STREAM-GROUNDWATER INTERACTIONS ALONG STREAMS OF THE EASTERN SIERRA NEVADA, CALIFORNIA: IMPLICATIONS FOR ASSESSING POTENTIAL IMPACTS OF FLOW DIVERSIONS[1]

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Abstract: One of the most fundamental hydrologic determinations to be made in assessing the probable impacts of flow diversions on riparian vegetation is whether flows are gaining or losing water to groundwater in the reach of interest. Flow measurements on eight streams in the Owens River and Mono Lake basins show that stream- groundwater interactions can produce substantial changes in flow; these changes can vary among streams, along one stream, and in different seasons. Over one stream reach, autumn baseflow increased nearly three-fold from groundwater contributions; in another, summer flow decreased 50 percent.

Increasing recognition of the ecological importance of riparian zones (Johnson and others 1985) coupled with a recent proliferation of proposals to divert water from streams for hydroelectric development has led to growing interest in developing techniques to assess the probable impacts of flow diversions on riparian vegetation. The potential impact of a diversion on riparian vegetation will depend on a variety of factors, including the magnitude of the diversion and/or storage relative to the natural flow, and the geomorphic, hydrologic, climatic, and ecological characteristics of the site.

One of the most fundamental hydrologic determinations to be made is whether a stream is *gaining water* from groundwater (a gaining reach), l*osing water* to groundwater and evapotranspiration (a losing reach), or *in equilibrium* with respect to groundwater. There is general agreement that riparian vegetation along losing reaches may be more sensitive to flow reductions than that along gaining reaches: The shallow water table in a losing reach is probably dependent on flow, whereas, in a gaining reach, riparian vegetation may be supported by inflowing groundwater (Risser and others 1984).

Flow gains and losses were measured on eight reaches of streams draining the eastern slope of the Sierra Nevada in California. Seven of these reaches (tributaries to the Owens River) have been proposed for diversion for hydroelectric development and were studied expressly to develop data for assessing the probable impacts of the developments (FERC 1986); the eighth stream (Rush Creek, a tributary to Mono Lake) was studied for a fish habitat study conducted for the California Department of Fish and Game (Kondolf 1988). The purpose of this paper is to present data on gains and losses in flow for all eight study reaches and their implications in assessing probable impacts of flow reductions on riparian vegetation.

Study Area

The study reaches are located along the steep, eastern front of the Sierra Nevada Mountains, California (figures 1 and 2). Topographic relief is remarkably high, with peaks exceeding 4000 m in elevation less than 30 km west of the floor of the Owens Valley, where elevations are generally less than 2000 m. Precipitation occurs primarily as snow at higher elevations. The area east of the mountain range lies in a rain shadow; the town of Bishop receives only 145 mm of precipitation annually (California Department of Water Resources 1980). As a result of this climatic pattern, most runoff in the study streams is derived from snowmelt high in the watershed. The lower reaches of these snowmelt-fed streams (including the study reaches) flow through a semiarid environment.

Riparian vegetation in the study area is found primarily along perennial stream courses and major springs, and is extremely limited. In the Inyo National Forest, where most of the study reaches are located, riparian areas account for only 0.4 percent of all land (Kondolf and others 1987). Riparian vegetation has already been affected in this century by numerous diversions for extrabasin water transfers, hydroelectric generation, and irrigation in the Owens and Mono basins (Vorster and Kondolf, these proceedings). The California Department of Fish and Game has estimated that 88 percent of the stream miles in the Owens-Mono region have been affected by diversion, including 20 percent totally diverted (Wong and Shumway 1985).

