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Effect of geomorphic channel restoration on streamflow and groundwater in a snowmelt-dominated watershed

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[1] Reengineering of stream channels is a common approach used to restore hydrologic function in degraded landscapes, but there has been little published research analyzing its effectiveness. A key challenge for impact assessment is disentangling the effects of restoration from climate variability. Trout Creek, near Lake Tahoe, California, was reengineered to reestablish hydrologic connectivity between the stream and its former floodplain. Gauges located above and below the site, along with groundwater well measurements, were used to analyze prerestoration and postrestoration hydrology. Results show that restoration has a seasonal impact with statistically significant increases in streamflow during the summer recession period and decreased groundwater table depths across a wide range of streamflow conditions. Paired gauges and statistical models that are robust to serial autocorrelation demonstrate a feasible approach for assessing hydrologic restoration in regions where climate patterns lead to substantial within-year and between-years variation in streamflow.

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1. Introduction

[2] The alteration of riparian and stream ecosystems through urban and agricultural land use practices has prompted widespread and costly restoration projects [*Palmer et al.*, 2005; *Bernhardt et al.*, 2005; *Booth*, 2005]. Most of these projects involve engineered alteration of streamflow and groundwater to support the restoration of aquatic and riparian ecosystem structure and function. It is therefore critical that assessment of the effectiveness of restoration efforts include consideration of changes to both streamflow regimes and groundwater dynamics [*Booth*, 2005; *Ward et al.*, 2002].

[3] Undesirable human-induced changes to the hydrology of riparian areas and streams can arise through a variety of mechanisms and can occur across a range of scales. Associated restoration strategies reflect the type and scale of impacts associated with different land use practices. Common examples of relatively local impacts include overgrazing and construction in riparian zones, channelization of streams as part of agricultural and urban conveyance systems, and down cutting of stream channels leading to dewatering of riparian areas [*Mant and Janes*, 2005; *National Research Council (NRC)*, 1992]. In these cases, stream restoration activities often seek to directly modify stream channel and riparian zone surface and subsurface drainage properties.

[4] There is a variety of stream modification techniques designed to enhance hydrologic function. These techniques range from approaches that focus largely on altering the channel itself to more geomorphically based approaches that include consideration of surrounding floodplain or riparian area (*NRC* [1992]; *De Laney* [1995]; *Poff et al.* [1997]; *Hillman* [1998]; *Swanson Hydrology and Geomorphology* (*SHG*) [2004]; D. S. Lindquist and J. Wilcox, New concepts for meadow restoration in the northern Sierra Nevada, Feather River coordinated resource management, 2000, accessed 27 February 2006 at http://www.feather-river-crm.org/publications/abstracts/ieca.htm (hereinafter referred to as Lindquist and Wilcox, 2000); U.S. Forest Service, Lake Tahoe Basin Management Unit, Draft environmental assessment Big Meadow Creek: Cookhouse Meadow stream restoration project, 2004). Recently, biotechnical restoration techniques are replacing older restoration methods involving "hard" engineering solutions such as riprap, concrete, sheet piling, dams, and levies [*Goodwin et al.*, 1997; *NRC*, 1992]. Biotechnical approaches, which incorporate natural materials such as rock, root wads, and native vegetation, can often times perform the same functions as hard engineering techniques with arguably improved hydrologic, ecologic, and aesthetic results [*SHG*, 2004]. Preliminary studies in stream and meadow restoration projects have indicated that reengineered channels utilizing biotechnical techniques can successfully raise groundwater levels and reconnect channels with their floodplains [*SHG*, 2004]; see also Lindquist and Wilcox (2000). Nevertheless, inadequate monitoring and evaluation continues to be one of the major criticisms of river restoration projects, and further research is needed to asses the response of streamflow and groundwater regimes to channel modifications [*Ralph and Poole*, 2002; *Reeve et al.*, 2006; *Palmer et al.*, 2005]. Studies are needed across a broad range of geographic settings, and explicit consideration of interactions between hydroclimatic processes and restoration

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effects are needed to support generalization of monitoring results. This study provides an assessment of the restoration impacts on both streamflow and groundwater dynamics for Trout Creek in the Sierra Nevada. Restoration of Trout Creek used a biotechnical approach and was designed to improve connectivity between channel and floodplain through infilling of an incised channel coupled with a significant reworking of the surrounding floodplain. Hydroecologic goals of the Trout Creek project included reducing flood flow and nutrient loading by increasing overbank flow, decreasing channel erosion and restoring riparian vegetation by improving summer groundwater availability [*Wigart*, 2004].

[5] Estimating changes to hydrologic regimes following restoration is often confounded by multiple and interacting variables that shape observable hydrologic behavior, such as streamflow and groundwater table elevations. Disentangling the impacts of restoration from natural variation due to climate can be particularly challenging. Trout Creek is situated in a region where spring snowmelt and warm dry summers are the primary hydroclimatologic controls on hydrologic processes. Flow regimes (especially those in snowmelt-dominated watersheds) exhibit large interannual and intra-annual variations due to these seasonal changes [*Wohl et al.*, 2005; *Poff et al.*, 1997; *Smakhtin*, 2001]; see also Lindquist and Wilcox (2000). Groundwater measurements are rarely available for more than a few years. Stream gauge measurements may be available for longer periods, on the order of decades at some sites. However, even with longer-term data sets, climate shifts may make subtle changes due to restoration difficult to detect or lead to a misidentification of the effects. In the western United States, for example, recent studies have shown trends toward lower summer base flows for many streams in the Oregon Cascades and Sierras, due to climate-driven reductions in snow accumulation and melt [*Knowles and Cayan*, 2002; *Bales et al.*, 2006]. Given the potential interaction between climate-driven changes and the impacts of restoration efforts, assessment strategies are needed that can disentangle these effects.

