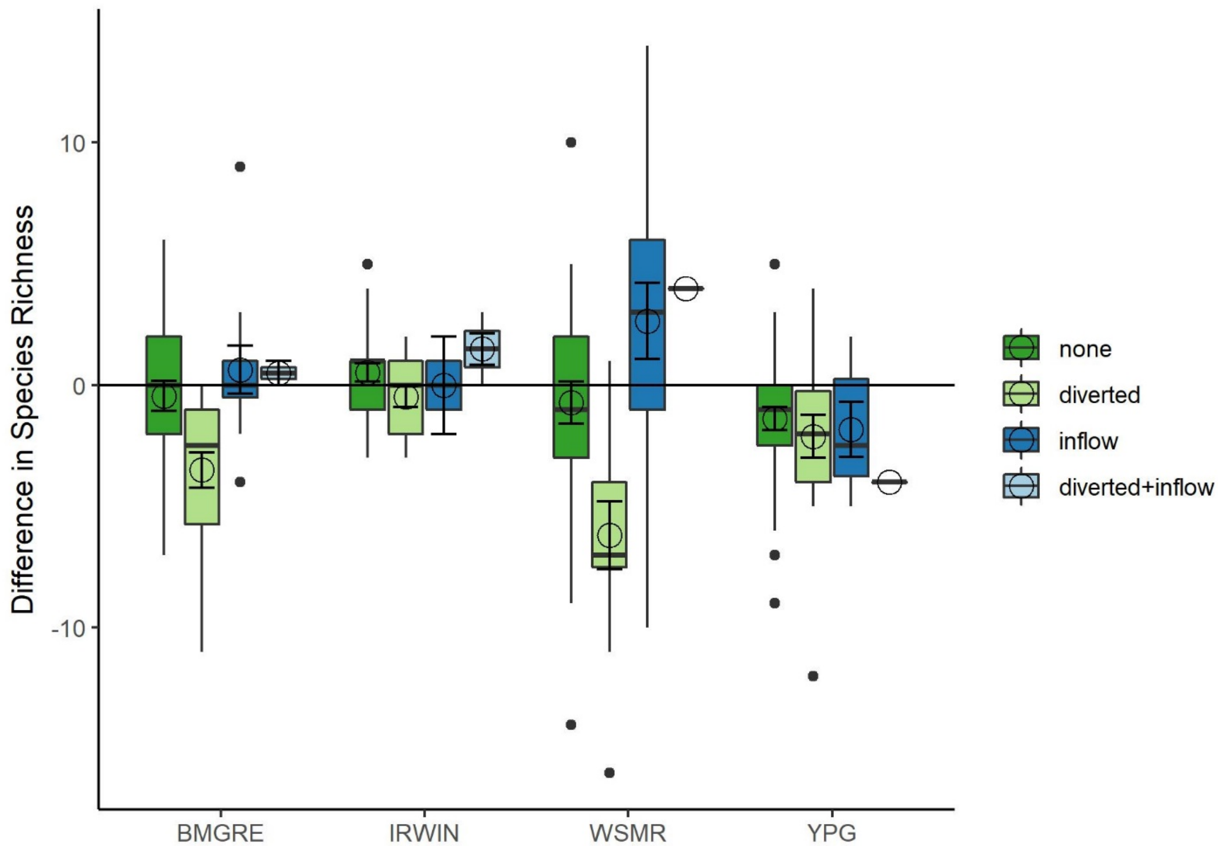

Figure 16. Difference in species richness between upstream and downstream reaches among hydrologic impact types at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG. See Figure 7 caption for description of symbology and box plots.

