PROCEEDINGS OF THE TWENTY-SIXTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2013
Pomona College, Claremont, CA

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KECK GEOLOGY CONSORTIUM
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Keck Geology Consortium: Projects 2012-2013
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INTRODUCTION

Fresh water in the western continental U.S. is a scarce resource that is becoming more difficult to obtain (Miller and Piechota, 2011). The discharge of mountain streams is closely monitored in many areas to ensure the proper amount is allocated from runoff and storage to supply the needs of downstream agriculture and municipalities. Since seasonal snowmelt generates a large percentage of the fresh drinking water in the western USA, the processes that govern its distribution and melt rate must be understood to better predict the amount of runoff and hence water storage and use restrictions. Monitoring of discharge emphasizes large streams or main tributaries, because these are the most economically significant and easiest to measure. Small catchments are less closely monitored, but a clear understanding of catchment-scale processes is vital to predicting the timing of flows in larger basins downstream.

Small (<10 km^2) alpine catchments cover significant area in the headwaters of Colorado river basins. These catchments vary widely in both open-channel and subsurface flow, depending on factors including precipitation characteristics, snowpack distribution, and surficial materials, challenging efforts to construct comprehensive regional runoff models. Climate change poses additional challenges, both for obtaining water and for predicting temporal shifts in surface and groundwater flow from alpine regions (Lapp et al, 2005; Laghari et al., 2012). Present groundwater contributions to alpine runoff exceed 50% in some basins (Liu et al., 2004; Clow et al., 2003). Understanding water storage and transmission characteristics of these basins is critical to predicting how alpine discharge will change over time (Day, 2009).

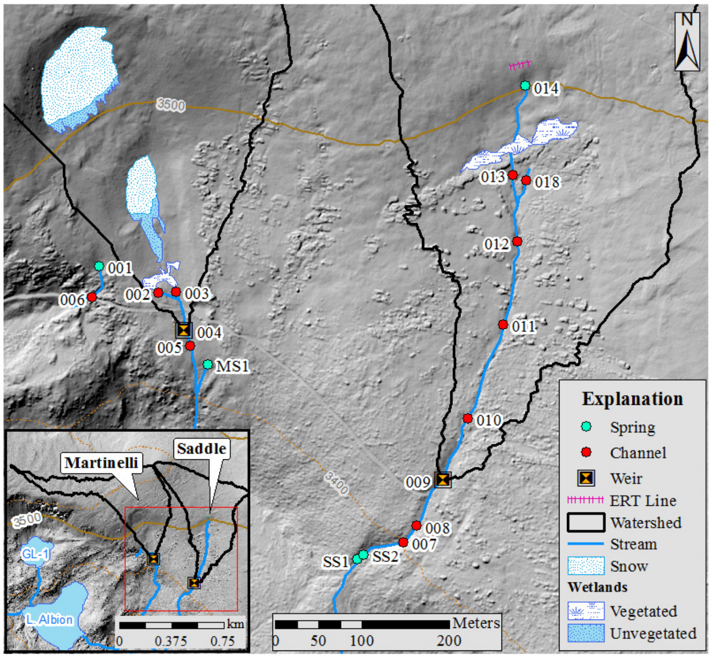

Figure 1. Martinelli and Saddle streams and measurement locations. Inlay: the study areas in a larger context of the basin. Both use hillshaded LiDAR DEM basemap (Anderson et al., 2012).

Most hydrogeological research in the Niwot Ridge area has focused on the Martinelli (Fig. 1) catchment. Caine (1989) investigated subsurface contributions to discharge. More recent studies (Liu et al., 2004; Clow et al., 2003) constructed simple water budgets for Martinelli as part of broader studies. Cowie (2011) and King (2012) analyzed the hydrologic budget of Saddle Stream (Fig. 1). Both studies used groundwater measurements, which do have advantages—but also spatial and physical limitations. To construct a more comprehensive surface-water budget, this study uses field measurements of snowpack area, discharge and temperatures, and estimates of sublimation, evaporation, and evapotranspiration from previous research.

The central concept of a water budget is that in a watertight basin, the input quantity of water equals the output plus evapotranspiration. If the inputs and outputs (measured and assumed) do not equal one another, some combination of the measurements or assumptions is incorrect (i.e. perhaps the basin is leaky). The focus of this project is using measured and estimated values to examine short- and long-term water budgets for two adjacent basins: Martinelli and Saddle.