[6] Paired catchment studies have been widely used to separate the effects of climate variability and land use change, particularly in studies that analyze the affects of logging on streamflow (reviewed by *Bosch and Hewlett* [1982] and *Best et al.* [2003]). The application of a paired catchment approach requires that the two watersheds be both proximal and similar and that the control catchment not change over the course of the analysis. Similarity is generally defined in terms of climate, geology, vegetation, topography, and land use. Critiques of the paired catchment approach often center on whether the degree of similarity is sufficient to distinguish changes of interest from changes due to climate [*Best et al.*, 2003].

[7] In the case of channel modification and near stream restoration, a refinement of the paired catchment approach is to use two gauges on the same stream—one upstream and one downstream of the restoration site. Given that a substantial proportion of the contributing area will be shared by both gauges, this approach should maximize similarity. In this study, we take advantage of this modified version of the paired catchment approach or paired gauge approach, using longitudinal stream gauges to assess the impact of channel reconstruction for Trout Creek. We compare the gain in discharge, measured between gauges upstream and downstream of the restoration site, for prerestoration and postrestoration periods. We use streamflow gain defined at a daily time step in order to examine seasonal variation in the impact of stream restoration. We also compare relationships between groundwater well observations and streamflow for prerestoration and postrestoration periods.

[8] The Trout Creek Stream Restoration and Wildlife Enhancement Project in South Lake Tahoe was completed in 2001. Over 3000 m of channel was excavated and most of the original channel infilled followed by significant reworking of floodplain to construct a new channel. The new stream alignment exhibited enhanced sinuosity, a raised channel elevation, reduced slope, and an overall increase in channel length. Parts of the old channel were infilled to reduce the likelihood of stream recapture, while other segments (expected to fill in time by natural processes) were left to enhance diversity and function as small oxbow lakes. Bioengineering techniques were used during construction to maximize the biologic recovery of the stream corridor, improve stream habitat, and to allow for increased hydrologic connectivity between the stream channel and the floodplain.

[9] Changes to the channel and floodplain were designed to raise local groundwater tables, lower channel gradients, increase riparian zone storage, and increase transit time in the channel. Given the seasonality of flow regimes, the impact of these changes on streamflow and groundwater would be expected to differ during winter, snowmelt recession, and summer and early fall base flow periods. Specifically, we made the following hypotheses.

[10] 1. Following occasional large autumn rainfall events and in the early to peak snowmelt recharge period, restoration will lead to a decrease in the gain in streamflow measured between gauges above and below the restoration site. During these recharge periods, channel modifications should reduce channel flood flows, particularly if opportunities for overbank flow are increased. Restoration should also increase the storage in the riparian area and further support reduced streamflow downstream of the restored site (relative to flow at the upstream gauge).

[11] 2. During the recession period following peak snowmelt recharge, streamflow downstream of the restored site will increase, relative to upstream site, supported by the slower draining riparian groundwater system. Groundwater levels will also be elevated relative to prerestoration conditions.

[12] 3. Later in the summer and early fall, we hypothesize that higher riparian groundwater levels will persist but their influence on streamflow will diminish. High groundwater in late summer may also increase riparian evapotranspiration and potentially decrease summer base flow. In fact, increased evapotranspiration was one of the implicit goals of the project, designed to reduce the dewatering of riparian vegetation due to channel incision.

[13] We used available streamflow and groundwater measurements to test whether the hypothesized effects took place. More generally, our analysis tests whether changes to the hydrograph described above take place and thus support our conceptual model of potential restoration effects on

