Impacts of Hydroelectric Development on Riparian Vegetation in the Sierra Nevada Region, California, USA

RICHARD R. HARRIS
Department of Forest Science
Oregon State University
Corvallis, Oregon 97331, USA

CARL A. FOX
Research and Development Department
Southern California Edison Company
Rosemead, California 91770, USA

ROLAND RISSER
Department of Engineering Research
Pacific Gas and Electric Company
San Ramon, California 94583, USA

ABSTRACT / Fourteen streams in the Sierra Nevada in the USA were sampled to determine whether diversions of streamflow for hydroelectric development had caused significant changes in riparian vegetation. Several streams showed significant differences in vegetation cover, community composition, or community structure between pairs of diverted and undiverted reaches. On some streams, environmental conditions rather than streamflow diversions may have been responsible for vegetation differences. Streams in the Sierra Nevada respond individualistically to diversions. Prediction of vegetation responses must take into consideration environmental characteristics of specific stream reaches.

There are numerous hydroelectric projects located on small- to moderate-sized headwater streams in the Sierra Nevada range in California in the United States. Many more projects have been proposed throughout California and in the other western states. These projects typically involve the diversion of some or all streamflow from natural channels to a conveyance structure (penstock) and powerhouse. Downstream from the powerhouse, the water is usually returned to the natural channel. There has been a growing concern regarding the effects of diversions on riparian vegetation and associated resource values within the dewatered reaches.

Regulatory agencies involved in licensing new or relicensing existing facilities must require instream flow releases for protection of riparian resources. Although methods exist for evaluating impacts of diversions on fisheries resources (Weshe and Rechard 1980) and setting instream flows, methods do not exist for evaluating diversion effects on streamside vegetation. These impacts are poorly understood and regulatory agencies have little scientific information on which to base their decisions.

Dams and fluctuations of streamflow due to hydroelectric facilities may cause increased or decreased downstream cover (Pelzman 1973, Turner 1974, Turner and Karpiscak 1980, Nagel and Dart 1980), changes in species composition (Turner and Karpiscak 1980), and changes in growth rate or mortality of riparian species (Sackett 1977, Franz and Bazzaz 1977, Reily and Johnson 1982). Most existing studies of vegetation response to altered streamflow have been concerned with the effects of permanent flooding or increased duration of flooding upstream from impoundments. This is not a major issue on mountainous streams where most small-scale hydroelectric development occurs. The principal issues in mountainous regions are the effects of altered high- and low-flow regimes on downstream vegetation.

For the past three years, an interdisciplinary team has been studying the impacts of diversions on riparian vegetation in the Sierra Nevada. The objectives of the research are to determine the effects of diversions, improve impact prediction tools, and provide guidelines for mitigating impacts of hydroelectric development. This work has led to some conclusions about potential responses of vegetation to diversion. This article reports findings to date as a benchmark for use by researchers and managers.

KEY WORDS: Hydroelectric development; Sierra Nevada; Riparian vegetation; Impact assessment

Study Area

The study area consisted of the western and eastern slopes of the Sierra Nevada range in California, USA (Figure 1). We selected nine streams on the western

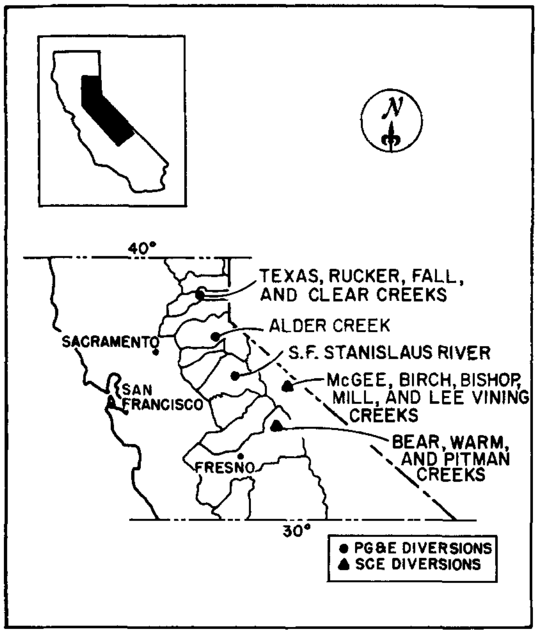

Figure 1. Location of study streams in the Sierra Nevada region.

slope and five streams on the eastern slope for study. Each of these streams has at least one hydroelectric diversion operated either by the Southern California Edison Company or by the Pacific Gas and Electric Company.