RESEARCH AREA

Study Sites

Saddle and Martinelli streams (shown in Fig. 1) are located in the Green Lakes Valley on the south flank of Niwot Ridge in the Colorado Front Range (Fig. 1 of Dethier and Ouimet, this volume). Although the watersheds share similar geology, summer diurnal flow, size (both measure 0.25 km^2 contributing area above their respective weirs) and position, they are distinct in their processes of accumulation of snow and their small-catchment hydrology.

Martinelli accumulates a snowfield that persists late in the summer, and part of the catchment has a morphology and directionality that make it an unusual south-facing nivation hollow. The snowfield melts completely during roughly half of the years (Caine, unpublished data). The accumulation of windblown snow in the hollow produces this unusual south-facing snowfield. In contrast, the snowpack in the Saddle catchment may only last into early summer and the stream is not fed by an extensive snowpack late in the season. Thus discharge at the weir disappears more quickly during the melt season at Saddle than it does at Martinelli. Snowpack size and persistence is the cause of many differences in the hydrologic and biologic makeup of the two basins.

Climate

The study sites are slightly above treeline in the alpine climatic zone. In 57 years through 2010, the Saddle Tundra Lab meteorological station (several hundred meters upslope of the Saddle Stream at 3528 m) had recorded a yearly mean temperature of -2.2 ^{o}C and 930 mm of mean annual precipitation (NWTLTER, 2010). As much as 80% of the precipitation (Caine, 1995) falls as snow from storms carried in by northwesterly airflow or by upslope easterly winds. In the warm summer months, strong convective storms bring precipitation as rain or hail. Average wind velocity in the high alpine at D1 meteorological station (2.1 km west-northwest at 3750 m) was 8 m/s through 2010, and recorded maximum gusts of 50 m/s in the most extreme winter conditions. These winds prevent snow from accumulating on top of the ridge. Some of the blown snow from the ridge accumulates in hollows like Martinelli and, to a lesser extent, in topographical depressions like Saddle basin.

METHODS

My data were provided by field measurements, and by ongoing monitoring of discharge in both Martinelli and Saddle by the Niwot Ridge LTER (NWTLTER) program and the University of Colorado at Boulder's Institute of Arctic and Alpine Research (INSTAAR). In addition to using long-term weir data, I measured short-term discharge and water temperature at 17 sites in Martinelli and Saddle two days a week. I measured discharge at ~50-100 m intervals along the channel using a stopwatch and a heavy duty trash bag placed flush with the bed of the channel. Measurements were taken from the bottom to the top of Saddle catchment on Tuesday and Thursday mornings, and in the Martinelli catchment in the afternoons. Martinelli measurement locations (Fig. 1) were numbered 001-006 (discharge from MS1, the Martinelli weir was not used) and Saddle locations were originally named SS1, SS2, and 007-014 from the lowest "Saddle Spring" sites to the top. Measurement site 018 (10m east of 013) was added later.

I also measured the area of Martinelli snowfield with a Trimble GeoXT handheld GPS unit running ESRI ArcPad software. T. Nelson Caine provided long-term measurements of snowfield area, discharge at the Martinelli and Saddle weirs, and short-term measurements of rainfall and ablation rate. Runoff at Saddle and Martinelli are calculated using gage height flow measurements at each of the weirs.

On average, the Martinelli snowpack ablates 0.1 m per day, and during the post-peak discharge period has an average density (ρ) of 0.5 (Caine, personal communication; modified from Gutmann et al., 2012). Using these values, plus snowpack area measurements from the years 1991-2012 (Caine, unpublished data), I obtained an estimate of meltwater volume for each field day in cubic meters. I then compared corresponding days' discharge records (Caine, unpublished data) with the 284 snowmelt estimates to obtain a daily yield from calculated snowmelt; since in a watertight basin, daily discharge recorded at the weir should exceed the daily volume of meltwater produced by the snowpack. This process is summarized in Equation 1:

$$\frac{Q}{a * \rho * A}$$

where Q is measured daily discharge in m^3d^{-1}, *a* is ablation in md^{-1}, ρ is snow density, and *A* is snowpack area in m^2.