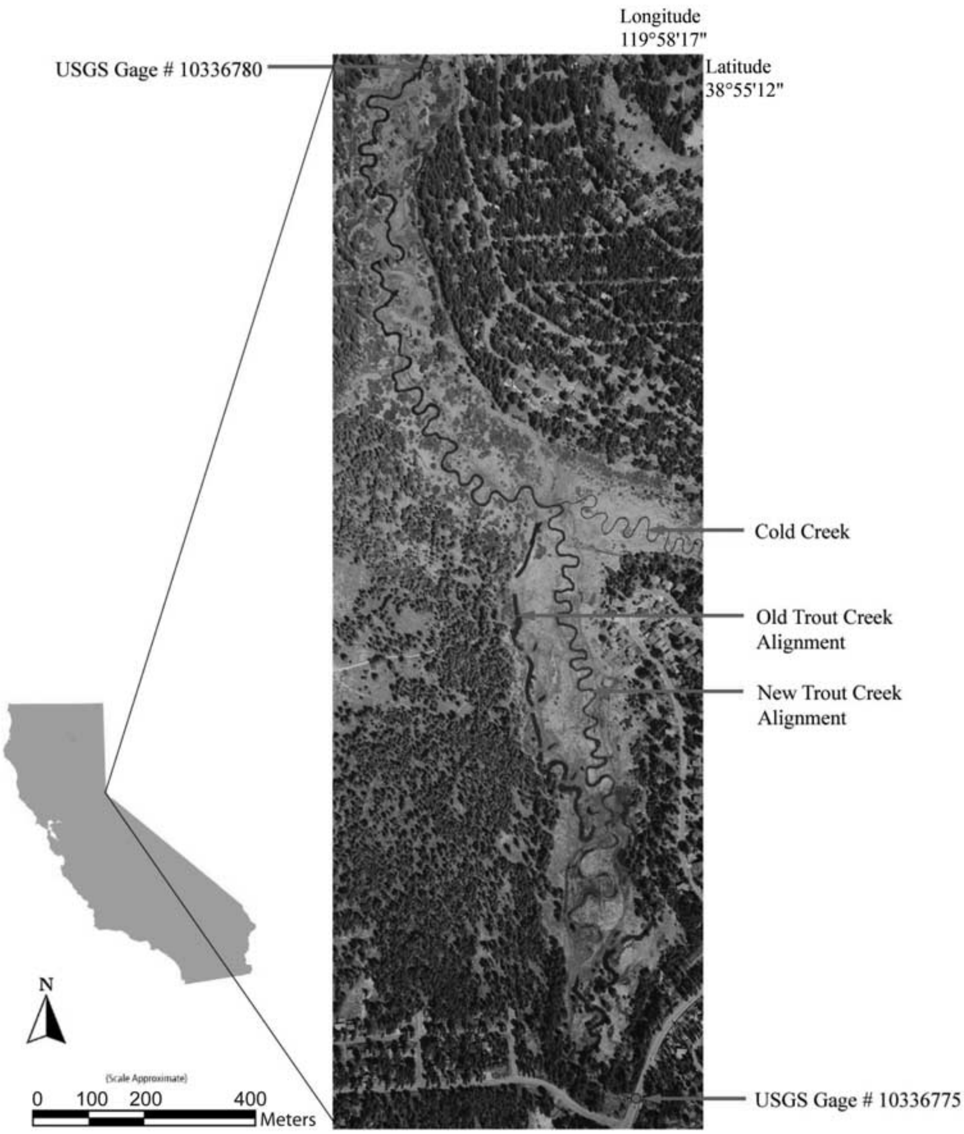

Figure 1. Location map of Trout Creek.

streamflow and groundwater dynamics in this snowmelt-dominated system.

2. Methods

2.1. Site Description

[14] Trout Creek watershed is located in the southern portion of the Lake Tahoe Basin in El Dorado County, California. Trout Creek has a drainage area of 106 km^2, and the main channel length is approximately 19.5 km long. The watershed ranges from a high of 3317 m above mean sea level at Freel Peak to a low of approximately 1897 m, where it enters Lake Tahoe. In the Lake Tahoe area, most precipitation occurs in the winter as snowfall, and summer drought is typical. Mean annual precipitation ranges from 50 cm to 100 cm, and approximately 94% of the annual precipitation occurs between late November and mid-May.

[15] The Trout Creek study site lies just north of Pioneer Trail and south of Martin Avenue in the City of South Lake Tahoe. The two gauges used in this study are located at the upper and downstream ends of a riparian meadow (Figure 1). Snowmelt at the meadow generally occurs from mid-May to mid-June, and a vast majority of the snow in the upper watershed has usually melted by late July. Although summer thunderstorms do occur, they are infrequent and seldom contribute to significant streamflow pulses. The meadow substrate comprises well-sorted alluvial and glacial deposits, and the study site comprises vegetation typical of high-altitude montane environments in the Sierra Nevada. Plant community structure varies throughout the meadow system and includes a variety of riparian vegetation bounded by dryer upland vegetation communities. Meadow vegetation comprises sedges, rushes, grasses, annual and perennial forbs, and a variety of willow species. Dominant meadow species include *Carex nebrascensis, Juncus balticus, Muhlenbergia richardsonis, Poa pratensis, Arnica chamissonis*, *Aster occidentalis, Achillea millefolium, Lupinus polyphyllus,* and *Salix lutea.* Upland species adjacent to the meadow are primarily coniferous