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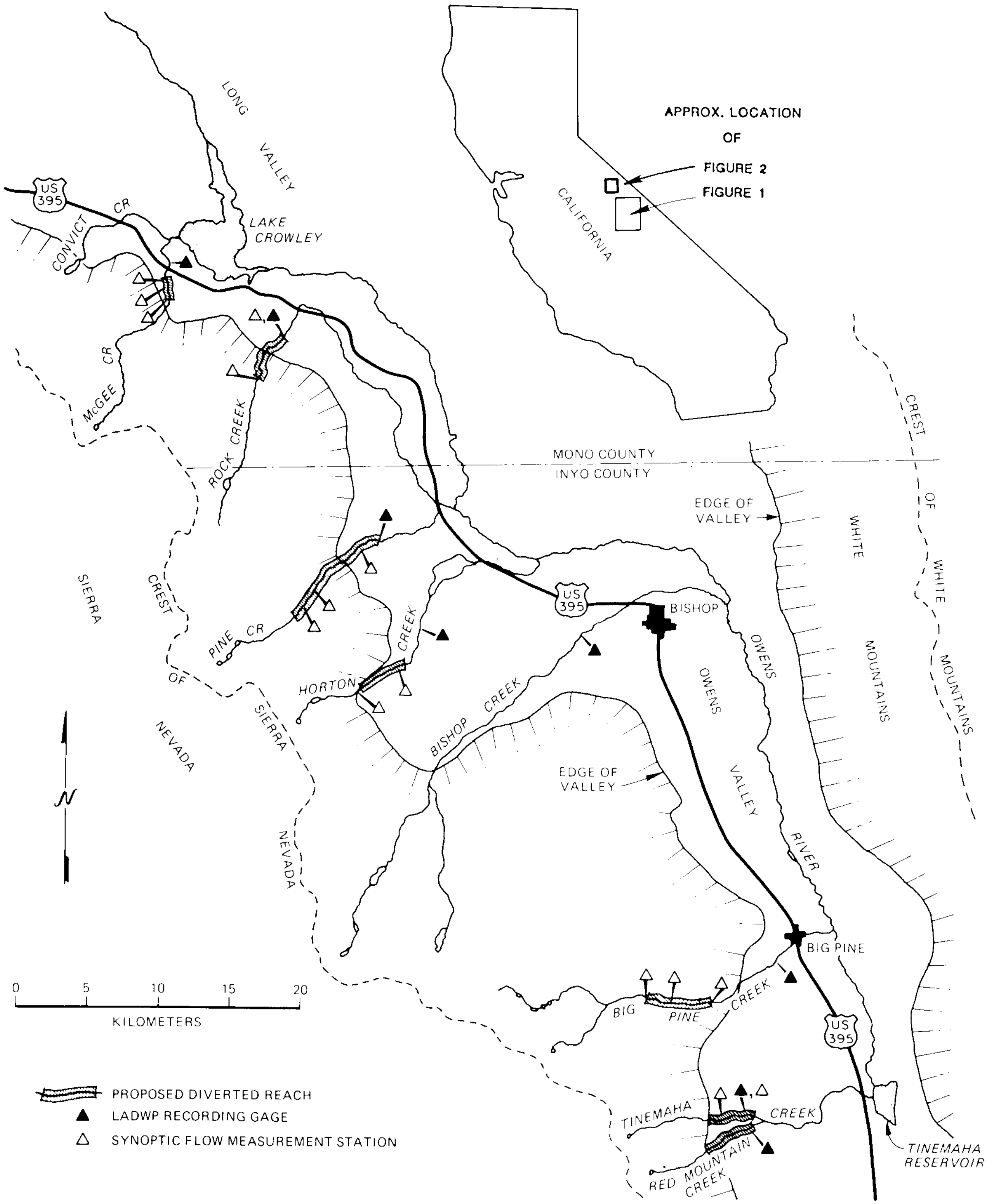

Figure 1— Location map for streams tributary to the Owens River. Reaches proposed for hydroelectric diversion are *highlighted*; stream gages are designated by *solid triangles*; synoptic flow measuring sites are designated by *open triangles*; (Adapted from Kondolf and others 1987)