Table 1. Summary of hydroclimatic values from Niwot Ridge and nearby locations (after King, 2012).

	Elevation (m)	Precipitation depth	Sublimation	Evapotranspiration	Evaporation	Runoff depth	Yield (%)
Saddle	3420	930	*140*	*0 - 260*	*0 - 223*	230	24.7
Martinelli	3428	930	*140*	*~ 0*	*0 - 223*	310	33.3
Como	2910	800	*140*	*0 - 260*	*0 - 223*	168	21.0
GL-4	3515	993	*0 - 140*	*~ 0*	*0 - 223*	883	88.9

Values expressed in millimeters unless otherwise noted. Italics indicate estimate. Range describes spatially variable value.
Runoff is based on gage records, 1982-2012 for Martinelli and 1999-2012 for Saddle, from Caine (unpublished data), and NWTLTER (2012); 2009 for Como from Cowie (2011); and 1981-1993 for GL-4 from Caine (1995). Precipitation is from NRCS (2010) at Saddle and Martinelli, Leopold et al. (2010) at D-1 for GL-4, and Cowie (2011) for Como. Sublimation is from Hood et al. (2010), ET is based on Greenland (1989), and evaporation is based on Knowles et al. (2012). Elevation of Como and GL-4 are from Cowie (2011).

This study relies heavily on previous studies of climate-controlled factors like precipitation, sublimation, evaporation, evapotranspiration, and runoff (shown in Table 1). Sublimation has been calculated using eddy covariance techniques to interpret wind speed, and humidity data from the Tundra Lab (Hood et al., 1999). Evapotranspiration could be as much as 260 mm yr^{-1} below treeline, but all of Martinelli and most of Saddle is above treeline, so this is likely an overestimate. Knowles et al., (2012) estimate combined sublimation and evaporation to equal 39% (or ~360 mm yr^{-1}) of Saddle's mean annual precipitation atop the ridge, but ridgetop measurements differ from those on the slopes because standing water in flat wetlands receive much more radiation than does water in slopeside channels. Subtracting Hood et al.'s estimate of sublimation (140 mm yr^{-1}) from the Knowles et al. (2012) value (evaporation plus sublimation ≅ 360 mm yr^{-1}) gives ~220 mm yr^{-1} of precipitation-equivalent evaporation, which I also consider to be anoverestimate for the slopes of the Martinelli area.

The specific yield of a basin measures the percent of precipitation in a basin that discharges as surface water. The value is calculated by comparing a known amount of discharge per basin area to a known amount of precipitation. In order to calculate the short-term specific yield of each basin, I analyzed an extended storm event that occurred during the 5^{th} – 10^{th} of July, 2012. The timing of the storm was convenient, because it allowed weir values from around this time to be field-checked, and it was late enough in the season that the Saddle weir was recording no daily discharge before the event started, which allowed me to assume that all discharge was storm-related. I compared discharge values during this event from the Green Lake 4 (GL4) watershed (Fig. 1, Dethier and Ouimet, this volume) to Saddle and Martinelli values. This 2.3 km^2 basin contains the Arikaree glacier and makes up the head of the Green Lakes Valley. Since the GL4 stream and most of the rest of the watershed is underlain by glacially polished bedrock, and should be approximately watertight, it serves as a standard of comparison for the two basins used in this study. Watershed areas for the three basins were calculated from a LiDAR DEM base (Anderson et al., 2012).

Baseflow (non storm-related discharge) for each short-term specific yield calculation was estimated by averaging the pre-storm (July 4) and post-storm (July 10) discharge values measured at each basin's weir. In the case of Saddle, the pre-storm discharge was zero, so the discharge that resulted is presumed to be entirely storm-related, and therefore the baseflow is calculated as zero. Precipitation values were estimated using various gage records and other studies (Table 1).

RESULTS

Field measurements show that the Saddle Stream follows an atypical discharge pattern over distance. Discharge consistently increases over the first 450 meters downstream from the Saddle source (Fig. 2), and then decreases by more than 50% over less than 100 meters of ground distance between site 010 and the Saddle weir, site 009. The first synoptic measurement, from July 10th, was made soon after a significant rain event, which raised the water table in both shallow and deep monitoring wells in Saddle and Martinelli basins, (M. Zeliff, University of Colorado, unpublished data).