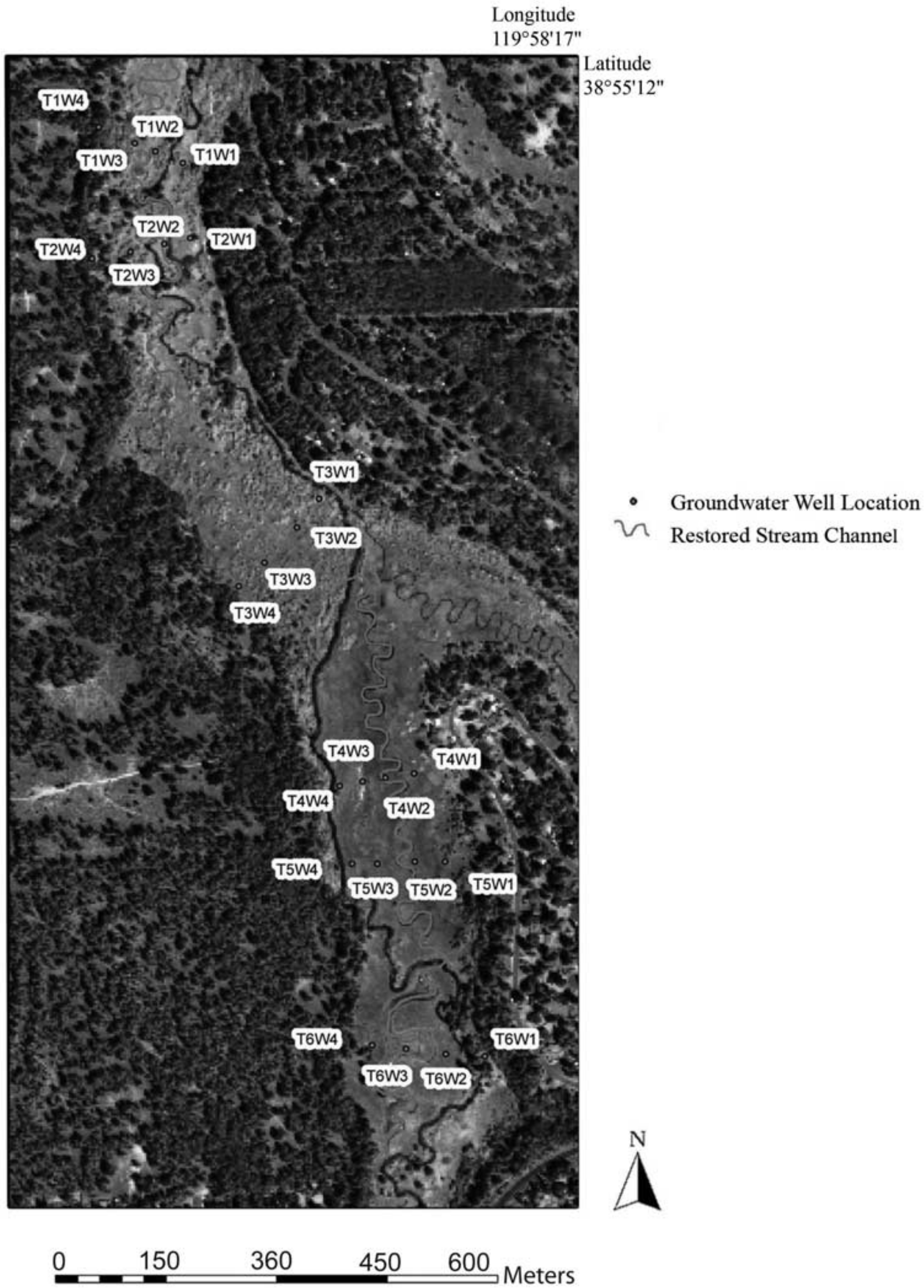

Figure 2. Map showing groundwater well locations and preretoration and postrestoration stream alignments.

trees, including *Abies concolor, Pinus contorta, Pinus jeffrey,* and *Pinus ponderosa*.

[16] The U.S. Geological Survey (USGS) has operated a streamflow gauging station on Trout Creek continuously since 1 October 1960 (station number 10336780). The gauge is located just downstream of the project site at the Martin Avenue crossing. A second USGS gauge (station number 10336775) is located upstream of the project site, and approximately 1 km upstream of first gauge, at the Pioneer Trail crossing. This gauge has been providing continuous streamflow data since 1 October 1990. There is a small tributary, Cold Creek, which intersects Trout Creek between the two gauges. No significant land cover changes occurred in the Cold Creek watershed throughout the study period and flow contributions from Cold Creek are relatively small. Groundwater data was collected by the City of South Lake Tahoe from 24 wells situated within the meadow. The monitoring wells were installed in October of 1999 and were arranged in 6 transects oriented perpendicular to the stream channel. Transect and well locations can be seen in Figure 2. Piezometers were constructed out of perforated PVC pipe 1.8 m in length, and monitored by lowering a hydrolight until the water table was detected.

Groundwater readings were taken on a bimonthly basis from November 1999 to June 2003.

2.2. Data Analysis

[17] In order to assess the effect of restoration on streamflow, we use a paired guage comparison. We examine the relative difference in daily streamflow between the upper and lower gauges at a daily time step for the preperiod (1990–2000) and postperiod (2001–2004). As discussed above, both the effect of restoration and the relative difference between the upper and lower gauges are expected to vary seasonally.

[18] Using the daily streamflow data for both gauges over the entire period from 1990 to 2004, we define proportional streamflow gain as

$$\Delta q_{rel} = \left(q_{upper} - q_{lower}\right)/q_{upper}, \quad (1)$$

where q_{upper} and q_{lower} are measured discharge at the upper and lower gauges averaged for each day. It follows that Δq_{rel} represents the daily increase in discharge between the two gauges as a proportion of streamflow at the upper gauge. Differencing the data in this way takes out any effects that are common to both gauges, such as interannual variation in the timing and magnitude of snowmelt. Our aim is to determine whether restoration has any effect on proportional streamflow gain and whether the effect differs by time of year.

[19] In order to identify the potential restoration effect by month, we estimate a regression model with the following specification:

$$\Delta q_{rel} = \alpha + \boldsymbol{\beta}'\mathbf{m}_t + \boldsymbol{\delta}'\mathbf{R}_t\mathbf{m}_t + \theta wydev_t + \varepsilon_t, \quad (2)$$

where $\mathbf{m}_t$ is a vector of 12 binary dummy variables, one for each month January through December, R_t is a binary dummy variable indicating whether the observation is during the postrestoration period, $wydev_t$ is the annual deviation from the annual mean streamflow at the upper gauge, and ε_t is a random error term. Annual streamflow is computed by water year, which is defined as October through September. Deviation is computed as the difference between annual streamflow in each water year and the long-term mean annual streamflow over the period of record. Deviation from mean annual streamflow is included to control for year-to-year variation in atmospheric conditions (temperature and precipitation) that may drive differences between streamflow at the upper and lower gauges. Since water inputs are dominated by spring snowmelt, annual (water year) streamflow should provide a good surrogate for the magnitude of primary water input throughout the melt season and into the summer.

[20] The vector of coefficients β will provide estimates of the monthly differences between gauges before restoration. As required whenever including a set of mutually exclusive categorical variables in a regression model (i.e., 12 months in a year), one category must be omitted to avoid perfect multicolinearity. We omit the month of May, meaning that the estimated coefficients in β are interpreted as the average difference in proportional streamflow gain between the corresponding month and May for the period 1990 through 2000. The coefficients δ, which are of primary concern, are interpreted as the differences in the monthly averages for the years 2001 through 2005. In other words, the estimates of δ are interpreted as the monthly effects of restoration on the proportional streamflow gain.