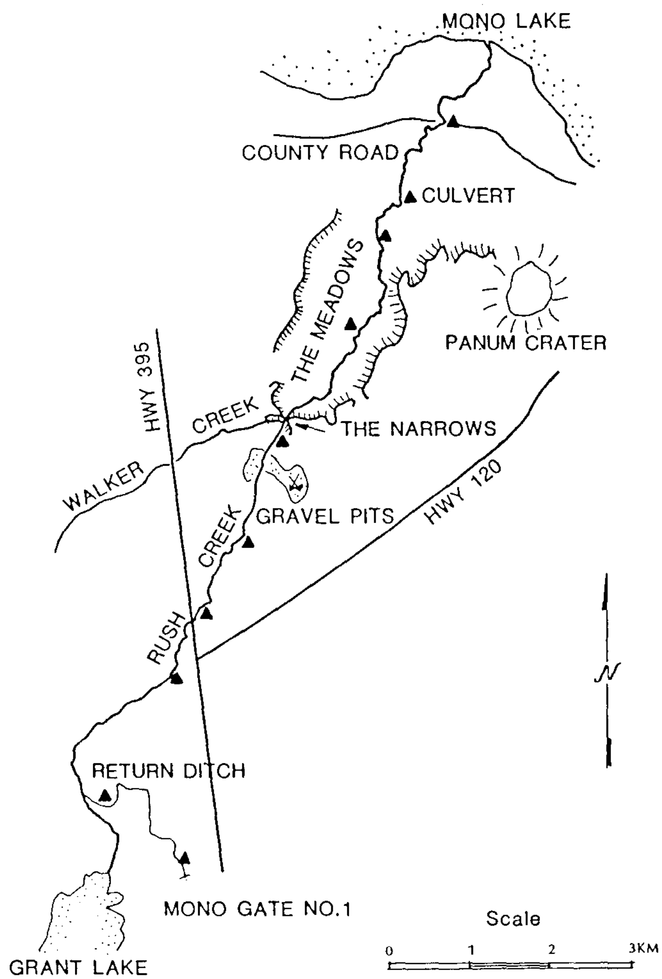

Figure 2 – Location map for Rush Creek below Grant Lake, showing the Hwy 395 crossing and the culvert, sites of principal flow losses. Synoptic flow measuring stations are designated by *solid triangles*.

Methods

To quantify gains and losses in streamflow, *synoptic flow measurements* were made along seven of the study reaches. The procedure was to select days of steady or very slowly changing stage, measure the flow at two or more sites along the length of the stream, and, allowing for tributary contributions and surface diversions, compute the gains and losses in flow between the measuring stations. The measurements are treated as simultaneous, and with the assumption of steady flow, changes in flow can be attributed to groundwater interactions or evapotranspirative losses along the intervening reach. Water velocity was measured with Price AA or pygmy current meters, and standard procedures of the US Geological Survey (Rantz and other 1982) were employed in computation of flow. On Red Mountain Creek, downstream changes in flow were computed from historical flow records for the existing gage and a discontinued gage upstream (Kondolf and others 1987).

On the Owens River tributaries, flow was measured at only two or three sites, and measurements were repeated three times or less, all at flows reflecting natural runoff from the basins. However, on Rush Creek, flow was measured at eight-to-ten sites, and the measurements were repeated six times in different seasons and at different flow releases from an upstream reservoir. As a result, more detailed information is available on downstream flow changes in Rush Creek than in the other streams.

Locating cross sections with flow characteristics favorable for flow measurement was challenging. The Owens tributary study reaches were very steep (table 1) and consisted largely of boulder cascades with extremely turbulent hydraulics. Measurements in such sites would be subject to large errors because of the nonlogarithmic form of the vertical velocity profile (Jarrett 1985). To measure potentially subtle changes in flow, it was necessary to locate (after extensive searching) sites with more uniform flow characteristics (usually in lower gradient pools), even if this required going several hundred meters upstream of the study reach boundary. The Rush Creek study reach was nearly an order of magnitude less steep than the other sites, and good sites were not as difficult to locate. Nonetheless, extreme care was taken to locate the best possible sections there as well. At most measuring sites, rocks were rearranged on the channel bed to achieve more uniform flow and thereby improve measurement accuracy.

Results and Discussion

General Observations

Net unit changes in flow for the study reaches are presented, with other hydrologic data for the study reaches, in table 1. All the study reaches lying entirely east of the base of the mountain front were characterized by net losses, while the only study reach entirely west of the front (Big Pine Creek) was gaining, as was one of the two reaches crossing the mountain front (Pine Creek)(figure 1).

The study reaches on Tinemaha and Red Mountain Creeks are typical of stream reaches crossing alluvial fans along the eastern Sierra Nevada front. The fans are composed of relatively permeable sediments with water tables typically at depths of tens of meters, although perched water tables may exist immediately under the riparian corridors of the streams. (Unpublished groundwater data on file at the Los Angeles Department of Water and Power office, Bishop, CA.)