The study streams are located at elevations ranging from 1200 to 3000 m above sea level (a.s.l.). They are generally of small to moderate size and located in rugged terrain or on alluvial fans. Geologically, the Sierra Nevada is predominantly granitic, but some of the streams are underlain by metamorphic rocks or glacial till (Bailey 1966). The climate in the western Sierra and at higher elevations in the eastern Sierra is classified as humid mesothermal with snow accounting for 23%–70% of yearly precipitation, depending on altitude (Thornthwaite 1931, Major 1977). Lower elevations in the eastern Sierra are arid. The Sierra Nevada is noted for its recreational attributes, but timber harvesting, grazing, and mining are major land uses. All of the study streams have been diverted for 50 or more years (Fowler 1923). Descriptive detail on the streams is available from Jones and Stokes Associates (1984 and 1985).

Methods

There were no possibilities for conducting pre- and postdiversion effects studies in the region. No quantitative data on prediversion vegetation conditions exist. The possibilities for comparing undiverted streams to diverted streams are also limited; this is due to the extreme variability of conditions and lack of control (Jones and Stokes Associates 1985). We, therefore, chose to use a paired-reach comparison method. We compared reaches above and below existing diversions on each stream to determine whether changes such as those reported in the literature could be discerned. In one instance, we compared an undiverted reach on one stream to a diverted reach on another stream. By using the paired-reach approach, we assumed that vegetation and physiographic conditions were the same in both reaches before diversion. This assumption was statistically tested as part of our research.

Field Sampling Techniques

All streams in the western Sierra and two streams in the eastern Sierra were sampled during summer 1983. The remaining streams in the eastern Sierra were sampled during summer 1984. Our methods for field sampling differed in the two field seasons. In 1983, we collected data on vegetation and physiographic conditions by placing a cluster of 8–10 transects in each reach (upstream and downstream from diversion) on each stream. The first transect location in each reach was as close as practical to the diversion structure. Subsequent transects were positioned systematically at 10- to 20-m intervals perpendicular to the stream channel. Endpoints for transects were placed at the edges of floodplains as determined by topographic, edaphic, and vegetation indicators (Dunne and Leopold 1978, Huffman 1981, Richards 1982). A line-intercept method (Canfield 1941, Mueller-Dombois and Ellenberg 1974) was used to record data along transects. Data were collected on cover percentage by stratum (tree, shrub, herbaceous), species richness, and vegetation structure as well as several physiographic characteristics. In total, 216 transects were sampled during 1983.

We modified our sampling techniques during 1984 when we collected data on the three additional east-slope streams. The principal changes were that we increased the sample size per reach to 20, and we used 3-m-wide belt transects rather than line-intercept. The larger sample size was needed because we sought to examine diversion effects with greater statistical accuracy. Belt transects were used because we wished to collect data on additional variables (tree density and basal area, and species diversity). During 1984, 80 transects were sampled.

Data Analysis Techniques

Data collected during 1983 were analyzed by comparing vegetation cover, shrub height class distributions, species composition, and species richness on each stream above and below diversions. The Mann-Whitney test (Conover 1980) was used for comparisons of cover and species richness, the Kolmogorov-Smirnov two-sample test (Sokal and Rholf 1980) was used to compare height class distributions, and the Jaccard index of community similarity (Mueller-Dombois and Ellenberg 1974) was used to compare community composition.