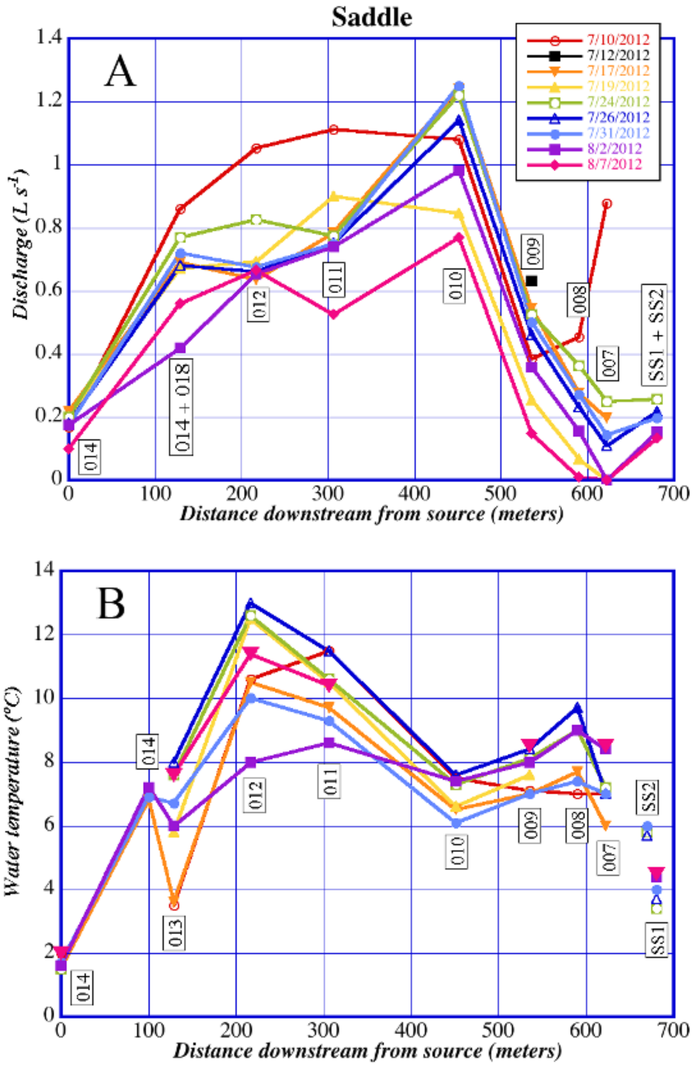

Figure 2a. Saddle Stream discharge and b. water temperature, plotted versus distance downstream from source to measurement location. Measurements were collected in the morning, as often during the field season, the stream ceased to run to the weir in the afternoon.

Temperature values measured in each basin varied widely. Predictably, water temperatures at springs were colder than surface flow. For Saddle Stream, temperature generally increased for the first 200-300 meters downstream from the source, then decreased reliably to measurement point 010.

Martinelli stream showed similar discharge irregularity (Fig. 3). Discharge decreased towards the gage throughout the field season, and the small channel fed by a cold spring (site 001) west of the watershed boundary appeared to direct most of its discharge out of the basin, and soon disappeared back into the ground. Below the lowest measurement point, near the glacial wall of the U-shaped valley, cold water reemerged in a side channel that was measured at 1 liter per second on August 7. Even further down the channel, as the slope increased and bedrock exposures could be seen, the discharge increased again significantly with no obvious surface source.

When I compared the estimated snowmelt volume with the gage records in Martinelli over the period 1991-2012, I found that Martinelli had an average daily yield equivalent to 39.4% of calculated snowmelt volume, with a standard deviation of 34.6% (n = 284). The Saddle snowpack is much smaller and the number of days when measurements were taken is much lower (n = 5). Moreover, the average daily yield for these five days in 2010 and 2011 in Saddle exceeds the calculated discharge from the snowpack. Thus, the relationship between the Saddle snowpack and discharge cannot be used to quantitatively constrain specific yield calculations. Specific yield calculations for both Martinelli and Saddle weir locations were similarly low (Table 2). Using the early July rain event and the associated spike and recession in discharge, I calculated a short-term specific yield of 2.2% for Martinelli and 2.7% for Saddle, compared to 51.5% for the nearby Green Lake 4 basin (Table 2).