Table 1– Hydrologic data for study reaches, eastern slope Sierra Nevada

Stream	Drainage Area [a] (km^2)	Avg. Flow [a] (m^3/s)	Reach Distance [b] (km)	Avg. Slope [b] (m/m)	Date of Msmt.	Upstrea m Flow (m^3/s)	Unit Change ($m^3/s/km$)
PERCHES ON BEDROCK-FLOORED VALLEYS WEST OF ESCARPMENT							
Big Pine Creek	82	1.18	4.3	0.099	8/19/85	1.44	0.032
					10/31/85	0.39	0.014
PERCHES ON ALLUVIAL AND GLACIAL SEDIMENTS EAST OF ESCARPMENT							
McGee Creek	54	0.84	1.8	0.082	7/31/85	0.97	-
					10/29/85	0.46	-0.032
Horton Creek	35	0.24	3.1	0.165	10/31/85	0.12	-0.001
Tinemaha Creek	21	0.24	2.4	0.115	8/13/85	0.39	-0.033
Red Mountain Creek [c]	24	0.12	4.2	0.099	Aug-mean	0.20	-0.008
					Oct. mean	0.10	-0.005
Rush Creek	131	2.39	13.0	0.015	8/21/87	0.57	-0.024
					9/05/87	1.74	-0.026
					9/07/87	1.29	-0.029
					9/09/87	2.71	-0.028
					10/22/87	0.38	-0.012
					11/28/87	0.58	-0.015
PERCHES CROSSING THE EASTERN ESCARPMENT							
Rock Creek	93	0.86	4.3	0.072	8/20/85	0.72	-0.030
					10/30/85	0.41	-0.004
Pine Creek	98	1.34	7.0	0.07	7/30/85	0.88	0.097
					8/20/85	0.42	0.109
					10/07/85	0.25	0.099

a Average flows from Los Angeles Department of Water and Power (LADWP) gaging records through 1985. Drainage areas for LADWP gages from USGS topographic maps.

b. Owens River tributary study reaches were reaches proposed for diversion. Lengths and gradients were measured from USGS topographic maps.

C. Flow losses in Red Mountain Creek were determined from analysis of historical gaging records for an upstream-and-downstream gage pair; values presented here correspond to long-term mean monthly flows for August and October.

Given this geomorphic setting and the fact that virtually all the runoff is derived from high-elevation snowmelt, it is not surprising that such stream reaches typically lose water to groundwater. Historical gaging records for the upstream-downstream gage pair on Red Mountain Creek indicate that losses are greater for higher summer flows (Kondolf and others 1987).

The McGee and Horton Creek study reaches flow between lateral moraines, and thus can be assumed to be flowing largely over till. Till would likely be less permeable than alluvial fan deposits, but these reaches consistently showed losses as well. Conditions on Rush Creek are more complex, but under the present hydrologic regime, it too, loses water to groundwater over the study reach.

The Big Pine Creek study reach lay west of the mountain front and was characterized by gains in flow. The Rock Creek study reach, which traversed the mountain front, evinced losses in flow. The largest changes in flow were observed over the Pine Creek study reach, which gained a relatively constant 0.1 $m^3/s/km$ from groundwater as it crossed the mountain front.

In summary, reaches flowing over the alluvial and glacial deposits east of the mountain front were generally losing, while two out of three reaches west of or crossing the mountain front were gaining (figure 3).

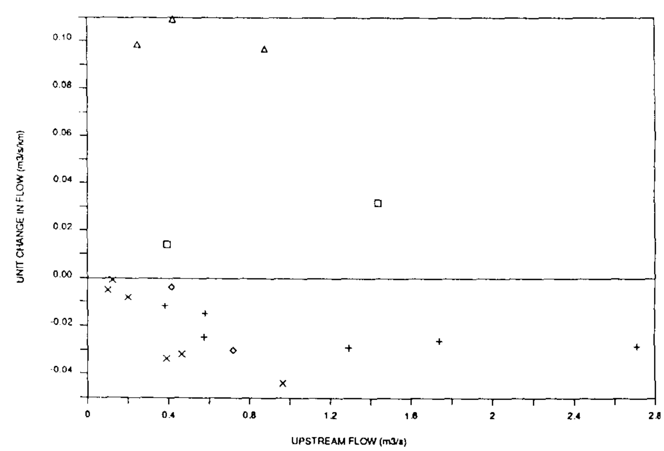

Figure 3- Rates of downstream change in flow plotted against flow at the upstream end of each study reach. Data from table 1. Symbols: Rush Creek (+'s), other streams east of the escarpment (*x*'s), Big Pine Creek (*squares*), Pine Creek (*triangles*), and Rock Creek (*diamonds*).