Further analysis of community composition was performed using two-way indicator species analysis (TWINSPAN; Hill 1979). This technique classifies samples (transects) on the basis of species composition and species' relative cover. The Mann-Whitney test was then applied to determine whether diversion effects were discernible on a vegetation-type basis.

We used more rigorous statistical techniques to analyze 1983 data primarily because we wanted to separate diversion effects from other environmental effects on vegetation. Specifically, the analysis was to (a) verify that the reaches in a pair were truly comparable on a physiographic basis, (b) evaluate differences in vegetation between reaches, and (c) assess whether observed vegetation differences were due to diversion or physiography. The standard *t*-test or Welch's approximation of the *t*-test for unequal variances (Snedecor and Cochran 1980) was applied in two-sample comparisons. Multiple linear regression and path correlation analysis (Kleinbaum and Kupper 1978) were used to detect routes of influence on dependent vegetation variables.

Results and Discussion

Results from analysis of 1983 data are presented and discussed below. The analysis of 1984 data is presented and discussed in a separate section entitled *Factors affecting response to diversion.*

Vegetation Cover

Cover data for streams sampled in 1983 are presented in Table 1. Five of the streams showed decreased cover in one or more strata downstream from diversions ($p \leq 0.05$). Two streams showed increased cover downstream in one stratum ($p \leq 0.05$). The remaining four streams showed no significant differences in cover (Table 1). Increased cover was interpreted as an upgrowth of plants or enlargement of the riparian zone due to reduced scouring by high flows. Decreased cover was interpreted as a thinning of foliage or mortality due to moisture stress.

Species Richness and Composition

Species richness, measured as number of species encountered per transect, was not significantly different between reaches on any of the streams. Species richness was correlated with floodplain width and herbaceous cover (Spearman rank correlation test; $p \leq 0.05$). These findings suggest a species–area effect and that richness is driven by the herb stratum. The latter has been reported for other California riparian communities (Harris 1985).

Species composition differences were analyzed using the Jaccard index (Table 2). Compositional differences between reaches tended to be most pronounced in the herb stratum, especially on those streams where herb cover represented a minor proportion of overall cover. There appeared to be possible shifts in species composition due to diversion. On one stream (Rucker Creek), obligate riparian shrubs were absent on 70% of downstream transects. On two other streams (Texas and Alder Creeks), there was reduced frequency of one or more obligate riparian shrubs in the downstream reach. On Alder Creek, there also was a shift in dominance from *Cornus sessilis*, an obligate riparian shrub, to *Acer macrophyllum*, a tree that occurs in upland locations as well as riparian zones. Finally, on McGee Creek, riparian tree and herb species were apparently replaced by tree, shrub, and grass species with more xeric affinities on the downstream reach.

Vegetation Structure

We compared layering (cover percentage by stratum) and height class distributions of shrubs above and below diversions on the nine west-slope streams (Figure 2). There were significant differences in layering on all streams that had significant differences in cover (Figure 2).

Frequency distributions for all shrubs, by height class, are shown for west-slope streams in Figure 3. The Kolmogorov-Smirnov two-sample test showed that distributions were dissimilar on five streams ($p \leq 0.05$). Rucker and Fall Creeks had fewer shrubs in the smallest height class (<1 m) below diversion. Texas and Alder Creeks had more shrubs in the smallest height class below diversion. Alder and Warm Creeks had fewer tall shrubs (>3 m) in the downstream reaches.

Structural responses to diversion could include reduction in frequency of small shrubs (representing vegetative reproduction or seedlings) due to reduced availability of water for seedling or sprout establishment, or increased frequency of small shrubs due to

Table 1. Vegetation cover data for sampled streams.