Dr. Matthias Leopold of the Technical University of Munich collected electrical resistivity tomography (ERT) data with NSF student Gabriel Lewis in a crucial location to this study, approximately 25m above the source of the Saddle Stream. The purpose was to discover if the unusually cold water temperatures measured at the source were caused by melting of one or more local ice lenses. Lewis (this volume) interprets

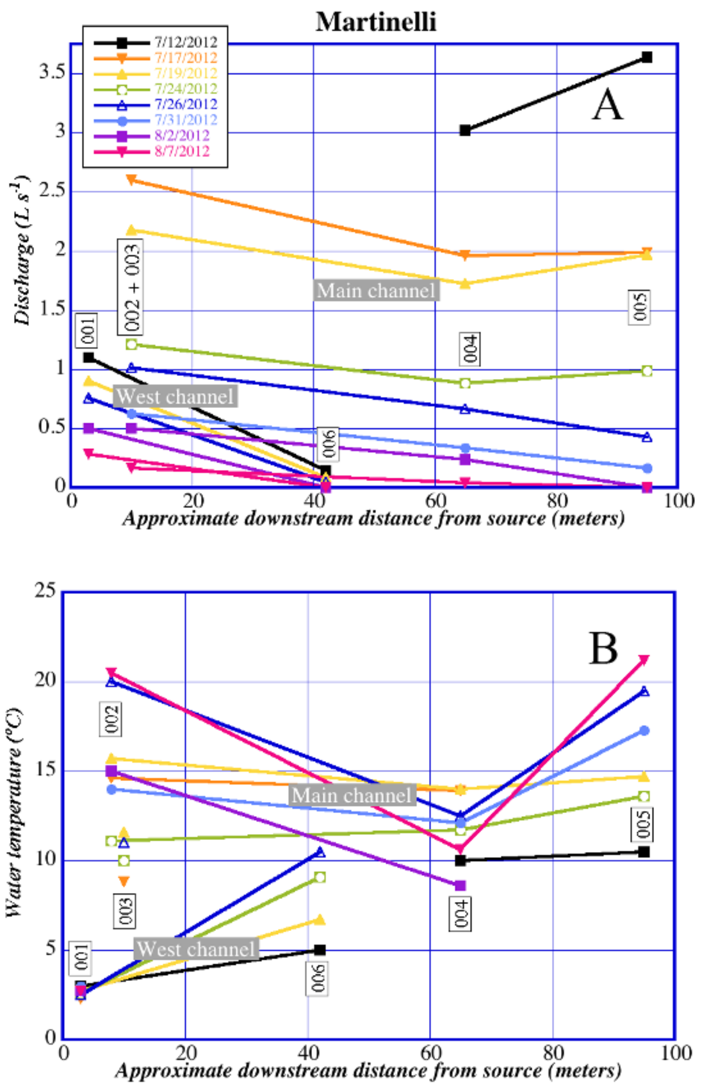

Figure 3a. Martinelli discharge and b. water temperature, plotted by channel and organized by date versus distance downstream from emergence point.

the ERT data as showing no ice lens in the subsurface, but he finds silty, gravelly sand over openwork cobble gravel starting at ~70 cm depth and extending more than 5 meters into the subsurface. The ERT line did not find bedrock.

DISCUSSION

The yield of a typical basin should approximately equal the amount of precipitation minus that removed by evaporative forces. Although Martinelli lateral flow changes are not as unusual as those in Saddle Stream, the basin yields almost as little surface water at the gage. Predicted daily values of snowmelt for the basin exceed measured discharge yield values especially at low flow, even though the groundwater inflow and precipitation that adds to its discharge. Because snowmelt is not the only input to discharge at Martinelli (a steep basin without significant vegetation where ET and evaporation are probably low), the fact that the daily yield volume only exceeds the daily snowmelt volume estimate on 11 days when *n* = 284 implies strongly that some process or alternate hydrologic pathway is allowing discharge to elude the gage.

Table 2. Calculations of specific yield, using values greater than baseflow for the period of July 5-10, 2012.