Pine Creek

Flow in Pine Creek showed remarkable downstream increases from groundwater inflow near the fault-bounded mountain front. The increases included contributions from two short, spring-fed tributaries as well as from direct groundwater inflow. The net downstream increase remained quite constant over the course of three measurements in July, August, and October. Because this seasonally consistent increase was added to a progressively declining contribution from upstream, the percentage increase over the study reach rose from 77 percent in July to 275 percent in October.

These measurements contradicted earlier estimates of the amount of water available for diversion at the upstream end of the reach proposed for diversion. The only gage in the Pine Creek study reach is operated by the Los Angeles Department of Water and Power (LADWP) and is located near the downstream end of the reach. To estimate flow upstream at the proposed point of diversion, the applicant for the hydroelectric project adjusted the gage flows for the smaller drainage area at the upstream site and for differences in precipitation. Based on these considerations, the applicant assumed flows at the proposed point of diversion to be 76 percent of the flows at the LADWP gage (Keating 1982). During weeks of high snowmelt flows, this is probably a reasonable approximation. However, during other times of the year, actual flows are probably quite different.

The applicant's estimate of flow at the upstream site can be compared with the results of synoptic flow measurements in July, August, and October, all expressed as percentages of total flow at the downstream gage, in figure 4. These measurements indicate that there is considerably less water available at the proposed diversion site than assumed by the applicant, a fact with potentially profound implications not only for riparian vegetation in the reach, but also for the economic viability of the project itself.