[21] A potential concern with the model specified by equation (2) is that Δq_{rel} is highly serially correlated, which implies that the error term ε_t is serially correlated. Not accounting for serial correlation poses a problem for making statistical inference. Serial correlation is a ubiquitous problem in streamflow analysis [*Worrall et al.*, 2003]. Temporal aggregation (e.g., using monthly or annual streamflow rather than daily values) is a commonly used approach to avoid problems associated with serial correlation. Aggregation, however, is problematic when data are limited and sample variation is high, as is the case here. Aggregation also smoothes the data, thereby reducing the information content at finer time scales that may be important when the effect (of restoration) varies at relatively fine time scales. Parametric autoregressive models are another widely used approach, such as specifying an AR1 process for the error term [e.g., *Worrall et al.*, 2003], but these require the researcher to assume a specific functional form of the serial correlation.

[22] Here we use a nonparametric approach that allows for robust statistical inference. Specifically, we report *Newey and West* [1987] standard errors that enable statistical inference that is robust to both heteroskasticity and any form serial correlation up to a specified lag. Reporting these standard errors is a commonly used approach in the economics literature to account for serial correlation [*Wooldridge*, 2002]. The relative advantage of the Newey-West approach is that it does not require any assumptions about the structure of the serial correlation, but rather, assumes the number of time periods over which serial correlation will be accounted for. For comparison purposes, we use lags of 15 and 30 days, which should cover the window over which serial correlation is a concern for our streamflow data. To demonstrate the effect of this approach, we compare the Newey-West standard errors and consequent statistical significance with those corresponding to standard ordinary least squares (OLS) estimation. Note that OLS is used to estimate the only set of coefficients that we report, as the Newey-West standard errors are derived using postestimation methods and do not affect the coefficient estimates.

[23] In addition to streamflow data, we compare groundwater table elevations in the prerestoration and postrestoration periods. Figure 2 illustrates the piezometer locations. As with streamflow, groundwater elevation is expected to vary with atmospheric conditions; however, changes in the relationship between groundwater elevation and streamflow are likely to reflect changes directly due to restoration. In order to examine this relationship at our study site, we estimate the following regression model:

$$gwlevel_{it} = \lambda q_{upper} + \varphi R_t + \gamma R_t q_{upper} + \rho distance_{it} + \nu_i + \upsilon_{it}, \quad (3)$$

where $gwlevel_{it}$ is the depth to groundwater table (meters of depth below the surface) for well i at time t, the variables q_{upper} and R_t are defined the same as above, $distance_{it}$ is the distance (in meters) from well i to the channel at time t, the term ν_i is a unique intercept for each well, and υ_{it} is an error

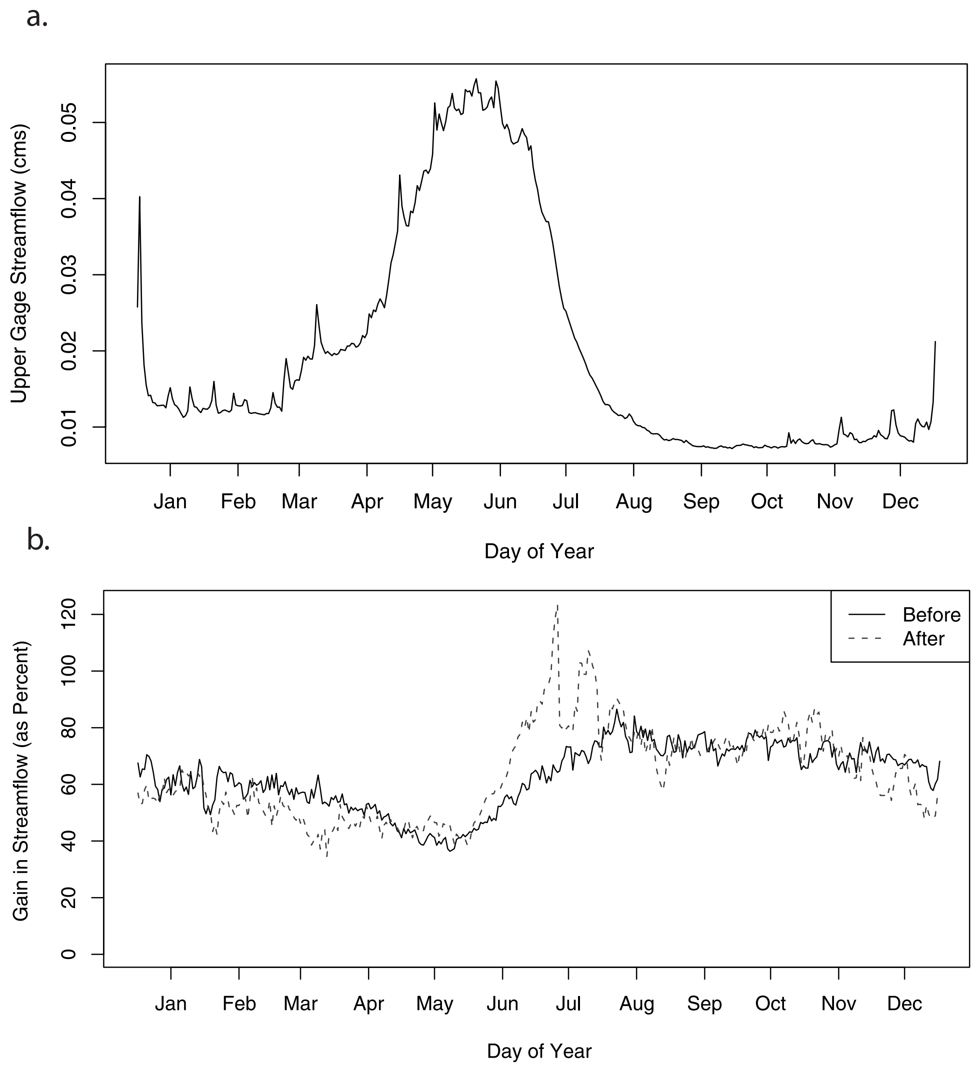

Figure 3. (a) Daily streamflow for the upper gauge (q_{upper}) averaged by day of year over water years 1990–2004 and (b) proportional difference (Δq_{rel}) in daily streamflow, averaged by day of year, for prerestoration and postrestoration periods.