Stream/reach	n	Mean percent cover: Tree	Shrubs	Herb	Differences in downstream cover
Rucker					
Upstream	10	46	46	9	Decreased shrub and herbaceous cover
Downstream	8	28	9*	2*	
Clear					
Upstream	10	34	57	32	None
Downstream	10	8	78	27	
Fall					
Upstream	10	29	30	12	Increased shrub cover
Downstream	10	7	71*	8	
Texas					
Upstream	9	2	89	9	Decreased shrub cover
Downstream	9	2	9*	7	
Alder					
Upstream	10	50	33	0	Increased herbaceous cover
Downstream	10	65	13	3*	
South Fork Stanislaus					
Upstream	10	37	16	3	Decreased tree cover
Downstream	10	11*	26	3	
Warm					
Upstream	10	9	77	14	None
Downstream	10	8	76	25	
Bear					
Upstream	10	39	26	1	None
Downstream	10	19	40	0	
Pitman					
Upstream	10	9	16	2	None
Downstream	10	8	10	1	
Lee Vining					
Upstream	10	0	47	23	Decreased shrub cover
Downstream	10	0	25*	28	
McGee					
Upstream	10	11	60	66	Decreased herbaceous cover
Downstream	10	11	50	10*	

* Indicates significant difference at $p \leq 0.05$.

dampening of damaging floodflows. Decreased frequency of taller shrubs downstream from diversions was interpreted as a response to diversion-induced moisture stress (mortality or growth suppression).

Responses by Riparian Community Types

We used TWINSPAN to classify the 176 west-slope samples into five floristic riparian community types. The analysis showed that the vegetation was sufficiently heterogeneous that adjacent transects in the same reach were classified into different floristic types. We then grouped transects from diverted reaches by floristic type and compared them to similarly classified transects from undiverted reaches. Comparisons were made for tree, shrub, and herbaceous cover (Table 3). Four of the types showed significant differences in cover downstream from diversion. *Alnus rhombifolia* and Boreal riparian scrub types showed greater downstream herbaceous cover; the *Alnus tenuifolia* type showed decreased downstream tree cover; and *Cornus stolinifera–Salix lasiolepis* type showed decreased downstream shrub cover ($p \leq 0.05$ for all). In another study (Harris and others 1985), we showed that *Cornus stolinifera* and *Salix lasiolepis* both tend to be located near the stream channel. This suggests that a possible mode of response to diversion in this type is thinning or loss of near-stream plants rather than narrowing of the riparian zone, as suggested by Taylor (1982).

Factors Affecting Response to Diversions

The variety of observed potential responses to diversion and concurrent research on relationships be-

Table 2. Jaccard index values for sampled streams.

Stream	Jaccard index for compared reaches[a]		
	Tree	Shrub	Herbaceous
Rucker	33	33	7
Clear	67	15	43
Fall	20	10	32
Texas	0	50	18
Alder	43	43	0
South Fork Stanislaus	17	40	13
Warm	33	50	32
Bear	100	22	0
Pitman	100	45	6
Lee Vining	N/A	50	32
McGee	37	67	25

[a] J_t = 0 means that composition is totally dissimilar. J_t = 100 means composition is identical. Values indicate percentage of species in common between reaches.