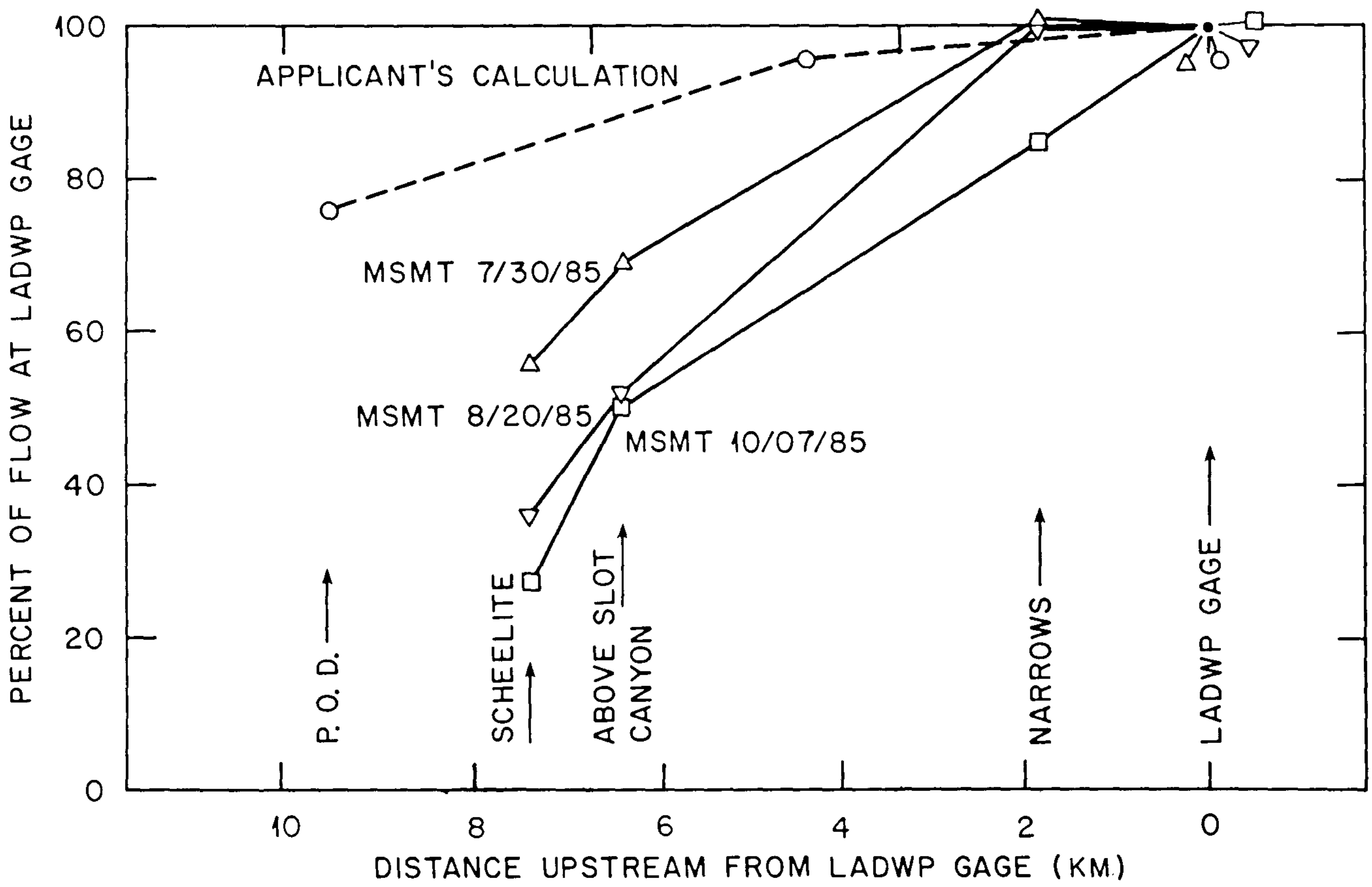

Figure 4— Flows in Pine Creek upstream of stream gage as calculated by applicant (*dashed line*) and as measured in this study (*solid lines*), expressed as percentage of flow at gage. Downstream is from left to right. (Adapted from FERC 1986)

Rush Creek

Rush Creek, the largest tributary to Mono Lake, flows from the eastern Sierra front across alluvium and deposits of a large Pleistocene lake, into the modern lake (figure 2). Results of flow measurements along Rush Creek show some interesting patterns (figures 5 and 6). First, flow losses are concentrated at two points in the channel, both at transitions (contacts) in the underlying geological units. The greatest flow loss, averaging 0.2 m^3/s occurred over a 2 km reach near the US Highway 395 bridge. It is at about this point that the creek, which had been flowing on silty lacustrine deposits, cuts through those deposits and flows over gravels (deposited by the ancestral Rush Creek) with a deep water table (Lajoie 1968). The high permeability of the gravels and the deep water table result in high rates of infiltration. Downstream, the stream continues to flow mostly over gravels through the meadow reach, but here the water table is relatively shallow and the streamflow is relatively constant as groundwater and tributary inflow are balanced by evapotranspirative demand and losses to groundwater. However, about 11.5 km downstream of Grant Lake, the stream begins to flow over volcanic blast deposits from a nearby crater. (Unpublished map prepared by R. Bailey, USGS, Menlo Park, CA.) These deposits are very permeable and, evidently, well-drained so that an average 0.1 m^3/s is lost into them over a 2 km reach.

Second, losses can be quite high. Of the minimum flow release presently required from Grant Lake (0.54 m^3/s), 50 percent is lost along the study reach during summer months.

Third, for a given flow, losses are very different from summer to winter, but are quite similar at very different releases in one season. In the summer, net flow losses over the entire reach varied only from 0.32 to 0.38 m^3/s for releases ranging from 0.54 to nearly 2.83 m^3/s. At a flow release of about 0.54 m^3/s, flow loss in the winter measurement was only 0.20 m^3/s, compared to a loss of 0.32 m^3/s in the summer measurement.