term. The control variables specified in (3) have several advantages. The unique intercept term for each well, or fixed effect, enables us to control for any time-invariant, unobserved heterogeneity that explains the groundwater elevation at each well. The inclusion of $distance_{it}$ controls for changes in groundwater elevation that may be due to changes in the distance of the channel from each well after restoration. This is important because the position of individual wells relative to the stream channel changed following restoration, with the average distance to the channel decreasing by 30 m. We note that lateral distance is an approximation of groundwater flow path distance [*Woessner*, 2000]; however, it was the only readily available measure for the study site. Finally, the inclusion of q_{upper} accounts for the effect of streamflow on groundwater depth that is not due to either restoration or distance.

[24] The coefficients φ and γ are of primary interest, as they will provide estimates of the restoration effect on the overall groundwater depth at all wells and on the relationship between streamflow and groundwater depth. Once again, we account for serial correlation by reporting standard errors that are clustered on each well. As with the Newey-West approach described above, the clustering is robust to any form of potential serial correlation. But in this case, we assume a lag that covers the entire study period. We also experimented with specifications that included further interaction terms with distance (i.e., to determine whether the relationship with streamflow and the restoration effect varied with distance), but we do not report these models because none of the interactions yielded coefficients that were statistically significant.

3. Results and Discussion

3.1. Effects of Restoration on Streamflow

[25] Figure 3a shows mean streamflow by day of year for the upper gauge and depicts the seasonality of flow. Snowmelt-dominated flow begins in early March with the peak snowmelt period falling between mid-May and mid-June. Snowmelt recharge supports recession flow through July and into August, followed by a base flow period extending into late October. Periodic rainfall (or snowmelt) events do

Table 1. Linear Regression Results for Monthly Changes in Streamflow[a]

Variable	Coefficient	OLS SE[c]	Newey-West SE[b]	
			15-Day Lag	30-Day Lag
β_Jan	0.211	0.015***	0.028***	0.032***
β_Feb	0.183	0.015***	0.027***	0.031***
β_Mar	0.165	0.015***	0.038***	0.044***
β_Apr	0.095	0.015***	0.030***	0.034***
β_Jun	0.116	0.015***	0.034***	0.037***
β_Jul	0.277	0.014***	0.048***	0.056***
β_Aug	0.363	0.014***	0.060***	0.074***
β_Sep	0.322	0.014***	0.044***	0.052***
β_Oct	0.334	0.015***	0.028***	0.031***
β_Nov	0.295	0.015***	0.023***	0.026***
β_Dec	0.262	0.015***	0.021***	0.023***
δ_Jan	−0.028	0.017	0.028	0.031
δ_Feb	−0.067	0.018***	0.029**	0.034*
δ_Mar	−0.110	0.017***	0.042***	0.047*
δ_Apr	−0.037	0.018**	0.041	0.048
δ_May	0.035	0.018**	0.027	0.028
δ_Jun	0.112	0.019***	0.059*	0.062*
δ_Jul	0.240	0.018***	0.102**	0.124*
δ_Aug	−0.009	0.018	0.069	0.082
δ_Sep	−0.002	0.019	0.058	0.070
δ_Oct	0.028	0.017	0.054	0.064
δ_Nov	0.034	0.018*	0.037	0.041
δ_Dec	−0.094	0.017***	0.021***	0.018*
θ_wydev	0.010	0.004**	0.014	0.018
Constant	0.408	0.010***	0.018***	0.020***
Observations	6179			
R^2	0.281			

[a]The dependent variable is Δq_{rel}. May is the omitted category for the month dummies. Single asterisk indicates significant at 90% level; double asterisk indicates significant at 95% level; triple asterisk indicates significant at 99% level.
[b]*Newey and West* [1987] standard error.
[c]Ordinary least squares standard error.

occur throughout the November to March period. While these effects are smoothed through multiyear averaging in this seasonal hydrograph, increased flow associated with several large December and January rain and rain-on-snow events can be seen.

[26] Figure 3b depicts the proportional gain in streamflow between upper and lower gauges for pre and post restoration periods, averaged by day of year. As expected, the effects of restoration differ seasonally and there are distinct responses during the peak snowmelt recharge period (mid-May through mid-June), the initial snowmelt recession period (June–July), and the late summer and early fall period (August–October). Changes in streamflow gain during the winter and peak snowmelt recharge periods show the expected tendency toward lower values (supporting hypothesis 1) in February–April and November–December. The largest relative changes in streamflow occur during the snowmelt recession period. Increased streamflow in the lower gauge relative to the upper gauge during this period is consistent with our hypothesis 2 that increased riparian storage and reduced riparian channel gradients support higher flow during snowmelt recession. These increases diminish throughout the summer and early fall base flow periods (hypothesis 3). Note that late summer and early fall base flow patterns are likely to combine two effects: First, toward the tail of the streamflow recession period, the impact of increased storage and slower drainage remains although it diminishes relative to June–July increases. Second, during this late summer and early fall period, higher groundwater levels may support increased evapotranspiration losses leading to reduced flow. The combination of remaining effects of increased storage support for base flow and increases in evapotranspiration may effectively cancel each other leading to no observed change in late season base flow.