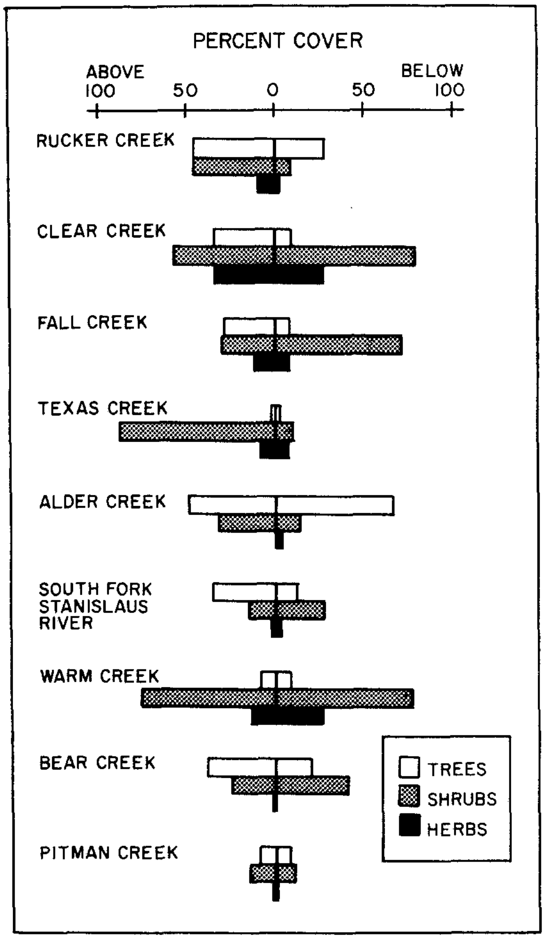

Figure 2. Lifeform layering diagrams for sampled streams in the western Sierra Nevada.

tween riparian community characteristics and stream environmental characteristics (Harris and others in preparation) led us to further statistical analysis of environmental factors affecting response. Several variables besides streamflow can have a controlling influence on the distribution and abundance of riparian vegetation on headwater streams. These include factors potentially affected by diversion (channel width and depth) as well as some that are unaffected by diversion (elevation, floodplain gradient, stream incision, and floodplain width) (Harris and others, in preparation). To evaluate the role of these variables, we used a technique known as path analysis. Path analysis uses multiple correlation coefficients (between a dependent variable and several independent variables) and partial correlation coefficients (between two variables after controlling for effects of other variables) to uncover spurious relationships among variables and identify intervening variables (Kleinbaum and Kupper 1978). The technique was applied to two comparisons on the east slope of the Sierra Nevada: an undiverted reach on Lee Vining Creek and a diverted reach on Mill Creek and South Fork Bishop Creek above and below its diversion.

Lee Vining Creek and Mill Creek differed significantly in five of six physiographic variables and in four of eight vegetation variables. Mill Creek was higher in elevation ($p = 0.007$) and had a steeper gradient ($p = 0.002$). Channel width, wetted perimeter, and floodplain width were greater on undiverted Lee Vining Creek ($p < 0.0001$ and $p = 0.02$, respectively). Canopy cover <3 m tall was greater on Mill Creek ($p = 0.006$) and canopy cover >9 m tall was greater on Lee Vining Creek ($p = 0.02$). Lee Vining Creek also had a larger vegetated channel width ($p = 0.05$) and riparian zone width ($p = 0.03$).

The potentially confounding influences of environmental differences were evaluated for all significantly different vegetation variables. For canopy cover <3 m tall, the total direct and indirect influence of diversion was significant ($p = 0.03$). About 70% of the difference between the reaches was statistically due to diversion. Environmental differences had minor influences. This indicates that recruitment on Mill Creek may have been enhanced by diversion-induced dampening of damaging flooding. The influence of diversion on canopy cover >9 m was marginally not significant ($p = 0.08$). The indirect influence of wetted perimeter as an intervening variable was opposite to the direct influence of diversion, reducing total net influence. Vegetated channel width was negatively correlated with diversion status and the direct and indirect influence of diversion was significant ($p < 0.005$). Diversion ef-