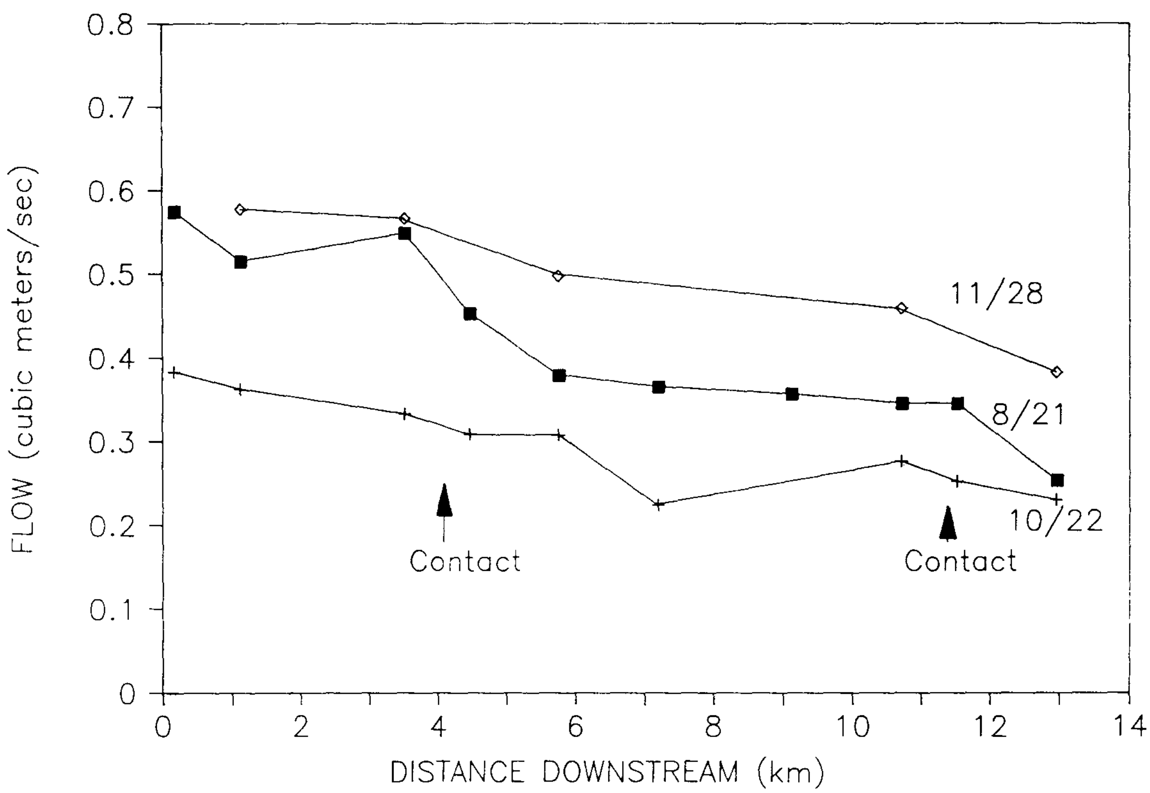

Figure 5– Flow measurements along Rush Creek at releases of 0.54 m^3/s and plotted against distance downstream of Grant Lake Reservoir. Each point represents a nearly simultaneous measurement of flow on the date indicated at the right. Losses were concentrated at two geological contacts: between lake silts and gravels (at about 2.5-3.0 km), and between granitic gravels and volcanic blast deposits (at about 7 kn). For the same 0.54 m^3/s release, net flow loss was much greater in August than in November.