[27] We use the regression model represented by equation (2) to test whether the seasonal effects evident in Figure 3b are statistically significant. Table 1 reports the estimated coefficients. As noted above, coefficients δ denote changes in monthly differences between gauges following restoration and are the primary focus of the analysis. The coefficients β provide estimates of the monthly differences between gauges that are constant from 1990 to 2004. Coefficients β differ across months and are statistically significant for all months. Monthly differences show that there are seasonal differences in the relationship between the upper and lower gauges. It is also worth noting that year-to-year differences in the timing and magnitude of snowmelt inputs, as reflected in the deviation of total water year streamflow from the norm ($wydev_t$), do not have a significant effect on relative streamflow differences.

[28] The estimated coefficients δ support the hypothesis (hypothesis 2) that during the recession period the relative gain in flow between the upper and lower gauges will increase. There is a statistically significant increase in percent gain for both June and July following restoration, and the July increase is the largest monthly effect. The magnitudes of these increases are substantial: the increase in flow at the lower gauge, relative to the upper gauge, is 11% in June and 24% in July. Note in Figure 3b that June and July are high-

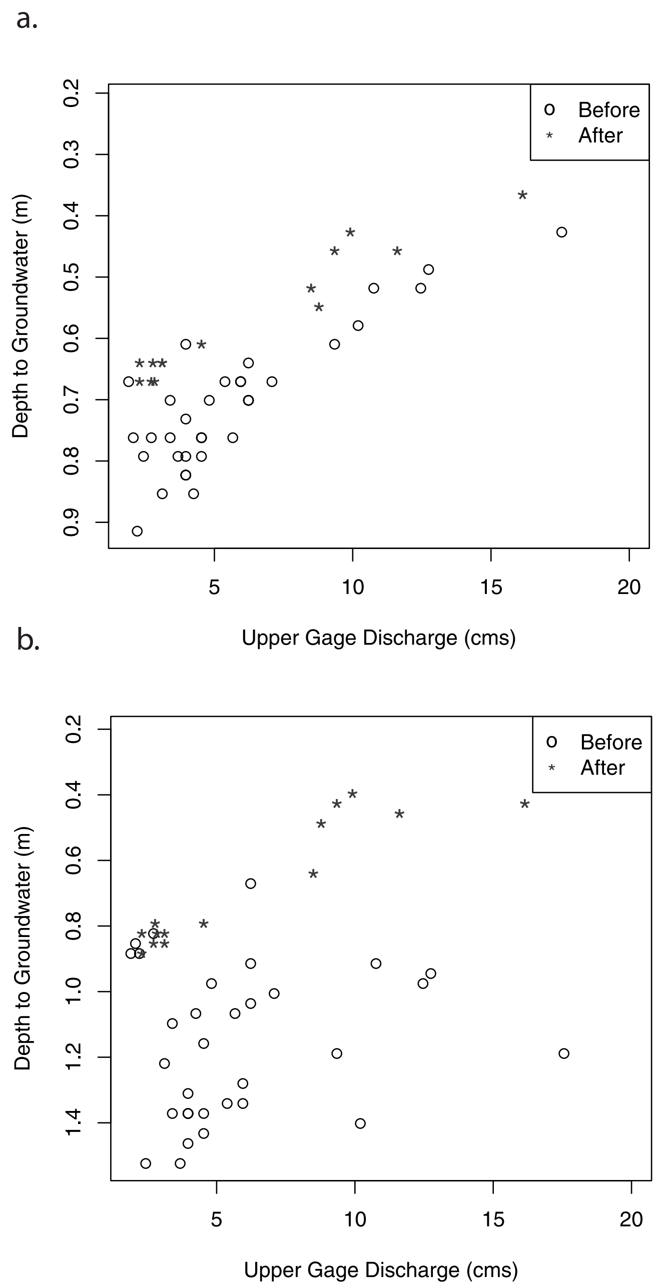

Figure 4. Depth to groundwater versus discharge at the upper gauge for prerestoration and postrestoration periods for (a) groundwater well T1W2 and (b) groundwater well T5W3.

flow periods; thus these relative increases correspond to substantial changes in absolute flow volumes.

[29] Accounting for serial autocorrelation using with the Newey-West standard errors decreases the level of statistical significance of the changes in June and July, from 99% to 95% or 90%, depending on the size of the lag. We assume that a significance level greater than 90% reflects a meaningful change in streamflow behavior, and thus the estimated changes in streamflow for June and July are robust to the effects of serial autocorrelation.

[30] During the winter and early snowmelt periods, relative streamflow generally decreases, as predicted by hypothesis 1, although the coefficients are not always statistically significant. The decrease in streamflow is statistically significant in February and March, even with the 30-day lag to account for serial correlation. In August through October, there is no statistically significant effect of restoration on streamflow.

3.2. Effects of Restoration on Groundwater

[31] Figure 4 shows the relationship between depth to groundwater and discharge for two wells, T1W2 and T5W3, for which the distance to the channel increased (22 to 40 m) and decreased (48 to 28 m) respectively following restoration. As expected, overall depth to groundwater decreases, and depth to groundwater values for a given streamflow value are lower following restoration. The slope of the discharge-groundwater relationship, however, does not appear to change. A high groundwater table (lower depth)

Table 2. Linear Regression Results for Changes in Groundwater Levels[a]

Variable	Coefficient	OLS SE[b]	Clustered SE
λ_q_{upper}	−0.027	0.003***	0.005***
φ_R	−0.324	0.029***	0.052***
γ_Rq_{upper}	0.003	0.003	0.004
$\rho\_distance$	0.0001	0.0003	0.0002
Constant	1.144	0.029***	0.065***
Well fixed effects (18)	yes		
Observations	842		
R^2 (within)	0.47		

[a]The dependent variable is $gwlevel_{it}$. Single asterisk indicates significant at 90% level; double asterisk indicates significant at 95% level; triple asterisk indicates significant at 99% level.
[b]OLS SE, ordinary least squares standard error.

following restoration is consistent with our conceptual model that restoration increases storage in the riparian zone.