Date	University Camp ppt (mm)	Est. GL4 ppt † (mm)	GL4 Q (m^3d^{-1})	Martinelli Q (m^3d^{-1})	Saddle Q (m^3d^{-1})	Calculation
4-Jul-2012	0	*0*	15931	182	0	
5-Jul-2012	7.62	*5.11*	15476	207	22	
6-Jul-2012	78.74	*52.76*	74142	424	313	
7-Jul-2012	12.7	*8.51*	39911	319	108	
8-Jul-2012	17.78	*11.91*	21623	279	90	
9-Jul-2012	0	*0*	17040	215	71	
10-Jul-2012	0	*0*	14915	182	47	
11-Jul-2012	2.54	*1.70*	12446	161	51	
12-Jul-2012	0	*0*	19045	149	13	
Total, 7/05 - 7/10	116.84	*79.98*	183107	1626	651	
			15423	182	0	Baseflow ‡
			90570	534	651	Stormflow (m^3)
			41.19	2.15	2.63	Storm runoff (mm)
			51.49	2.20	2.68	Specific yield (%) §

† GL-4 precip. calculated using linear rainfall-distance function between U.Camp, Albion, and GL4 (GL4 = U. Camp ppt * 0.67)

‡ calculated as average of daily discharge values from before and after storm flow (July 5 and 10), except for Saddle where all discharge was assumed to be storm-related

§ Martinelli and Saddle yield calculated using Albion precipitation for 7/05 - 7/10 (98 mm) as proxy

Short-term specific yield calculations (Table 2) are well constrained in Saddle due to the fact that no discharge was being recorded at the weir before the storm, so we can assume baseflow is zero and any subsequent recorded discharge is runoff. In the short term, some precipitation that falls on the basin is used to recharge groundwater, but since long-term calculations show similarly low yield for both basins, the above hypothesis is reinforced.

Fundamental to the study of surface water hydrology is the idea that discharge characteristically increases downstream as basin area increases. Flow in the study areas does not follow this pattern (Figs. 2a, 3a). Discharge in Saddle basin decreases sharply over less than 100 m of channel distance. None of the evaporative processes can cause this decrease in discharge between the two locations because it occurs so suddenly. Therefore, water loss must be caused by flow into a more favorable hydrologic pathway.

Water temperature over distance changes nearly as dramatically as discharge. Summer stream water temperature, like discharge, typically increases asymptotically downstream as it is exposed to the ambient air and solar radiation. In Saddle, the results show that temperature reached a peak near 200-300 meters downstream from the source, but then rapidly became colder again as discharge increased. However, discharge increased in the absence of any surface tributary, so we must assume that groundwater admixed with the surface water, possibly in an elongate vadose zone.

After the maximum discharge occurred at site 010 in Saddle, the amount of discharge measured at site 009 was approximately 0.6 liters per second less. When the Martinelli calculated snowmelt is compared with measured discharge, it is evident that groundwater discharge increases at higher flows, so the same is likely true at Saddle.

ERT data (and soil pits) suggest that there are stratigraphic layers on the south-facing slope of Niwot Ridge that can accommodate large volumes of water. Due to the fact that this surface is covered in inactive periglacial features, it is reasonable to hypothesize that periglacial processes buried gravel layers such as that described by Lewis (this volume) or old stream channels on the south-facing slopes drained by Martinelli and Saddle. Discharge of 0.6 liters per second disappeared between Saddle locations 010 and 009 at low flow this field season, bypassing the weir. Heath (1982) states that just a 1m^2 cross-section of gravel bed can transmit 100 m^3 to approximately 5000 m^3 of groundwater flow per day. Thus, losses to groundwater are capable of accounting for at least some of the missing discharge in both basins.

CONCLUSIONS

The study demonstrates a significant disparity between the inputs and outputs of the water budgets of Martinelli and Saddle streams, similar to that reported for Como Creek. This finding could be due to permeable, subsurface stratigraphic layers that provide subsurface hydrologic pathways that bypass gages.

Future work should include estimating annual subsurface yield values based on the results shown. Other work could involve applying a two-component mixing model to the water in the Saddle Stream in order to estimate the volume and temperature of the colder subsurface water added to the surface channel.

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