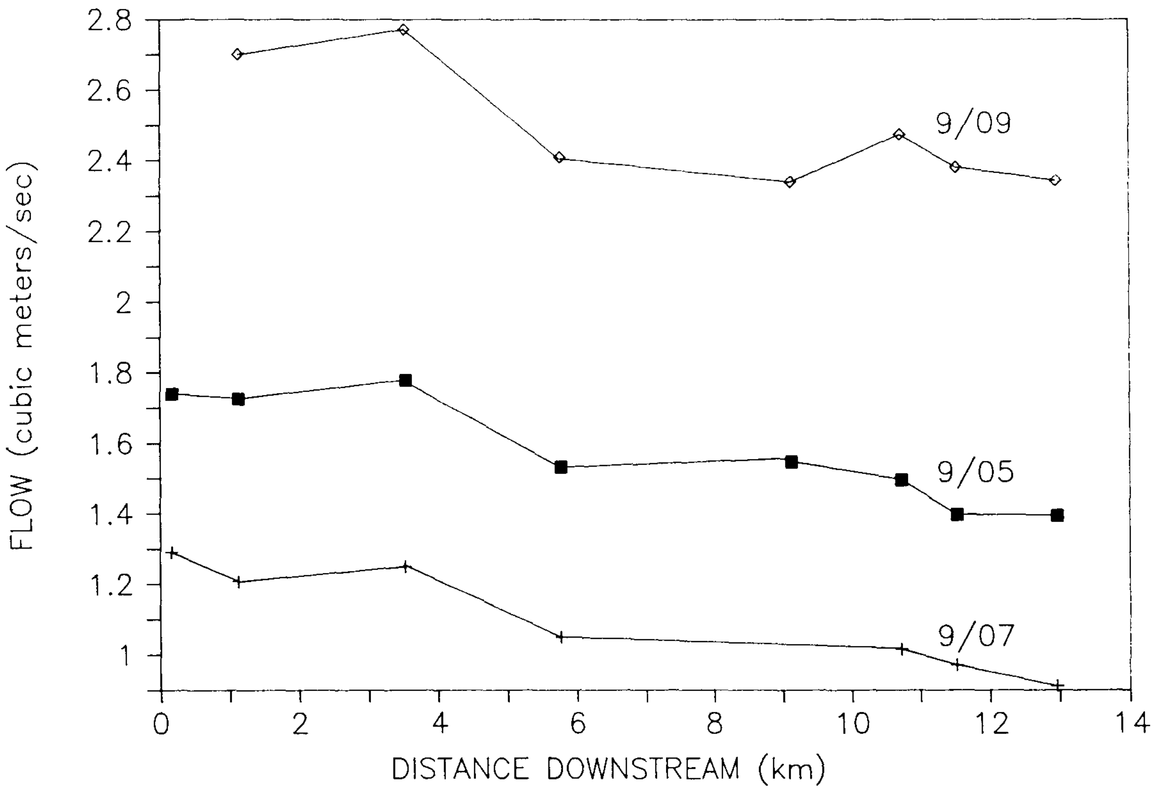

Figure 6– Flow measurements along Rush Creek at releases of 1.3, 1.7, and 2.8 m^3/s in early September. Despite the wide range in releases, net flow losses were similar.

One is inclined to attribute these seasonal differences in loss rates to evapotranspirative demand (ET). In this case, however, the differences may be greater than can reasonably be explained by ET. Estimates of woody riparian acreage along Rush Creek and probable rates of ET indicate that only about 0.023 m^3/s can be attributed to ET from woody vegetation in the summer months. (Unpublished data, Duncan Patten, Arizona State Univ., Tempe, AZ.) This estimate does not include ET from meadows, and much of the vegetation is newly emergent, so its ET demand may be higher than expected. Earlier estimates of ET losses were comparable in magnitude to the seasonal difference (NAS 1987). Thus, the seasonal pattern is not entirely explained, but the empirical observations can still be profitably applied to specifying flow releases required from the reservoir to satisfy minimum flows for aquatic and riparian resources along the entire stream.

Historical gaging records show that Rush Creek was a gaining stream in the lowest 3 km of the study reach earlier this century. Some of this inflowing groundwater was probably derived from irrigation water extensively applied to lands adjoining the stream; some was probably simply natural drainage effected by the deep incision of the channel below the surrounding countryside.

Conclusions

Synoptic flow measurements demonstrate that streams of the eastern front of the Sierra Nevada can undergone substantial changes in flow along their lengths because of stream-groundwater interactions. For example, October baseflow on Pine Creek increased nearly threefold over the study reach from groundwater contributions, while on Rush Creek, the court-prescribed minimum flow release of 0.54 m^3/s decreased by over 50 percent over the study reach in the summer. Clearly, flow changes of this magnitude must be accounted for in any analysis of potential impacts of future flow diversions.

If losing streams are regarded as more sensitive to diversion than gaining streams (Risser and others 1984), it follows that, once losing reaches are identified, resources there should be monitored especially closely. The patterns of gain/loss have implications for the design of instream flow monitoring programs. For example, on a losing stream, flow should be gaged near the downstream end of the diverted reach, where flows are likely to be lowest. Thus, if instream flow requirements are met at the gaged site, they are probably met along the entire reach. Similarly, on gaining streams, instream flows should be monitored at the upstream end of the diverted reach, where flows can be expected to be lowest.

It is worth noting that reaches experiencing a net gain may include losing reaches (and vice versa). For example, Pine Creek is a losing stream in the upper 3 km of study reach, as evidenced by measurements of riparian water table levels (Kondolf and others 1987) and observations of a dry streambed along part of the stream in February of 1987. (Tom Felando, Inyo National Forest, pers. comm., 1987.) Thus, observations along different portions of a reach may be needed to pinpoint gaining and losing reaches.

Because stream-groundwater interactions vary among different streams, along a given stream, and over time, assessment of site-specific conditions requires site-specific measurements, repeated in different seasons. Nonetheless, the data presented here suggest a few generalizations. Reaches east of the mountain front flow across alluvial and glacial deposits, and generally lose water to groundwater. On Red Mountain Creek the rate of loss is higher at higher flows, while on Rush Creek, the loss rate is conservative with flow but varies by season. Reaches that lie west of the mountain front for at least part of their length may gain water from groundwater.

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