[32] Table 2 reports the results of regression model (3) applied using all available groundwater wells (as shown in Figure 2). As expected, depth to groundwater is significantly related to streamflow, with lower streamflow corresponding to greater groundwater depths. Depth to groundwater also increases with increasing distance from the channel, although this effect is not statistically significant. The depth to groundwater decreases significantly with restoration (R_t), but there is no significant change in the relationship between streamflow and groundwater table elevation ($R_t\ q_{upper}$). The decrease in depth to groundwater is substantial. For example, mean August base flow is 0.01 cm. At this August base flow value, for a well 0.5 m from the channel, the model estimates a decrease from 1.1 to 0.8 m in groundwater depth following restoration. Mean depth to groundwater for all sample dates and wells prior to restoration was 1.4 m, and 1.0 m following restoration.

[33] Riparian and aquatic ecosystems are dependent on the timing and magnitude of groundwater levels and streamflow. Thus changes to hydrologic regimes have been shown to impact specific organisms as well as overall ecosystem health [*Poff et al.*, 1997; *Kauffman et al.*, 1997]. Our analysis of paired gauge streamflow and groundwater well measurements provides evidence of a strongly seasonal pattern of hydrologic impacts of restoration for the snowmelt-dominated Trout Creek. Changes in streamflow, particularly the statistically significant increases in recession flow during June and July, indicate that restoration has lead to greater storage and slower drainage of near-channel areas. This interpretation is further supported by significant decreases in depth to groundwater in riparian zone wells. The seasonal pattern of results suggests that the primary impact of restoration on streamflow regimes occurs during the snowmelt recession period. Increases during the recession period (both absolute and relative) diminish as flow magnitude decreases throughout the summer.

[34] Changes to groundwater dynamics, however, are maintained throughout the summer period. One of the primary goals of channel restoration projects, including Trout Creek, is to reduce the dewatering of riparian areas and the associated impacts on the structure and function of riparian ecosystems. Decreases in depth to groundwater across a range of discharge conditions in Trout Creek suggest that restoration has successfully improved riparian water availability for vegetation. In a report by *Western Botanical Services*, Inc. [2003], a general trend toward a wetter, more hydric plant community was observed throughout the Trout Creek meadow, and most of the mesic species present before restoration exhibited declines in cover values. By the time the vegetative survey had been completed in 2002 vegetative cover of native perennial forbs had almost doubled. An increase in plant diversity and vigor had occurred despite droughtlike conditions in the preceding years. At the time of the survey, willow densities had not changed, but were still expected to increase as the new cuttings grew and matured. Initial postproject evaluation also found evidence of increases in invertebrate and fish populations [*SHG*, 2004; *Wigart*, 2004]. We note that the restoration of Trout Creek was an intensive undertaking that included reworking of both the channel and riparian zone was guided by geomorphic principles. Other less intensive restoration projects which focus solely on the stream channel may not yield comparable changes in hydrologic regimes.

[35] Underlying variability in hydrologic and climatic processes coupled with inadequate monitoring, infrequent reporting, and the relatively low number of adequate restoration sites continues to limit the availability of data to support restoration research [*Moerke and Lamberti*, 2004]. In an analysis of a restoration project in Idaho, for example, *Klein et al.* [2007] found no statistically significant changes to several hydrologic variables following restoration. They attribute the lack of statistical significance to small sample size and high interannual variability. These are common problems in postrestoration assessment, where monitoring data is limited and climate drivers of hydrologic variables tend to show significant interannual and seasonal variation. Aggregation of streamflow data into monthly or annual time scales further limits data availability. Aggregation, however, is often necessary in order to avoid the problem of serial autocorrelation in discharge measurements. In this study, the use of the Newey-West approach supported the use of daily data by accounting for autocorrelation. This study demonstrates the utility of the Newey-West nonparametric approach for robust statistical inference and offers an alternative to autoregressive methods commonly used in hydrologic science to account for serial autocorrelation. Unlike autoregressive methods, Newey-West does not require assumptions to be made about the form of the serial autocorrelation and thus is likely to be robust across a wider variety of situations. Assessment in this study was also supported by the availability of paired gauges above and below the restoration site. Paired gauges are not routinely included in restoration assessment planning, and this study demonstrates the potential utility of the approach.

4. Conclusions

[36] One of the primary objectives of reengineering the channel in Trout Creek was to improve ecologic function by increasing summer water availability in riparian areas. Analysis of streamflow and groundwater data in this study suggests that restoration did alter the relevant hydrologic processes and that these effects were significant, even given substantial climatic variation. Restoration projects such as the Trout Creek are likely to continue to be one of the main thrusts of restoration activities. Snowmelt-dominated envi-

ronments, where human impacts were once limited, have experienced significant development pressures in the past decades. Restoration projects will likely continue to receive significant public and private funding in these areas and the need for monitoring and assessment will continue [*Cobourn*, 2006; *Bernhardt et al.*, 2005]. Statistical techniques that increase extractable information from available data are important assessment tools. This study demonstrates the utility of paired gauge instrumentation and the Newey-West approach to account for serial autocorrelation, in addition to documenting postrestoration hydrologic change across a wide range of flow conditions. Further studies are still needed to provide a foundation of research on hydrologic effects of channel restoration in a wide range of geographic settings.

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