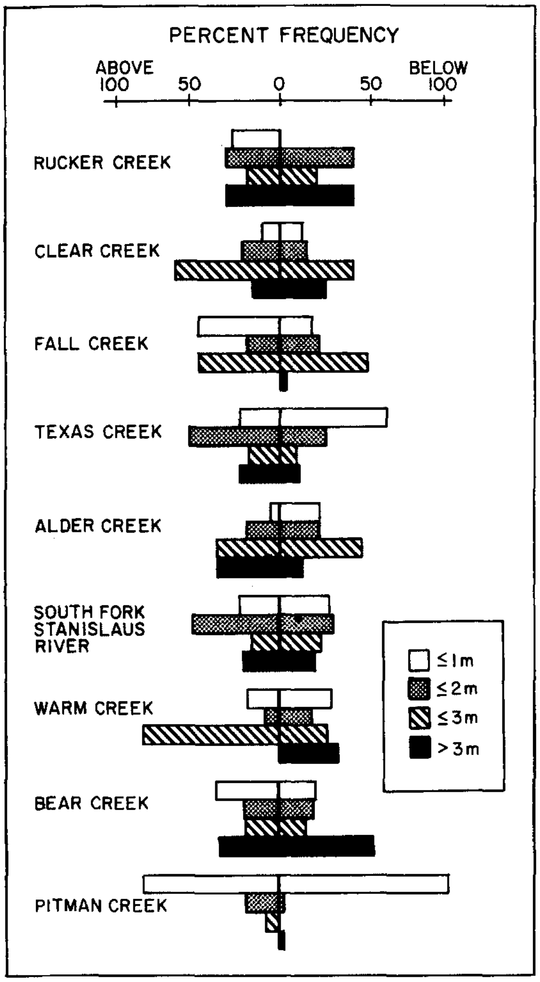

Figure 3. Height class distributions of shrubs on sampled streams in the western Sierra Nevada.

fects were routed through channel width as an intervening variable. Thus, diversion changes channel width, which then influences vegetated channel width. The influence of diversion on riparian zone width was not significant. Floodplain width, an independent variable unaffected by diversion, confounded diversion effects. In summary, the only impacts attributed to diversion were increased shrub cover and decreased vegetated channel width.

Analysis of South Fork Bishop Creek showed that the two reaches differed in five physiographic characteristics and four vegetation variables. The undiverted reach was at higher elevation and had a steeper gradient, wider channel, and larger wetted perimeter ($p < 0.0001$ for all). The diverted reach had a wider floodplain ($p = 0.0005$). Canopy cover 3–9 m tall was greater on the undiverted reach ($p = 0.02$) and canopy cover >9 m tall was greater on the diverted reach ($p > 0.0001$). Riparian zone width and species richness were both significantly greater on the diverted reach ($p = 0.0002$ and 0.003, respectively), the latter presumably a consequence of the species–area effect. Diversion effects were not significant for any of the vegetation variables. Elevation, gradient, and floodplain width all acted as confounding variables.

These results point out several important conclusions regarding vegetation response to diversions as measured by paired-reach comparison experiments. First, factors other than streamflow may have an overriding influence on riparian community characteristics. The relative importance of diversion as an impact is consequently difficult to discern. Second, these headwater streams are extremely variable in environmental characteristics. Even adjacent reaches may have different environments and associated vegetation. This variability impairs the possibility of generalization about vegetation responses. Finally, some community characteristics may not be affected by diversion. For example, riparian zone width was not significantly affected by diversion; it is controlled by the width of the floodplain, which represents available habitat for establishment of riparian plants. Harris and others (in preparation) showed that riparian zone width was almost totally explained by floodplain width on diverted ($r^2 = 0.97$) and undiverted ($r^2 = 0.96$) reaches in the eastern Sierra Nevada. Floodplain width in turn was controlled by physiographic conditions such as geology and erosional/depositional status. This finding is significant since past work in the region (Taylor 1982) has reported reductions in riparian zone width as a response to diversions.

Summary and Conclusions

Our field experiments and analysis suggest that riparian communities in the Sierra Nevada respond in an individualistic manner to hydroelectric diversions. This could be true in other mountainous regions of the western USA as well. We found a wide variety of responses, some of which might be responses to environmental conditions rather than streamflow diversions. Our work on this subject is continuing. At the present we are investigating species' responses to flooding (Harris and others 1985) and moisture stress, relationships between streamflow and floodplain soil moisture, and use of aerial photographs for classifying groundwater conditions. The ultimate aim is to construct a model that may be used to predict vegetation responses to diversion.

Meanwhile, the manager of hydroelectric facilities and the regulatory agencies which must license them

Table 3. Results of Mann-Whitney tests for cover differences in TWINSPAN vegetation types.