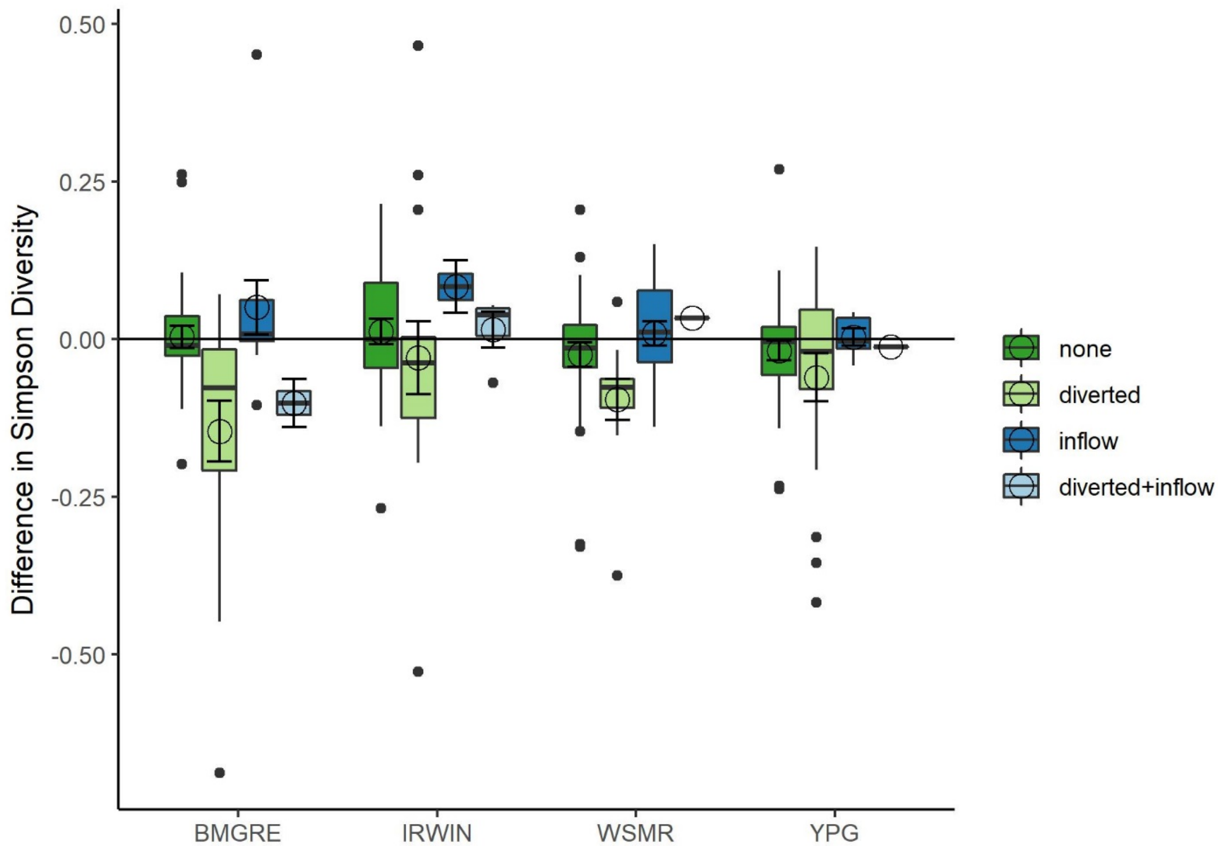

Figure 17. Differences in Simpson diversity between upstream and downstream reaches among hydrologic impact types at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG. See Figure 7 caption for description of symbology and box plots.

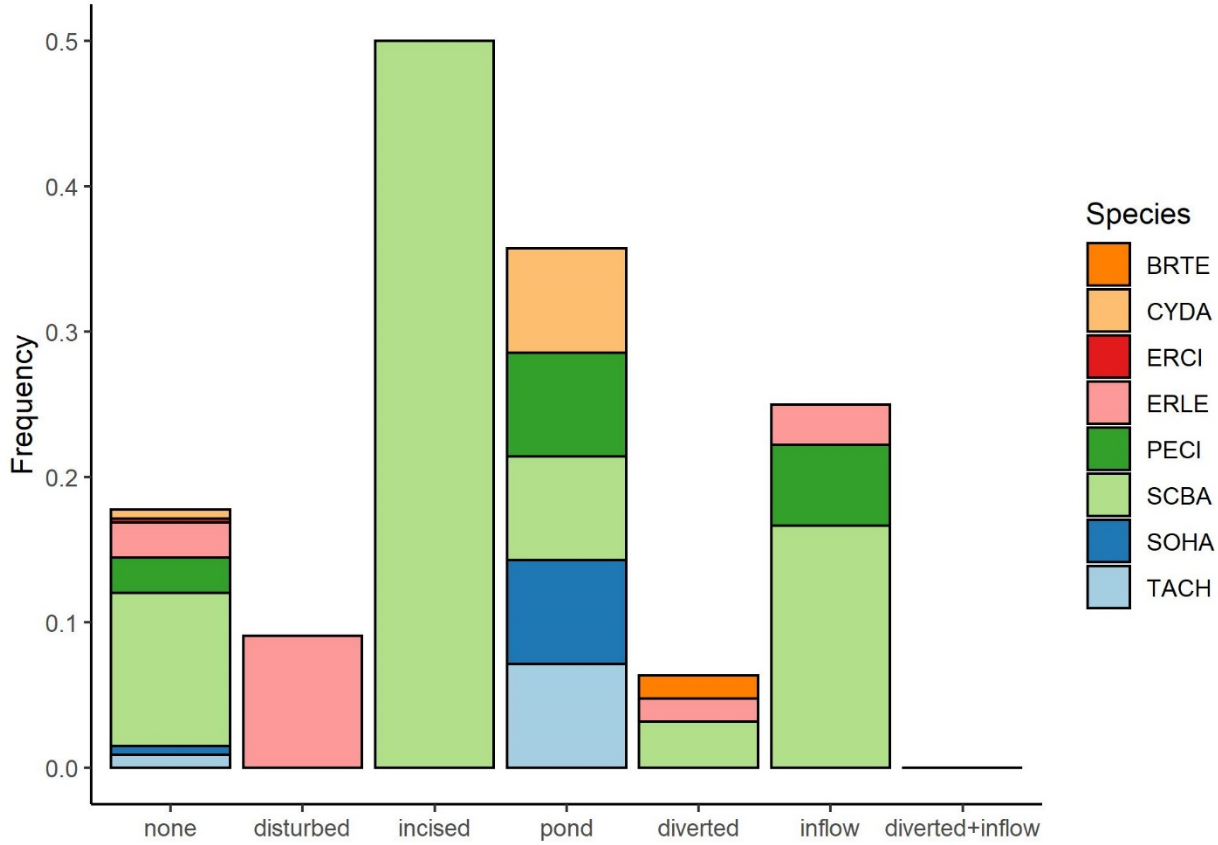

Figure 18. Frequency of invasive plant species among hydrologic impact types at 228 stream crossings at BMGR-E, IRWIN, WSMR, and YPG.