Vegetation type	*n*		Cover difference by stratum[a]		
	Diverted	Undiverted	Tree	Shrub	Herbaceous
Alnus rhombifolia	13	10	None	None	Increased downstream cover
tenuifolia	53	43	Decreased downstream cover	None	None
Cornus stolinifera–Salix lasiolepis	10	13	None	Decreased downstream cover	None
Salix lasiolepis	6	5	None	None	None
Boreal riparian scrub	6	7	None	None	Increased downstream cover

[a] Differences significant at $p \leq 0.05$.

must analyze diversion effects and make decisions. We feel that our work can contribute to better impact prediction and decision making. In the short term, intensive field studies and professional judgements must substitute for accurate quantitative analysis. The following suggestions are offered for assistance in conducting these field studies.

Canopy cover may decrease or increase as a result of diversion on headwater streams. Increased cover may result when diversions reduce the intensity of peak flood events, allowing plants to establish or grow in formerly scoured locations. Response will depend on the steepness of the reach and the availability of substrate. On very steep reaches with limited substrate, increases in cover may be insignificant. On moderately steep reaches with adequate rooting medium, significant increases in near-stream cover may occur, perhaps to the detriment of fisheries resources (Pelzman 1973). On reaches of relatively flat gradient where natural flooding is not so destructive, reducing floodflows may not have a discernible effect through this mechanism.

Decreased cover may occur due to thinning of foliage or mortality due to moisture stress. Hydroelectric diversions do not often reduce low flows below naturally occurring levels. Requirements for instream releases for fisheries will prevent this. Decreased cover will result when diversions curtail recharging of soil moisture in floodplain aquifers. This is a very site-specific problem. Potentially sensitive reaches may be identified by sandy substrate, wide floodplains, and relatively flat gradient. Elimination of overbank flooding has been documented as a factor in reduced growth rates of riparian species on alluvial streams (Reily and Johnson 1982) and a similar response may occur on depositional reaches of headwater streams.

Changes in vegetation structure (height class distribution) may result from upgrowth of formerly arrested shrubs and trees, reduced reproduction due to moisture stress (or shade from upgrowth), or mortality due to moisture stress. Upgrowth is most likely on reaches where destructive effects of flooding are naturally severe and dampened by diversion. Reduced reproduction and mortality are most likely on reaches where streamflow meets a relatively high proportion of plant moisture requirements.

Species composition changes in riparian communities have been attributed to diversions (Turner and Karpiscak 1980). Our work suggests that compositional changes may have occurred on some streams. Many of the higher elevation riparian communities in the Sierra Nevada are comprised of relatively few shrub and tree species. If changes in composition occur, they may be shifts from less drought-tolerant to more drought-tolerant species as may have occurred on McGee Creek. To predict compositional changes, much more data on autecological characteristics of typical riparian species would be needed.

Species richness in montane riparian communities is apparently related to floodplain width (species–area effect). Species richness and diversity are also determined by herbaceous cover (Harris 1985, Jones and Stokes Associates 1984 and 1985). Changes in herbaceous cover induced by diversion would be most likely to cause changes in diversity. This problem would be concentrated on reaches that have naturally diverse communities, which are apparently correlated with wider floodplains and sandy substrates.

Evidence collected to date indicates that the manager need not be overly concerned with impacts of diversion on the absolute width of riparian zones on headwater streams. The manager may need to consider shifts in location, however; that is, encroachment of vegetation into formerly scoured locations and losses at floodplain margins that are no longer irrigated by overbank floods. Some species have shown preferences for location on the floodplain, which may affect how a particular community responds (Harris and others 1985). Effects on vegetation overhanging the stream should be carefully considered because of the importance of overhang to fisheries habitat (Quigley 1981).

In the future, we may improve our abilities to classify and predict responses of montane riparian communities to hydroelectric and other types of diversions, or we may find site-specific field studies and informed judgements are necessary because of the individualistic nature of the systems. For at least the next few years, the manager must rely on the latter. Hopefully, this research has contributed to improved understanding.

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